2013

The Use of Phosphorus Sorption Isotherms to Project Vegetative Treatment Area Life

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Abstract
Beef feedlots of all sizes are looking for cost-effective solutions to manage feedlot runoff. Vegetative treatment systems (VTSs) are a potential option. VTSs consist of a solids settling structure followed by additional treatment components, such as vegetative infiltration basins (VIBs) and/or vegetative treatment areas (VTAs) that use soil and vegetation to treat nutrients in the applied runoff. Investigations have shown that VTSs can provide a cost-effective means of controlling feedlot runoff; however, their sustainability and life expectancy have not yet been determined. Thus, the objective of this work is to evaluate, based on the VTAâ€™s ability to sorb and utilize phosphorus, the expected phosphorus sink life of VTSs on beef feedlots in Iowa. In doing so, we evaluated three things: (1) phosphorus removal with vegetation harvest, (2) the extent of vertical redistribution of phosphorus in the soil profile, and (3) if a mass balance approach was capable of predicting changes in soil test phosphorus. Vegetation harvest removed 6% to 16% of the applied phosphorus, and a P mass balance did an adequate job of predicting the significant increases in soil P test concentrations. Deep soil cores (1.2 m) showed that phosphorus accumulation tended to be limited to the top 0.3 m but that vertical migration was increasing. Based on this success, we proposed a P mass balance and soil sorption model to project VTA life expectancy and evaluated the sensitivity of the estimated life to different design and management alternatives. The sensitivity analysis showed that phosphorus sorption capacity and loading rate were important, but the critical depth of the soil that can be saturated has the largest impact on VTA life.

Keywords
feedlot runoff, phosphorus sorption isotherms, vegetative treatment areas, VTA life, waste treatment

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
This article is from *Transactions of the ASABE* 56, no. 3 (2013): 935–949, doi:10.13031/trans.56.9871.

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J. F. Baker, D. S. Andersen, R. T. Burns, L. B. Moody

Abstract. *Beef feedlots of all sizes are looking for cost-effective solutions to manage feedlot runoff. Vegetative treatment systems (VTSs) are a potential option. VTSs consist of a solids settling structure followed by additional treatment components, such as vegetative infiltration basins (VIBs) and/or vegetative treatment areas (VTAs) that use soil and vegetation to treat nutrients in the applied runoff. Investigations have shown that VTSs can provide a cost-effective means of controlling feedlot runoff; however, their sustainability and life expectancy have not yet been determined. Thus, the objective of this work is to evaluate, based on the VTA's ability to sorb and utilize phosphorus, the expected phosphorus sink life of VTSs on beef feedlots in Iowa. In doing so, we evaluated three things: (1) phosphorus removal with vegetation harvest, (2) the extent of vertical redistribution of phosphorus in the soil profile, and (3) if a mass balance approach was capable of predicting changes in soil test phosphorus. Vegetation harvest removed 6% to 16% of the applied phosphorus, and a P mass balance did an adequate job of predicting the significant increases in soil P test concentrations. Deep soil cores (1.2 m) showed that phosphorus accumulation tended to be limited to the top 0.3 m but that vertical migration was increasing. Based on this success, we proposed a P mass balance and soil sorption model to project VTA life expectancy and evaluated the sensitivity of the estimated life to different design and management alternatives. The sensitivity analysis showed that phosphorus sorption capacity and loading rate were important, but the critical depth of the soil that can be saturated has the largest impact on VTA life.*

Keywords. *Feedlot runoff, Phosphorus sorption isotherms, Vegetative treatment areas, VTA life, Waste treatment.*

Animal feeding operations (AFOs) and concentrated animal feeding operations (CAFOs) produce large volumes of wastewater. This wastewater is a potential source of pollutants to surface and ground waters because it contains nitrogen, phosphorus (P), organic matter, solids, and pathogens. As a result, the U.S. Environmental Protection Agency (EPA) developed a set of effluent limitation guidelines (ELGs) that described the design and operating criteria for waste management systems on CAFOs (Anschutz et al., 1979). The U.S. EPA required open-lot beef feedlot CAFOs to contain all wastewater and runoff resulting from storms smaller than the 25-year, 24-hour event (EPA, 2006, 2008). These effluent limitation guidelines historically required collection, storage, and land application of feedlot runoff; however, the 2003 CAFO rule allowed the use of alternative technologies that met or exceeded the performance of containment basin land application systems (EPA, 2006).

Traditionally, beef feedlot runoff was collected in a settling basin, the solids settled out, and then the supernatant was transferred to a storage structure. Periodically, the effluent in these structures needs to be land applied to maintain sufficient storage capacity for a 25-year, 24-hour rain event. Increases in feedlot size require additional storage capacity to be constructed. This can be costly, as construction of containment basins costs on average $205 and $136 per head for AFO and CAFO feedlots, respectively (Bond et al., 2010). Beef producers have expressed interest in non-basin technology that eliminates the need for long-term storage and provides a more cost-effective option for feedlot runoff control (Woodbury et al., 2005). One way to decrease costs would be to use a vegetative treatment system (VTS). Bond et al. (2010) reported that construction costs for VTSs averaged $77 and $85 per head for AFOs and CAFOs, respectively. However, knowing the life expectancy of these systems is critical for comparing the costs to other systems.

VTSs consist of a combination of treatment components, at least one of which utilizes vegetation, to manage runoff from open lots. Typical components of VTSs included solids settling basins (SSBs), vegetative infiltration basins (VIBs), and vegetative treatment areas (VTAs).

Submitted for review in July 2012 as manuscript number SW 9871; approved for publication by the Soil & Water Division of ASABE in April 2013. Presented at the 2012 ASABE Annual Meeting as Paper No. 1008593.

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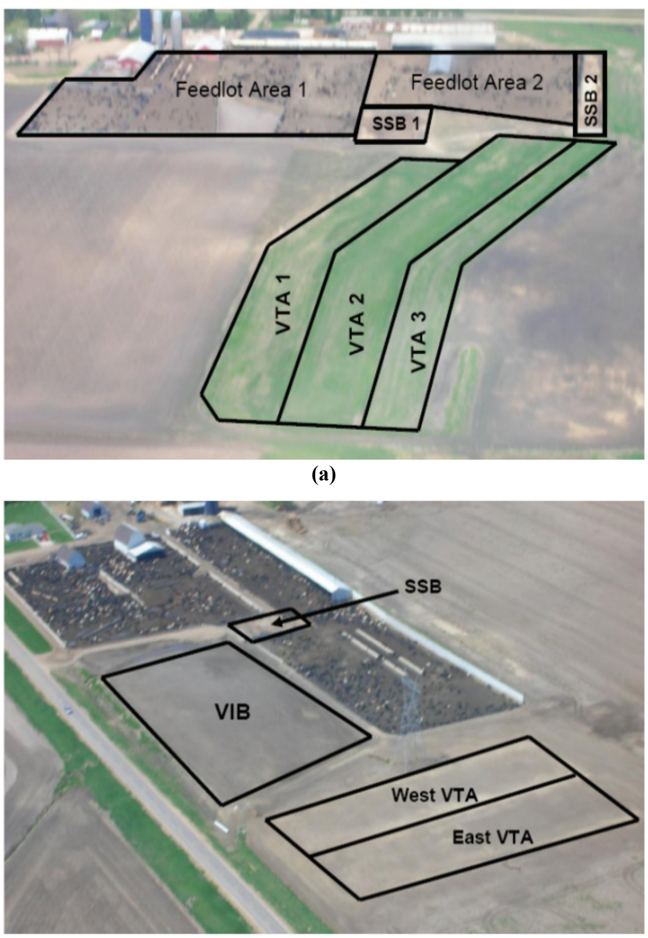
Figure 1 shows examples of SSB-VTA and SSB-VIB-VTA systems. Operation of these systems is as follows. During rainfall events, the SSB receives feedlot runoff. Runoff is held in the basin to facilitate solids settling. Effluent is then pumped or allowed to flow by gravity to the VIB or VTA. The VIB is a flat area, surrounded by berms, that is planted and managed to maintain permanent vegetation (Moody et al., 2006). Runoff effluent is flooded over the VIB surface. Effluent that percolates through the soil is collected in tiles buried 1.2 m (4 ft) underground and flows to a sump, where it is pumped onto the VTA for further treatment. The VTA is an area level in one dimension, with a slight slope along the orthogonal dimension to facilitate sheet flow, that is planted and managed to maintain a dense stand of vegetation (Moody et al., 2006). VTA operation consists of applying SSB effluent uniformly across the top of the vegetated area and allowing the effluent to sheet-flow down the slope (Moody et al., 2006). The VTA uses vegetation and soil to treat and utilize nutrients in the applied runoff effluent.

Vegetative treatment areas are being researched in many regions of the U.S. for control of different types of wastewater (Andersen et al., 2009; Zhang et al., 2009). In comparison to settling basin effluent releases, VTSs have



(a)

(b)

Figure 1. Diagrams of VTS configurations: (a) solids settling basin and vegetative treatment area (SSB-VTA) system; (b) solids settling basin, vegetative infiltration basin, and vegetative treatment area (SSB-VIB-VTA) system.

shown an ability to reduce feedlot runoff P concentrations and surface transport by 62% and 86%, respectively (Andersen et al., 2013). However, the sustainability and life expectancy of these systems has not been evaluated. Previous research (Khanijo, 2008; Zhang et al., 2009; Andersen et al., 2011) has suggested that P application rates often exceed the P uptake by the vegetation. This could cause P to build up in the soil, increasing the possibility of P leaching and reduced treatment in the VTS.

Phosphorus mobility in the environment is controlled in large part by the soil's P sorption properties (Bolster and Sistani, 2009). Thus, understanding and predicting P fate in a VTS requires knowledge of the soil's P sorption characteristics. Phosphorus sorption isotherms provide a widely used technique to compare and evaluate the P sorption capacities of different soils, i.e., the soil's phosphorus sink capacity (Sui and Thompson, 2000). The P sorption capacity of the soil can be determined by equilibrating a known mass of soil with a solution of known P concentration (Sui and Thompson, 2000). This technique provides a relationship that describes the partitioning of P between the solid (soil) and liquid (water) phases, and it provides information on a soil's ability to sorb and retain P. The P sorption capacity in combination with a P mass balance was used by Hu et al. (2006) to determine the time required to saturate the soil profile of a municipal wastewater treatment system's land application area with P. In this study, a similar approach was used to project the sustainability and life expectancy of VTAs used to control and treat feedlot runoff on Iowa feedlots.

The objectives of this study were to (1) evaluate if a mass balance approach was capable of predicting changes in soil test phosphorus concentrations on six vegetative treatment areas in Iowa, (2) evaluate changes in soil test phosphorus concentrations with time, (3) use deep soil cores to evaluate if leaching or vertical redistribution of applied phosphorus was occurring, (4) propose a methodology for estimating VTA phosphorus sink life, and (5) evaluate the sensitivity of VTA life to design and management changes. Knowing the life expectancy of a VTS could help producers determine whether a VTA would benefit their operation, improve vegetative treatment systems design, and evaluate the cost-effectiveness of this treatment technology.

MATERIALS AND METHODS

SITE DESCRIPTIONS

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

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

Site (and Abbreviation)	No. of Cattle	VTS Components	Drainage Area (ha)	SSB Volume (m^3)	VIB Area (ha)	VTA Area (ha)	VTA Area per 100 Head (m^2)
Central Iowa 1 (CN IA 1)	1000	1 SSB, 2 VTAs	3.09	4290	-	1.49	1500
Central Iowa 2 (CN IA 2)	650	1 SSB, 1 VIB, 1 VTA	1.07	560	0.32	0.22	340
Northwest Iowa 1 (NW IA 1)	1400	1 SSB, 1 VTA	2.91	3710	-	1.68	1200
Northwest Iowa 2 (NW IA 2)	4000	1 SSB, 1 VIB, 1 VTA	2.96	1120	1.01	0.60	150
Southwest Iowa 1 (SW IA 1)	2300	1 SSB, 10 VTAs	7.49	11,550	-	4.05	1800
Southwest Iowa 2 (SW IA 2)	1200	1 SSB, 1 VTA	3.72	6275	-	3.44	2900

VTA area, and normalized VTA area based on the number of cattle raised on the lot. The VTA areas per head of cattle were similar among the VTA-only systems, while the VIB systems had much smaller VTA areas due to the greater amount of pretreatment expected.

Central Iowa 1 (CN IA 1) was a 3.09 ha feedlot permitted for 1000 head of cattle (fig. 1a). Runoff drained into a solids settling basin designed to hold 4290 m^3 of effluent. The VTA consisted of two sections operated in parallel; each section was 24 m wide and averaged 311 m long. The VTA soil at CN IA 1 consisted of Clarion loam, Cylinder loam, and Wadena loam (USDA-NRCS, 2010).

The VTS at Central Iowa 2 (CN IA 2) consisted of an 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 the VIB tiles was pumped onto the VTA. Soils in the VIB consisted of Nicollet loam and Webster clay loam, and the VTA was Harps loam (USDA-NRCS, 2010). Northwest Iowa 1 (NW IA 1) consisted of a 2.91 ha feedlot permitted to hold 1400 head of cattle. Feedlot runoff was collected in an SSB with a volume of 3700 m^3. The SSB outlet pipe discharged onto a VTA consisting of Galva silty clay and Radford silt loam soils (USDA-NRCS, 2010). Northwest Iowa 2 (NW IA 2) had an SSB-VIB-VTA system designed to control runoff from a 2.96 ha concrete feedlot (fig. 1b). The settling basin collected the runoff and released it to the 1.01 ha VIB, which was 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, which was divided into two 27 m wide sections. The portion receiving effluent was switched manually by the producer. The soil at NW IA 2 consisted of Moody silty clay loam (USDA-NRCS, 2010). Southwest Iowa 1 (SW IA 1) was a 7.49 ha feedlot with an 11,550 m^3 solids settling basin that released effluent to a 4.05 ha VTA that was divided into ten sections. Tile lines were installed to control water table depth below the system and enhance infiltration of effluent into the soil that surrounded each of the VTA sections. Soils in the VTA at SW IA 1 consisted of mostly Judson silty clay loam and smaller areas of Colo-Ely complex (USDA-NRCS, 2010). Southwest Iowa 2 (SW IA 2) was a 3.72 ha feedlot. Runoff drained into a solids 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. The VTA soil at SW IA 2 consisted of Kennebec silt loam (USDA-NRCS, 2010).

Monitoring Effluent Flows and Phosphorus Concentrations to and from the VTAs

VTS monitoring data at CN IA 1, CN IA 2, NW IA 1, and NW IA 2 were collected from June 2006 through December 2009. Data collection at SW IA 1 and 2 began in the 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 (SSB, VIB, and VTA), and the effluent concentrations for multiple parameters (ammoniacal nitrogen, five-day biochemical oxygen demand, chemical oxygen demand, chloride, pH, total phosphorus, total Kjeldahl nitrogen, total suspended solids, nitrate-nitrogen, dissolved reactive phosphorus, and total dissolved solids). Complete descriptions of the monitoring methodologies can be found in Andersen et al. (2013).

Precipitation depths were measured using a tipping-bucket rain gauge (ISCO 674, Teledyne ISCO, Lincoln, Neb.). 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, which were generally snowfall.

The effluent monitoring method used at the settling basin was dependent on the outlet design. A low-profile area-velocity sensor (ISCO 750, Teledyne ISCO, Lincoln, Neb.) was used at settling basins with pipe outlets. A submerged probe (ISCO 720, Teledyne ISCO, Lincoln, Neb.) in conjunction with an 0.45 m (1.5 ft) H-flume was used to monitor the outflow for non-pipe outlets. 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 costs, a new sampling protocol was developed. Under the new protocol, an SSB sample was collected from the first SSB release after a rainfall event, and 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 5 cm (2 in.) turbine flowmeter (Neptune Technology Group, Tallassee, Ala.). An ISCO sampler was interfaced with the turbine flowmeter with an analog interface module (ISCO 780 Smart 4-20, Teledyne ISCO, Lincoln, Neb.). 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 outlets was accomplished using similar methods as those at the settling basin outlets. A low-profile area-velocity sensor (ISCO 750) was used at sites where the VTA had a pipe outlet, and a submerged probe (ISCO 720) in conjunction with an 0.45 m (1.5 ft) H-flume was used at 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 was not collected for a release event, the geometric average (Andersen et al., 2013) for that year and component was substituted. The yearly mass of each parameter released was the sum of the event release totals. The calculated mass release data were then used to determine flow-weighted effluent concentrations.

SURFACE SOIL PHOSPHORUS SAMPLING

Surface soil samples were collected on an annual basis in the fall and once before system operation began. These samples represented soil in the 0 to 30 cm (0 to 12 in.) depth range. A surface soil sample was collected near the VTA inlet, outlet, and at every 61 m (200 ft) along the length of the VTA. At each sampling location, ten soil cores from a radius of 3 m (10 ft) 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 changes in soil nutrient content with time to be tracked. The soil samples were delivered to the Iowa State University (ISU) Soil and Plant Analysis Laboratory, where they were tested for Mehlich-3 phosphorus content.

Statistical analysis of the soil phosphorus data was performed using SAS (ver. 9.2, SAS Institute, Inc., Cary, N.C.). Analyses were performed separately for each site. Each analysis was run as a block design, using sample location as the blocking variable and year as the fixed factor. The year × 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 comparisons.

Soil bulk density was monitored once at each site in the summer of 2007. At each site, three 7.62 cm (3 in.) diameter × 46 cm (18 in.) long soil cores were collected. The soil cores were dried to constant weight at 105°C (approx. 24 to 36 h). Soil bulk density measurements from all three cores were averaged 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 varied 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} would change the estimated amount of phosphorus in the soil by only about 6%.

DEEP SOIL PHOSPHORUS 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 outlet. Each sample location was marked with GPS coordinates so the same location would be subsequently sampled in following years, allowing changes in soil nutrient content with time to be tracked. At each soil sampling location, a soil sampling probe (Giddings Machine Co., Windsor, Colo.) was used to collect a 2.54 cm (1 in.) diameter soil core that was 122 cm (48 in.) long. The sample was then cut into segments to represent the 0 to 15.4 cm (0 to 6 in.), 15.4 to 30.5 cm (6 to 12 in.), 30.5 to 61 cm (12 to 24 in.), 61 to 94.4 cm (24 to 36 in.), and 94.4 to 122 cm (36 to 48 in.) depths. Each of these segments was put in a soil sampling bag and sent for analysis to the ISU Soil and Plant Analysis Laboratory. These soil samples were analyzed for Mehlich-3 phosphorus.

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 prior to harvest. This was done by collecting vegetation samples near the inlet, outlet, and every 61 m (200 ft) 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 soil surface. The sample was dried to constant moisture (approx. 72 h) in a convection oven at 25°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 comparison to producer-recorded masses of the harvested round bales. If the values did not agree within 10%, then the producer's harvested mass was used instead (this needed to be done if weather conditions at the site did not allow harvesting of all biomass). The sample was ground to pass a 1 mm sieve using a Model 4 Wiley Mill (Thomas Scientific, Swedesboro, N.J.). A 2 g subsample of the ground sample was sent to the ISU Soil and Plant Analysis Laboratory for analysis of total phosphorus and total nitrogen. Multiplying the measured phosphorus concentration of the harvested biomass by the yield provided an estimate of phosphorus removal.

SOIL PHOSPHORUS SORPTION ISOTHERMS

Soil samples were collected in the fall of 2009 from four VTA sites (CN IA 1, NW IA 1, NW IA 2, and SW IA 2) to determine the P sorption relationship for the soil from each site. The soil samples were collected from a grassed area outside of the VTA from three locations to a depth of 0.3 m (1 ft) and then composited. Samples were collected outside of the VTAs so that they would be comparable to the soil of the newly constructed VTA. Soils within the VTA had received heavy application of wastewater and significant amounts of P during VTS operation over the previous three years. Using soil that had not received the heavy P loading gave a better representation of the soil's original P sorption capacity. Soils were sampled to a depth of 0.3 m (1 ft) to correspond with the shallow soil sampling being conducted as part of the VTS performance monitoring effort. The soil samples were air-dried, crushed, and passed through a 2 mm sieve to remove plant vegetation and coarse fragments.

Subsamples of the soil were taken to the ISU Soil and Plant Analysis Laboratory. The soil was analyzed for pH, Mehlich-3 extractable Al, Ca, Fe, and P. Another subsample was used to determine the particle size distribution of the soil. The subsample was treated with hydrogen peroxide (H_2O_2) to remove soil organic matter (OM), and then the pipette method of Gee and Bauder (1986) was used to determine percentages of silt and clay. Soil organic matter (OM) was determined by loss on ignition at 550°C. Results of the soil analysis are shown in table 2. Of note is that the background P concentrations of these soils are quite high, as the Iowa interpretation of Mehlich-3 phosphorus suggests that any value greater than 31 is in the "very high" range. This suggests that the soils may have had a history of manure application. Observations at the sites suggest that the soils were in locations that may have historically received surface runoff from the feedlot, similar to what the VTA soils received, and thus these soils provide a reasonable approximation of the VTA soils at the time of system construction. In addition, these soils initially had high organic matter contents, slightly above what would be expected for grassland soils in Iowa. Soil reaction was typically neutral to slightly basic, and textures tended to be loams.

Phosphorus sorption relationships were determined using the method of Graetz and Nair (2009). One gram of air-dried soil was placed into each of seven 50 mL vials and mixed with 25 mL of 0.01 M calcium chloride ($CaCl_2$) solution containing P concentrations of 0, 2, 5, 10, 50, 100, and 200 mg KH_2PO_4-P L^{-1}. Three drops of chloroform were added to each vial to inhibit microbial growth. Samples were shaken on an orbital shaker for 24 h at 27°C ±2°C. The mixtures were then allowed to settle for 1 h. The supernatant was filtered through a 0.45 µm filter. Dissolved reactive phosphorus (DRP) concentrations were analyzed with an 880 nm wavelength spectrophotometer (Genesys 6, Thermo Electron Corp., Madison, Wisc.) using the ascorbic acid method (APHA, 1998). This process was carried out three times for the soil from each site, with duplicate samples used in each analysis. Soil P sorption relationships were modeled with the Langmuir sorption equation (eq. 1) using the P sorption equation spreadsheet developed by Bolster and Hornberger (2007):

$$S = \frac{S_{max} K C_e}{1 + K C_e} \tag{1}$$

where S is the total amount of P sorbed to the soil (mg P kg^{-1} soil), S_{max} is the maximum P sorption capacity of the soil (mg P kg^{-1} soil), K is the Langmuir binding strength coefficient (L mg^{-1}), and C_e is the equilibrium concentration of the P solution (mg L^{-1}), which is often approximated as the phosphorus concentration of the solution after equilibrating with the soil sample for 24 h (Bolster and Hornberger, 2007). The sorbed concentration of P (S) was calculated (eq. 2) as the sum of the P retained by the solid phase during the sorption incubation (S') and the amount of P originally sorbed by the solid phases (S_0) (Graetz and Nair, 2009):

$$S = S' + S_0 \tag{2}$$

The amount of P originally sorbed to the soil was assumed to be equal to the Mehlich-3 P concentration (Graetz and Nair, 2009). Equation 3 shows how the P retained by the solid phase was calculated:

$$S' = \frac{(C_i - C_e) V}{m} \tag{3}$$

where C_i is the initial concentration of the P solution (mg L^{-1}), V is the volume of the solution (L), and m is the mass of the soil sample (kg).

VTA Life Expectancy Model Development

For this study, VTA life was defined as the length of time required for the top 0.3 m (1 ft) of the soil profile to become saturated with P. This depth was selected because it represented the upper soil layer in the VTA soil profile, it was the depth to which soil samples were collected for isotherm determination, and it was the same depth to which soil samples were collected to assess phosphorus accumulation within the VTA. Other depths, such as 1 m (the approximate rooting zone of VTA vegetation), the depth to groundwater, or another depth of environmental significance for the site could have been selected. However, this would require collection of additional soil samples to evaluate changes in soil P sorption capacity with depth due to changes in soil texture, organic matter content, and soil pH. Ultimately, the selection of a critical depth plays a key role in the actual life of the VTA, and this depth should be selected based on the risk the system poses to water quality, the possibility for impact from hydraulic transport of the leached phosphorus, the level of environmental protection required, and the management and use that the area will be under once this critical soil depth is saturated with P.

VTAs are sized to contain and treat the runoff effluent applied, generally on the basis of nitrogen or hydraulic loadings (Woodbury et al., 2006). If the VTA is undersized,

Table 2. Chemical properties and particle size distributions of the four soils used in soil phosphorus sorption isotherm experiments.

		OM	Clay	Silt		Mehlich-3 Extractable Elements (mg kg^{-1})			
Site	pH	(%)	(%)	(%)	Soil Texture	P	Ca	Al	Fe
Central Iowa 1	7.5	7.6	20	40	Loam	542	3966	459	435
Northwest Iowa 1	7.0	7.7	31	57	Silty clay loam	323	3018	753	262
Northwest Iowa 2	7.3	7.2	23	47	Loam	189	3433	637	263
Southwest Iowa 2	6.6	8.8	25	44	Loam	331	2952	397	273

then runoff may occur or soil nutrients, such as P, will quickly build up, potentially leading to P leaching. Andersen et al. (2009) calculated the P loading factor (PLF) for six VTAs on beef feedlots in Iowa. This factor represents the average amount of P (in kg) that was applied to the VTA per 100 head of cattle per cm of precipitation that the feedlot received. We used a similar procedure as Andersen et al. (2009) to calculate the PLF for these six sites, including results from runoff monitoring in 2009. The calculated factors are shown table 3. These factors represent total phosphorus applied to the VTA at each of the sites. These factors provide a method for estimating the expected phosphorus applications under typical precipitation conditions for a location. Total phosphorus was used to calculate these factors, as Iowa recommendations suggest that all phosphorus in cattle manures is available within one year. Thus, although filtration by the soil or sedimentation could cause initial retention of the phosphorus, this phosphorus would either have to be incorporated into vegetation or react with the soil to ensure long-term retention.

In addition to P loading, soil bulk density, VTA size, soil P sorption capacity, effluent P concentration, and harvested material P removal are needed to determine VTA life expectancy. Effluent P concentrations for each site were estimated as the average of the yearly flow-weighted total P concentrations of either the solids settling basin or the vegetative infiltration basin, depending on which was applied to the VTA. The soil water equilibrium phosphorus concentration was assumed to be equal to that of the applied effluent (i.e., dilution from rainwater will approximately equal water loss with evapotranspiration). This assumption was made because typical precipitation in Iowa is roughly 61 to 84 cm, while measurements by Mueller et al. (2005) and Schilling and Kiniry (2007) suggest 41 to 91 cm of evapotranspiration; moreover, annual precipitation is typically 50% to 66% of potential evapotranspiration.

The applied effluent P concentration and the developed Langmuir soil P isotherms were used to determine the P sorption capacity of the soil. Figure 2 provides an example of how the P sorption isotherm and effluent concentration could be used to predict soil P sorption capacity. The soil P sorption capacity, which in this example is 1100 mg P kg^{-1} soil, was found by determining the soil P sorption capacity at the applied effluent P concentration (50 mg L^{-1} in the example shown). We used the applied P concentration to evaluate soil P sorption because this would effectively mean that the soil has become saturated with P, i.e., we chose this point because it would mean the VTA is no longer able to decrease the applied P concentrations. To aid in comparing different sites, VTA life expectancy equations were normalized by working with the variable APH_{100}, which is the VTA surface area per 100 head of cattle, instead of the VTA surface area and feedlot capacity. Equation 4 shows how APH_{100} was calculated:

Table 3. Phosphorus loading factors 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 are kg P per 100 head of cattle per cm precipitation.

	Site					
	CN IA 1	CN IA 2	NW IA 1	NW IA 2	SW IA 1	SW IA 2
Factor	0.68	0.07	0.87	0.14	0.63	1.06

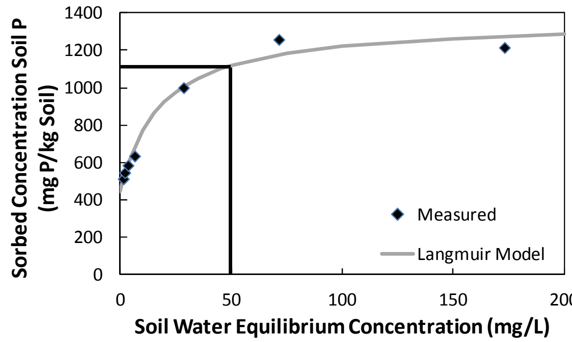


Figure 2. Example soil phosphorus isotherm demonstrating how the soil phosphorus sorption capacity was determined. Equilibrium soil water P concentration was assumed equal to the flow-weighted average of the applied effluent.

$$APH_{100} = \frac{100VTA_{area}}{Feedlot\ Capacity} \tag{4}$$

where APH_{100} is the VTA surface area per 100 head of cattle (m^2 per 100 head), VTA_{area} is the surface area of the VTA (m^2), and *Feedlot Capacity* is the number of cattle on the feedlot (head).

Several assumptions were made in developing the VTA life expectancy equations:

- The applied effluent is evenly distributed over the VTA surface.
- Effluent application does not affect soil P sorption capacity.
- 24-hour P sorption adequately describes long-term sorption capacity.
- The P moves through the soil as a piston front.
- No P is lost due to leaching below zone of interest (i.e., impacts of macropore flow were insignificant).
- All applied organic P is mineralized and needs to be sorbed to the soil or taken up by vegetation.

In practice, all these assumptions are violated to some extent in the field, but each aided in development of the VTA life model. In the following paragraphs, we examine the validity of the assumption and discuss what each means from a practical perspective. When possible, these assumptions will be evaluated in the Results and Discussion section.

The first assumption made was that of uniform effluent application. This assumption implies that phosphorus will be evenly distributed over the VTA surface. In practice, this assumption is readily violated because, during smaller precipitation-runoff events, the applied runoff may only cover a portion of the VTA, leading to greater nutrient loading on the covered portion. Our assumption provides a best-case scenario in which all the soil is used as effectively as possible. In reality, we would expect breakthrough of phosphorus to occur more quickly in the top half of the VTA, where more effluent is applied. Although this assumption imposes some limitations, the general patterns and recommendations developed based on the model would still be applicable. This assumption will be evaluated more thoroughly when the results of soil test P concentrations are evaluated.

The second and third assumptions, that the soil's P sorption capacity is not impacted by wastewater application and that 24 h sorption is indicative of long-term sorption, are perhaps the most limiting. The soil samples used to develop the sorption isotherm represent a snapshot in time of the soil. The application of wastewater will almost certainly impact the soil's sorption capacity, as the soil's pH, calcium, aluminum, and iron contents could all be impacted (Hu et al., 2005), as could the soil's redox status. However, the isotherm technique offers a means of obtaining a first-cut estimate of the soil's P sorption capacity and its P sink potential. Similarly, although 24 h is the often accepted standard for estimating P sorption potential, evidence that it may underestimate long-term sorption potential has emerged (Hu et al., 2006). Based on this evidence, this procedure would be expected to provide a conservative estimate of VTA life.

The next two assumptions, that phosphorus can be visualized as moving as a piston front through the soil and that it is not leached below the zone of interest, are probably violated. As discussed by Djodjic et al. (2004), loss of phosphorus by leaching in soils is often related to the presence of macropores in the soil that allow phosphorus-rich waters to bypass interacting with the soil matrix. By assuming no leaching and a piston front, we are implicitly assuming the impact of preferential flow to be minimal. In our model, preferential flow would actually cause an increase in the VTA's life expectancy, as the system would not be treating all of the applied phosphorus. However, the performance of the system could also be severely compromised, as phosphorus would be lost from the system to surface and groundwater, where it could potentially impact water quality. Based on our samples (discussed later in the deep soil sampling results), it appears that the assumption of a piston front is acceptable.

Our final assumption concerns the application of organic phosphorus in the runoff water. We assumed that all the applied phosphorus is mineralized. Some of the applied phosphorus could be in particulate form and thus could potentially be removed by soil filtration or settling rather than by sorption to the soil. However, based on Iowa recommendations of 60% to 100% P availability in cattle manure, a conservative estimate is to assume that this particulate phosphorus would be mineralized and hence needs to be sorbed by the soil or taken up by the vegetation to be retained. This approach provides a conservative assumption of VTA life, as it requires that all of the phosphorus applied needs to be accounted for in evaluating how quickly the phosphorus sinks (soil and vegetation) are filled to capacity.

The first step was to write a mass balance for the applied P. Since phosphorus leaching was assumed not to occur and all applied P was assumed to mineralize, the P needed to be either sorbed to the soil or removed with the harvested vegetation. This is shown mathematically in equation 5:

$$\mathrm{P}_{applied} = \mathrm{P}_{soil} + \mathrm{P}_{vegetation} \tag{5}$$

where $\mathrm{P}_{applied}$ is the mass of P applied to the VTA (mg P per 100 head of cattle), P_{soil} is the mass of P that the soil can sorb (mg P per 100 head of cattle), and $\mathrm{P}_{vegetation}$ is the mass of P removed with harvested vegetation (mg P per 100 head of cattle)

Mathematical descriptions of $\mathrm{P}_{applied}$, P_{soil}, and $\mathrm{P}_{vegetation}$ can also be written. These descriptions are shown in equations 6, 7, and 8, respectively:

$$\mathrm{P}_{applied} = \mathrm{PLF} \times Annual\_precip \times t_{saturation} \tag{6}$$

$$\mathrm{P}_{soil} = d \times \rho_b \times \mathrm{APH}_{100} \left(S_{sorption} - S_{initial} \right) \tag{7}$$

$$\mathrm{P}_{vegetation} = \mathrm{P}_{removal} \times \mathrm{APH}_{100} \times t_{saturation} \tag{8}$$

where PLF is the P loading factor from table 3 (mg P per 100 head of cattle per cm of precipitation), *Annual_precip* is average annual precipitation for the feedlot location (cm of precipitation per year), $t_{saturation}$ is the length of time until the soil profile is saturated with P (years), d is the depth of interest in the soil profile (m), ρ_b is the soil bulk density (kg m^{-3}), APH_{100} is the VTA area per 100 head of cattle (m^2 per 100 head) as defined in equation 4, $S_{sorption}$ is the soil P sorption capacity (mg P kg^{-1} soil), $S_{initial}$ is the initial P content of the soil (mg P kg^{-1} soil), and $P_{removal}$ is the annual mass of P m^{-2} removed due to harvesting of VTA vegetation (mg P m^{-2} $year^{-1}$).

Substituting equations 6, 7, and 8 into equation 5 and then solving for $t_{saturation}$ yields equation 9:

$$t_{saturation} = \frac{d \times \rho_b \times \mathrm{APH}_{100} \left(S_{sorption} - S_{initial} \right)}{\left(\mathrm{PLF} \times Annual\_precip \right) - \left(\mathrm{P}_{removal} \times \mathrm{APH}_{100} \right)} \tag{9}$$

RESULTS AND DISCUSSION

VEGETATION SAMPLING

Vegetation harvest and removal are critical for vegetative treatment system sustainability, as this process 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 (table 4). This was often related to the number of cuttings that the producer was able to harvest each year. In most cases, the ability of the producer to harvest the vegetation was related to the weather and soil conditions within the vegetative treatment area. For example, vegetation was only harvested one year at Central Iowa 2; this treatment system used a vegetative infiltration basin that drained continuously and kept a large portion of the small VTA in a saturated or nearly saturated condition, making harvest difficult. At the remaining sites, vegetation was harvested either once or twice a year. In certain instances, the VTA was only partially harvested during some of the cuttings, as certain areas were too wet to support the harvesting equipment. The yields of these six

Table 4. 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).

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

sites ranged from 5.29 to 14.8 Mg ha^{-1}. These yields are similar to those suggested by a University of Minnesota extension pamphlet on reed canarygrass, in which yields of 13.4 to 15 Mg ha^{-1} are reported for two-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 because 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 was not always the case, as Northwest Iowa 1 tended to have lower phosphorus removals than its 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. These data suggest that bromegrass is less able to utilize excess phosphorus than reed canarygrass. This is supported by the conclusion of Kovar and Claassen (2009) that reed canarygrass is more effective than smooth 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 processing wastewater land application area (31 kg P ha^{-1} versus 25 kg P ha^{-1} for reed canarygrass and smooth brome, respectively). In a second experiment, Sheaffer et al. (2008) found that phosphorus uptake could be greatly enhanced (up to 72 kg P ha^{-1}) by increasing the yield of the reed canarygrass through supplemental addition of nitrogen fertilizer. The uptakes reported by Sheaffer et al. (2008) are similar to the uptakes found in this study without supplemental nitrogen application, as we monitored phosphorus uptakes of up to 61 kg P ha^{-1}. The feedlot runoff vegetative treatment areas received substantially higher nitrogen application rates (593 to 1866 kg N ha^{-1} $year^{-1}$) than the potato processing wastewater application sites (250 kg N ha^{-1} $year^{-1}$).

SURFACE SOIL SAMPLING

Surface soil (0 to 0.3 m) phosphorus contents offer the first means of assessing phosphorus accumulation in the soil. Iowa soils are considered "very high" in phosphorus if the Mehlich-3 extractable phosphorus level exceeds 31 mg P kg^{-1} soil. As seen in table 5, the background soil phosphorus concentrations at all six sites were well in excess of these levels (ranging from 96 to 717 mg P kg^{-1} soil, i.e., 3 to 23 times the Iowa "very high" threshold).

Table 5. Average surface soil (0 to 30 cm) Mehlich-3 phosphorus concentration (mg P kg^{-1} 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).[a]

	CN IA 1	CN IA 2	NW IA 1	NW IA 2	SW IA 1	SW IA 2
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

[a] Values in the same column followed by different letters are significantly different at the 0.05 level.

Although these values may seem high, it needs be recognized that this recommendation based on Mehlich-3 phosphorus is interpreted as the amount of phosphorus at which a yield increase would not be expected from additional phosphorus application, not as an index of the potential for phosphorus to affect nearby water bodies. However, researchers have reported that increased soil test P can indicate increased P transport risk.

Table 5 provides average Mehlich-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 commenced. 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 levels. At Central Iowa 2, this occurred because phosphorus removal within the vegetative infiltration basin substantially limited phosphorus inputs to the VTA during subsequent years. However, no obvious explanation exists as to why levels at 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 every one or two years of system operation; however, within each site, there were anomalies to this pattern. 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, i.e., concentrated flow paths within the VTA that either minimized or maximized inputs of phosphorus to the specific sampling locations prior to soil sampling.

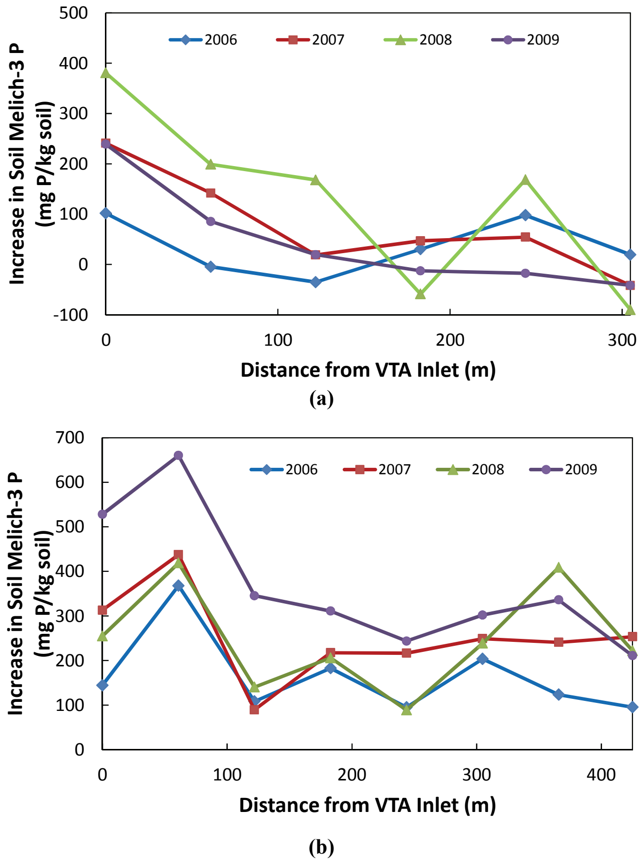


Figure 3. Change in surface soil (0 to 0.3 m) Mehlich-3 phosphorus as compared to background concentration as a function of distance from the VTA inlet for (a) Central Iowa 1 and (b) Northwest Iowa 1 vegetative treatment areas.

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 VTAs at CN IA 1 and NW IA 1 in figure 3. The plots show the absolute change in soil phosphorus concentration (as compared to the initial soil sample). Both plots showed a general pattern of greater accumulation near the inlet of the VTA, as expected, since this would be the area where solids that eroded from the feedlot and escaped the settling basin would settle out. Additionally, smaller settling basin release events would not distribute the applied effluent over the entire VTA but instead would only load the effluent over a fraction of the total treatment area. However, after the first couple of sampling points, the increases in soil test P appear to be relatively uniform with distance down the VTA.

Deep Soil Sampling

Deep soil samples (0 to 1.22 m) were collected to evaluate if phosphorus was migrating vertically through the soil profile. Results for the deep soil samples are shown in figure 4 for four sites (Central Iowa 1, Northwest Iowa 1, Northwest Iowa 2, and Southwest Iowa 1). 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 of 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. These results also indicate that, although not exact, the assumption of piston-front phosphorus migration should be acceptable for these sites.

Comparing Predicted and Measured Phosphorus Accumulations

The predicted concentration changes, based on a phosphorus mass balance, were then compared to the monitored changes in surface soil phosphorus concentrations. In making this comparison, a few of the sample results were discarded. The 2008 data point for Southwest Iowa 2 was not used due to 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. Additionally, we did not use the 2009 CN IA 1 soil sample data due to modification of the earthen flow spreaders, which compromised the results at two sampling points.

In general, the data points showed a reasonable fit between the predicted and measured increases in soil phosphorus concentration. This is shown graphically in figure 5 on (a) an annual change basis and (b) 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 some events would tend to cancel out events when loading was underestimated. Although errors in sampling vegetation were present, these would have little impact on the overall mass balance, as the phosphorus harvested with vegetation was a relatively small portion of the total phosphorus applied. Soil samples could be influenced by concentrated flow paths within the VTA that would result in either an under- or overestimation 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 will not eliminate the impact. Additionally, soil conditions during sampling could have had some influence on the 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 Mehlich-3 extraction technique. Thus, it is possible that a high prediction of soil phosphorus could indicate that phosphorus was leached below the 30

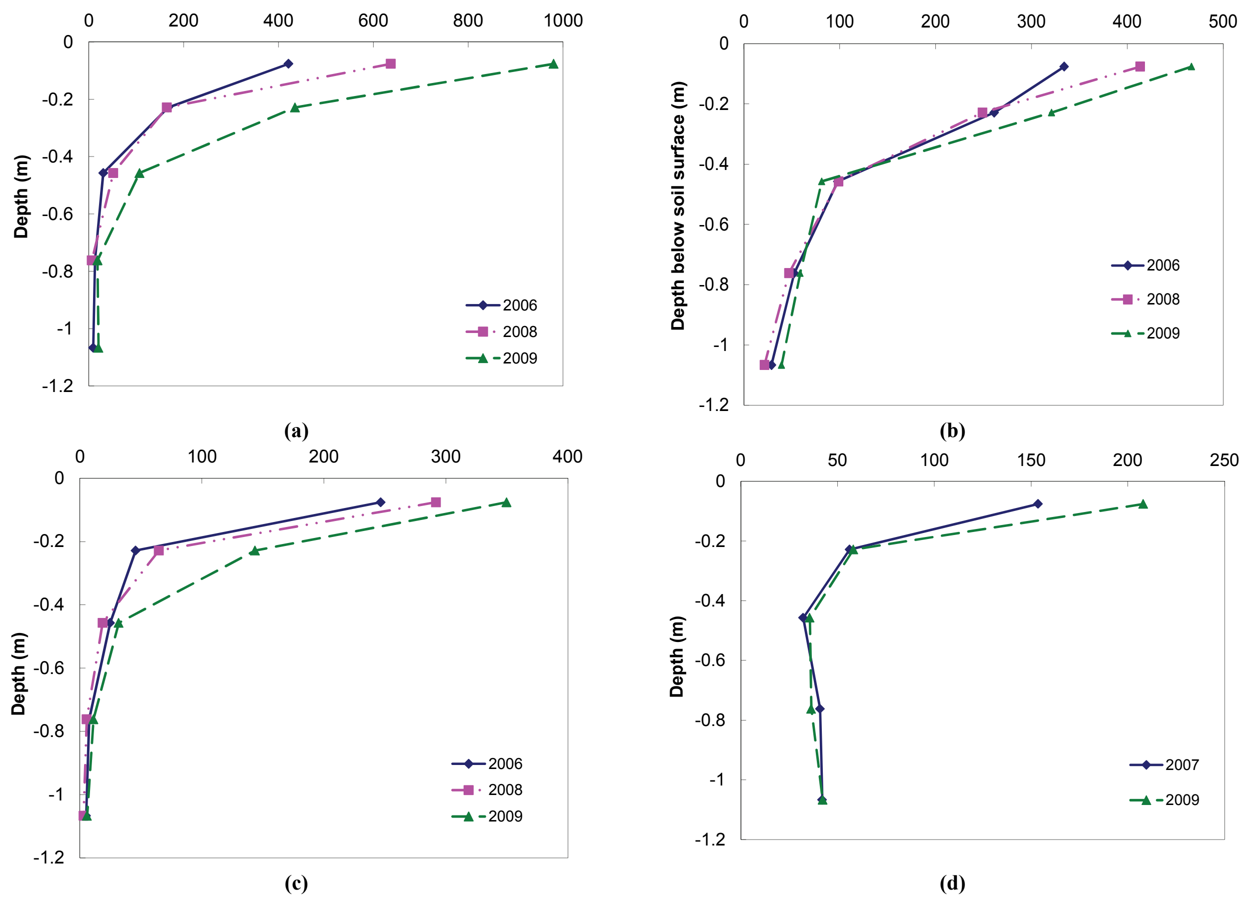


Figure 4. Mehlich-3 phosphorus concentration profiles from the surface to a depth of 1.2 m at (a) Central Iowa 1, (b) Northwest Iowa 1, (c) Northwest Iowa 2, and (d) Southwest Iowa 1.

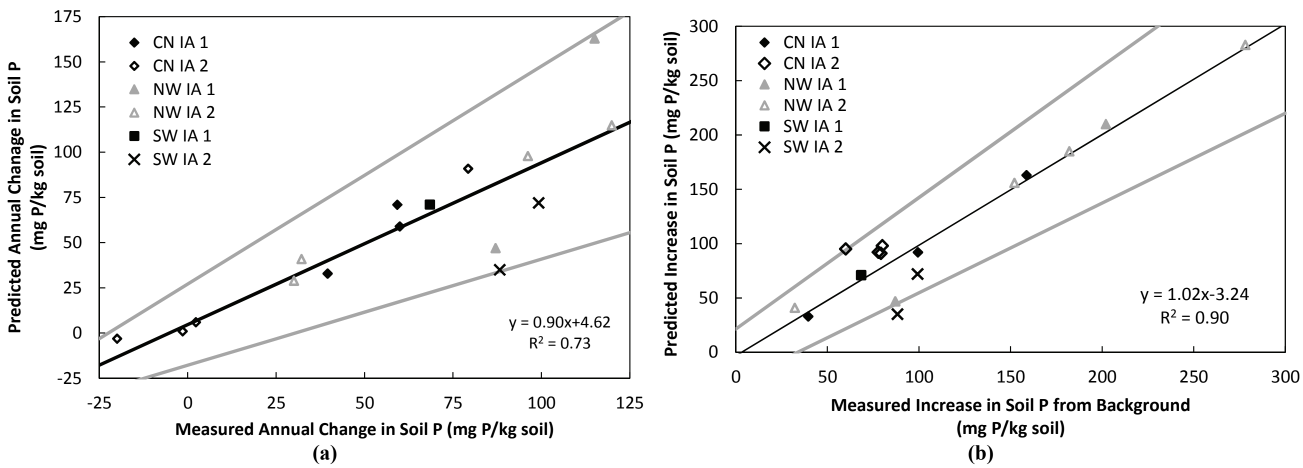


Figure 5. Comparison of soil phosphorus accumulations predicted using the mass balance approach and the monitored phosphorus accumulation shown on (a) annual basis and (b) cumulative basis.

cm depth or 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 resulted in concentrated flows around the sampling points.

Both methods of analysis, i.e., the annual change basis and the cumulative change basis, provided reasonable agreement between the monitored and predicted changes in soil test P. For both model fits, the intercept of the best fit line was not significantly different from zero and the slope was not significantly different from one at 95% confidence intervals. This indicates that the mass balance method adequately predicted the monitored changes in soil phosphorus. The fit of the cumulative change model was slightly better (R^2 = 0.90) than that of the annual change model (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 sampling errors would tend to be minimized by comparison to the larger change in soil phosphorus concentrations.

Soil Phosphorus Sorption Data Analysis

A correlation analysis was used to determine if a linear relationship existed between the maximum soil P sorption (S_{max}) and the Mehlich-3 Al, Mehlich-3 Fe, Mehlich-3 Ca, organic matter, clay content, and pH. Pearson correlation coefficients are shown in table 6. Calcium and pH showed strong positive correlations with S_{max}, while organic matter and clay content showed strong negative correlations. Ige et al. (2007), Zhang et al. (2005), and Zhang et al. (2009) also found a significant relationship between S_{max} and calcium content. Calcium is a positively charged ion and can bridge between negatively charged soil particles and phosphate ions ($H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}) or form precipitates with phosphates present in the soil solution. Thus, soils with high calcium contents potentially have more P binding sites in the soil and therefore have higher P fixing capacities, with more basic soils favoring reactions with calcium. Organic matter is often negatively charged and potentially competes with the phosphate ions for binding sites on the soil particles. This could explain the negative correlation between S_{max} and organic matter, as the organic matter present on the soil particles utilized potential binding sites, especially on clay particles. Soil pH affects P sorption by controlling the surface electrostatic potential, the dominant orthophosphate species (Bolster and Hornberger, 2007), and the solubility of calcium phosphates. Clay particles often are active binding sites for P, and thus a positive correlation was expected. However, the high organic matter content of these soils could indicate that the clay particles' binding sites were already utilized by the organic matter, limiting sorption of P additions. Aluminum and iron were both only weakly correlated with S_{max}. These two elements are often highly correlated maximum phosphorus retention. However, Kang et al. (2009) discovered that aluminum and iron are less effective for P sorption in soils with organic matter greater than 4.9%, presumably due to the active sites already being bound to organic matter. The organic matter content in these soils ranged from 7.2% to 8.8%. The high correlations between maximum sorption capacity with calcium and pH could indicate that calcium bridging between soil particles and P and the direct precipitation of calcium phosphates may be important P retention mechanism in these soils.

Average SSB effluent P concentrations were determined from four years of monitoring at four sites. Applied effluent orthophosphorus concentrations ranged from 27 to 48 mg P L^{-1} (CN IA 1 = 48 mg P L^{-1}, NW IA 1 = 38 mg P L^{-1}, SW IA 2 = 40 mg P L^{-1}, and NW IA 2 = 27 mg P L^{-1}). The sorption capacities of the soils at their effluent P concentration were determined from the soil P sorption isotherms. Central Iowa 1 had the greatest sorption capacity followed by Northwest Iowa 2 at soil P concentrations of 1125 ±35 mg P kg^{-1} soil (average ±standard deviation) and 1043 ±212 mg P kg^{-1} soil, respectively. Northwest IA 1 and Southwest IA 2 had lower P sorption capacities at 638 ±73 mg P kg^{-1} soil and 439 ±49 mg P kg^{-1} soil, respectively.

Table 6. Pearson correlation coefficients between S_{max} and various soil chemical properties.

	Al	Fe	Ca	Organic Matter	Clay Content	pH
S_{max}	0.2	0.21	0.66	-0.84	-0.57	0.80

Projected Phosphorus Saturation Life for Four Iowa VTAs

Projected 0.3 m phosphorus life expectancy of four Iowa VTAs was calculated using equation 9. The life expectancies of the four Iowa VTAs varied significantly, ranging from four to nine years before the top 0.3 m of the soil profile would become saturated with P. The results are discussed in detail below.

Central Iowa 1

CN IA 1 had a calculated life expectancy of nine years before P saturated the 0.3 m soil profile. This VTA had the longest life expectancy. This was primarily due to the high soil P sorption capacity, comparatively low initial soil P content, and low P loading factor. Vegetation was typically harvested annually, averaged approximately 3000 mg P m^{-2} $year^{-1}$ removal, and was assumed to continue at this rate. Starting in 2010, an additional VTA was used for treatment. This increased the VTA area from 1500 to 2100 m^2 per 100 head and increased the projected life to 13 years.

Northwest Iowa 1

NW IA 1 had the shortest life expectancy at four years. This was primarily attributed to the soil having a low P sorption capacity. Vegetation was harvested twice per year at this location and had average P removal of approximately 6000 mg P m^{-2} $year^{-1}$. Even though vegetation was harvested twice a year, it had little effect on the life expectancy due to the low capacity of the soil to sorb P.

Northwest Iowa 2

NW IA 2 had the second longest life, with a life expectancy of eight years. This was due to the high P sorption capacity of the soil, the low initial soil P concentration, and the low P loading factor. The lower P loading and small VTA area per 100 head are both attributed to this being a VIB-VTA system. Effluent was released from the SSB and allowed to infiltrate through the soil in the VIB, thereby reducing the amount of P applied to the VTA. This additional treatment typically allows smaller VTA size. Vegetation removal, 3000 mg P m^{-2} $year^{-1}$, had little effect on extending VTA life due to the small VTA surface area per 100 head. In 2009, this site added a third cell to its VTA. This increased the VTA surface area from 200 to 300 m^2 per 100 head, increasing the estimated VTA life to approximately 12 years.

Southwest Iowa 2

Southwest IA 2 had a calculated life expectancy of five years. This was lower than expected, as this site had the largest VTA area per 100 head. The reason it did not have the highest expected life was due to the low P sorption capacity of the soil and the higher P loading. Vegetation was harvested once a year but had little effect on VTA life, as only five harvests would occur before the soil profile would become saturated with P to 0.3 m depth.

VTA Life Expectancy: Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the impact of each variable on VTA P saturation life. This analysis was used to determine how measurement uncertainty of the utilized parameters or design/ management alteration to the system would impact the calculated life. The analysis also illustrated the importance of considering each parameter when initially siting and sizing a VTA. Figure 6 shows a comparison of the sensitivity of the VTA P saturation life, for the top 0.3 m of the soil profile, for each site to the size of the VTA per 100 head of cattle. Each site has a different slope for its VTA life expectancy function due to differences in soil P sorption capacity, initial soil P content, P loading factors, average annual rainfall, and differing amounts of P removed with vegetation harvest. This demonstrates how each site is unique, indicating that simple graphs and rules of thumb may not be sufficient to size VTAs for a specified P saturation life.

As can be seen in figure 6, NW IA 2 was the most sensitive to VTA size, as indicated by having the steepest slope (0.0069 year m^{-2} per 100 head of cattle). This was due to the low P loading at this site, which resulted in small changes to VTA area or soil P sorption capacity having large impacts on VTA life expectancy. The remaining sites had similar sensitivities, ranging from 0.002 to 0.008 year m^{-2} per 100 head of cattle.

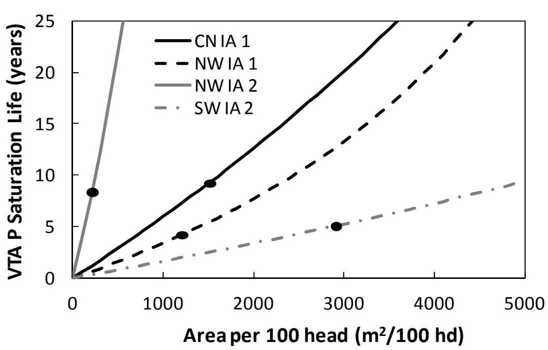


Figure 6. Comparison of VTA phosphorus saturation life expectancies for the top 0.3 m of the soil profile for each of the four sites as a function of VTA area per 100 head. Filled black circles represent the actual VTA area per 100 head at each site.

Table 7 shows the sensitivity of each site to soil P sorption capacity, initial soil P content, P loading factors, average annual rainfall, soil bulk density, differing amounts of P removal with vegetation harvest, critical depth in the soil profile, VTA surface area per 100 head, and required soil P equilibrium concentration. Vegetative treatment area P saturation life was not a linear function of the P loading factor, average annual rainfall, P removal with vegetation harvest, or VTA area per 100 head; however, it was approximately linear over the ranges investigated in this study (0.5 to 2 times the monitored value). These results indicate that picking an appropriate critical depth for VTA life is important, 0.14 to 0.31 years of estimated life was gained for each additional cm of soil profile considered. The results also show that approximately one year of life is gained for every 100 mg P kg^{-1} soil increase in soil P sorption capacity.

Varying the value of P sorption capacity of the soil can be interpreted in two ways. First, it can be interpreted as the importance in identifying soils around the feedlot that have a higher P sorption capacity to increase the phosphorus sink capacity of the soil and as a result increase the VTA life. Alternatively, it can be viewed as the impact of varying the allowable phosphorus concentrations in leachate from the VTA. To better evaluate the sensitivity of VTA life to the required phosphorus concentration, the last three rows in table 7 divide the phosphorus concentrations into three ranges. At lower required concentrations, the life expectancy can change very drastically, as the amount of phosphorus sorbed by the soil increases quickly with small changes in the allowable soil solution phosphorus concentration. This sensitivity greatly decreases at larger soil solution phosphorus concentrations because of the small changes in the amount of phosphorus that could be sorbed (fig. 2). These increases in sorbed phosphorus will increase soil test P levels and as a result will facilitate the movement of phosphorus in dissolved forms from these systems. Moreover, as the amount of phosphorus sorbed to the soil increases, the performance of the system, i.e., phosphorus retention, would be expected to decrease. This indicates that, although the system would still be serving as a sink for the applied phosphorus, it would be expected to capture a decreasing percentage of the amount applied.

Table 7. Sensitivity of VTA soil phosphorus saturation life to evaluated depth (*d*), soil phosphorus sorption capacity (S_s), initial soil phosphorus content (S_i), soil bulk density (ρ_b), VTA area per 100 head (APH_{100}), phosphorus loading factor (PLF), average annual precipitation, and phosphorus removal with vegetation ($P_{removal}$).

	Site				
Parameter	CN IA 1	NW IA 1	NW IA 2	SW IA 2	Units
d	0.31	0.14	0.26	0.17	year/cm
S_s	0.011	0.009	0.009	0.013	year/(mg P/kg soil)
S_i	-0.011	-0.009	-0.009	-0.013	year/(mg P/kg soil)
ρ_b	0.007	0.003	0.006	0.004	year/(kg soil/m^3)
APH_{100}	0.008	0.007	0.069	0.002	year/(m^2/100 head)
PLF	-0.00001	-0.00001	-0.00001	-0.00011	year/(mg P/100 head-cm precipitation)
Annual precipitation	-0.14	-0.05	-0.14	-0.08	Year/cm precipitation
$P_{removal}$	0.0003	0.0001	0.0002	0.0002	year/(mg P/m^2-year)
C_e (0 to 5 mg P L^{-1})	1.74	0.9232	0.4261	0.9224	year/(mg P/L)
C_e (5 to 15 mg P L^{-1})	0.257	0.103	0.280	0.096	year/(mg P/L)
C_e (15 to 50 mg P L^{-1})	0.038	0.014	0.124	0.013	year/(mg P/L)

VTA Life Expectancy: Design Implications

There are three areas to consider when designing a VTA to increase its P saturation life: siting, sizing, and management. The impact of each of these factors is discussed below.

Siting

The location of the VTA has a direct impact on the soil properties, including the P sorption capacity and the initial soil P content. Locations with a high P sorption and low initial P content should be sought, as this increases the P sink potential of the VTA soil. The sensitivity analysis showed that VTA P life of the top 0.3 m of the soil profile would increase by approximately one year for every 100 mg P kg^{-1} soil increase in available P sorption capacity, i.e., P sorption capacity minus initial P content. The available P sorption capacity for the four sites in this study ranged from 400 to 800 mg P kg^{-1} soil, which amounts to approximately a four-year difference in estimated VTA life for the top 0.3 m of the soil profile. The location also plays a key role in the P loading to the VTA by affecting the average annual precipitation. Sites with lower average precipitation would have less potential for P transport from the feedlot to the VTA. Thus, alternative treatment systems of the same size have a longer life in drier regions, assuming all other factors remain equal.

Finally, site selection plays a crucial role in determining the critical soil depth where VTA P saturation results in system failure. For the purposes of this study, the depth was set at 0.3 m, as this represented the depth of soil sampled for P isotherm determination and the depth of the soil samples used for phosphorus accumulation monitoring within the VTA. However, the actual critical depth should be selected based on the degree of environmental protection required and the environmental concerns specific to that location. Possible choices include the bottom of the root zone or the top of a shallow groundwater table, as both would represent times when a VTS fails to provide the desired level of environmental security, either through a direct effect to water quality or through accumulation of P that is not agronomically available. Determination of the critical depth plays a crucial role in determining the VTA life and should be considered carefully in siting VTAs. For the sites investigated in this study, VTA life increased by 0.14 to 0.31 years for every cm of the soil profile considered.

Sizing

The VTA surface area per 100 head affects the P loading rate, and size is an easily controllable design parameter. It provides an opportunity to more closely balance the P application and removal rates and also influences the size of soils' phosphorus sink capacity. At the sites discussed in this study, P removal through vegetation harvest accounted for 6% to 13% of the applied P. The remaining 87% to 94% needed to be sorbed by the soil.

The function relating VTA life to VTA area per 100 head is non-linear. When the P application rate greatly exceeded the P removal rate, only small increases in VTA life were seen with increased VTA area. As the P removal rate approached the application rate, large increases in VTA life were seen for small increases in VTA surface area. This non-linear relationship is primarily due to the impact of vegetation harvest, as the increase in the soil's phosphorus sink capacity is linearly related to the VTA size. This is illustrated in figure 7, which shows the relationship between the percentage of applied P removed with vegetation harvest and the projected VTA life. These data suggest that for a 50-year design life for the 0.3 m soil profile, between 30% and 60% of the applied P needs to be removed with harvested vegetation. Obtaining these P removals under current management conditions would require 6000, 6000, 950, and 16,080 m^2 per 100 head for CN IA 1, NW IA 1, NW IA 2, and SW IA 2, respectively. At these sites, this would represent VTA to feedlot drainage area ratios of approximately 3:1, 3:1, 1:1, and 6:1 for CN IA 1, NW IA 1, NW IA 2, and SW IA 2, respectively.

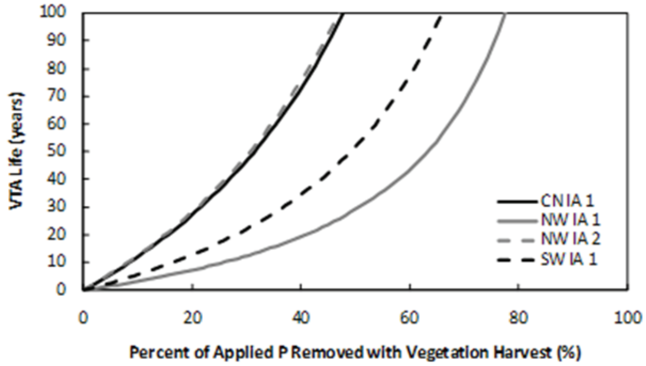


Figure 7. VTA life based on P saturation in the top 0.3 m of the soil profile as a function of the proportion of applied P that needs to be removed with harvested vegetation for four VTAs on feedlots in Iowa.

Management

Management is key to the success of any waste management system, and vegetative treatment systems are no exception. Several management functions that needed to be addressed were uniform effluent application over the VTA surface, maximizing the amount of biomass removed with harvest, and managing the solids settling and other treatment techniques to minimize the P loading on the VTA.

Uniform effluent application was implicitly assumed in all the analyses presented in this article. This maximized the calculated VTA P saturation life as it allowed failure, i.e., P saturation, to occur simultaneously over the entire VTA. On actual VTAs, uniform effluent application is difficult to achieve, especially if gravity flow is used to distribute the effluent. This needs to be considered when determining when P breakthrough would occur, as P would tend to accumulate more quickly at the upper end of the VTA.

Maximizing P removal with vegetation harvest is critical to designing sustainable VTAs. Operator experience has shown that it is difficult to harvest vegetation more than once or twice per year due to wet conditions in the VTA. Based on vegetation growth, it should be possible to harvest a mixture of reed canarygrass and smooth bromegrass between three and four times per year. Assuming that each harvest continues to average 3000 mg

P m^{-2}, additional harvests could increase P removal to 12,000 mg P m^{-2} $year^{-1}$, which could have a drastic impact on expected VTA life. A possible method to increase the opportunities for harvesting vegetation would be to construct multiple VTA sections. The producer could then rotate which section was receiving effluent and allow other sections to dry in anticipation of harvest. The effect on 0.3 m VTA P saturation life of increasing P removal through improved management and harvest of vegetation is shown in figure 7. In 2009, CN IA 1, NW IA 2, and SW IA 2 all harvested their VTAs twice (NW IA 1 harvested vegetation twice every year beginning in 2007), which approximately doubled the P removal from their VTAs. If twice a year harvest is continued at these three sites, it has the potential to extend their projected VTA life by approximately one year.

Finally, any pretreatment technique that decreases the amount of P applied to the VTA has a positive impact on VTA life. Examples of practices that could be implemented include dewatering the settling basin from the top down, actively managing the solids settling basin outlet to ensure that adequate settling has occurred, or filtering the feedlot runoff through biomass prior to release onto the VTA. For example, CN IA 1 reduced its P loading factor by 25% by switching from passive to active settling basin outlet control (Andersen et al., 2009). This change increased the projected VTA life by 27%. This indicates that successfully reducing P loading can have a large impact on VTA life.

CONCLUSIONS

The four VTAs (CN IA 1, NW IA 1, NW IA 2, and SW IA 2) had calculated life expectancies that ranged from four to nine years for P saturation in the top 0.3 m of the soil profile based on current design and management practices. The main factors that influenced VTA life were soil P sorption capacity, P loading rate, and the critical depth of the soil that could be saturated with P. The two VTAs with the highest sorption capacity had the longest life expectancies. The higher sorption capacity allowed the soil to absorb more P from the feedlot runoff before becoming saturated.

Two methods were determined to be effective in extending vegetation treatment area P saturation life. The first method is to locate VTAs in areas where the soil has a high P sorption capacity and relatively low initial P content. The second method is to approximately balance the P applied with the P removed through vegetation harvest. Methods of improving the balance include improving management of pretreatment components to lower P application onto the VTA, harvesting the vegetation more frequently to increase P removal from the VTA, and constructing larger VTAs. At the locations investigated, between 30% and 60% of the applied P must be removed with vegetation harvest to achieve a 0.3 m P saturation life of 50 years. To obtain these P removals under current management conditions of these four Iowa sites would require VTA to feedlot area ratios ranging from 1:1 to 6:1.

ACKNOWLEDGEMENTS

This work was funded by the Iowa Cattlemen's Association through a grant from the U.S. EPA and a USDA-NRCS Conservation Innovation grant and through an Iowa Water Center grant.

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