Final Report
Texas Cattle Feeders Association
Project Title: Means to Environmental Considerations: Assisting Feedyard Evaluations of Manure P Management.

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Introduction.

Source and transport factors affect potential runoff and leaching losses of phosphorus (P) from grassland and cropland soils (Sharpley et al., 1993). The source factors include soil chemical and physical properties, application methods and rates for manure or other P sources, and concentrations of P forms in manure and soil. For example, a plot of P rates in surface applications of manure or fertilizer on perennial grass illustrates a direct relationship between P rate and seasonal loss in runoff (Fig. 1) (Gaudreau et al., 2002). As illustrated in Fig. 1, runoff loss of total dissolved P from soluble, fertilizer-P tends to be greater than that of total P in manure applied on perennial grass.

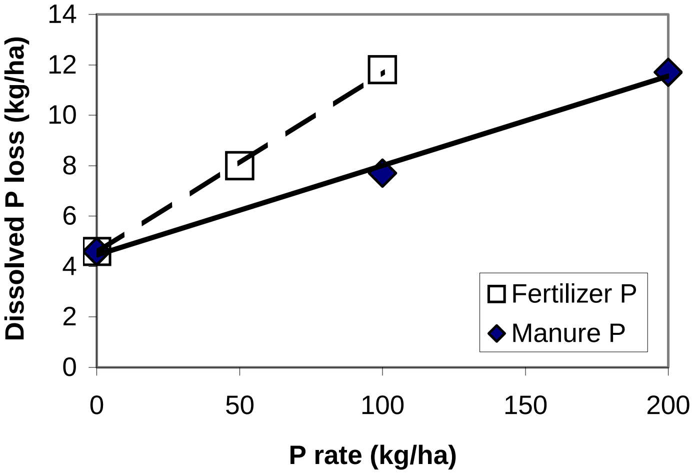

Figure 1. Total dissolved P loss as total P rate in inorganic fertilizer or aged manure increases over two growing seasons of perennial grass.

In addition to total dissolved P, a portion of the applied P is adsorbed to soil particles transported in runoff (Sharpley et al., 1993). The percent of total P adsorbed to the sediment or particulate fractions in runoff is typically inversely related to the portion lost as dissolved P. Loss of particulate P tends to be correlated with loss of sediment or solids suspended in runoff (Kleinman et al., 2002b, Turner et al., 2004). Maintaining dense vegetation or plant residues on the soil surface minimizes sediment loss and the portion of applied P lost in the particulate fraction of runoff (Andraski et al., 2003, Sharpley et al., 1993). For example, the amounts of P lost in the particulate fraction of runoff from established perennial grass was similar among P rates shown in Fig. 1 and totaled less than 0.6 kg P ha^{-1} over eight runoff events for each P rate (Gaudreau et al., 2002). Conversely, the particulate P can be a major portion (75 to 90%) of P transported in runoff from tilled soils (Sharpley et al., 1993).

In the absence of detailed short- and long-term records of P rates applied as manure, wastewater, or fertilizer, soil-tests are used to extract and analyze concentrations of P available to crop or forage plants. Historically, the soil tests were designed and used to determine P sufficiency and estimate rates of fertilizer or manure P needed to achieve crop production goals. As the size and density of confined animal feeding operations increased within regions of the U.S., including the Texas High Plains, land application of manure and wastewater was often the only practical option. Application of manure P in excess of crop requirements led to P accumulation and evaluations of soil-test analyses as indicators of potential runoff or leaching loss (Maguire and Sims, 2002, Sharpley, 1995). Early work indicated soil-test P quantified through Mehlich-3 extraction and analysis was linearly related to manure-P amounts mixed and incubated with soil, but the slope of regression lines differed among soil types (Sharpley, 1995). Similarly, concentrations of dissolved and particulate P in runoff were directly related to Mehlich-3 P content of the surface soil. Yet, the soil-specific nature of relationships between soil-test P and runoff P concentrations was evident in variation of slopes of regression lines.

A plot of soil-test P (Hons et al., 1990) versus the same runoff losses of dissolved P shown in Fig. 1 revealed linear relationships (Fig. 2), but slopes were similar between manure and fertilizer P sources. The soil-test P values represent extractable P forms from soil in addition to the extractable P forms added in manure or fertilizer. A comparison between Fig. 1 and 2 indicates a portion of the manure P applied over two years was not extracted in acidified NH_4OAc-EDTA (Texas A&M extraction solution) nor dissolved and transported in surface runoff.

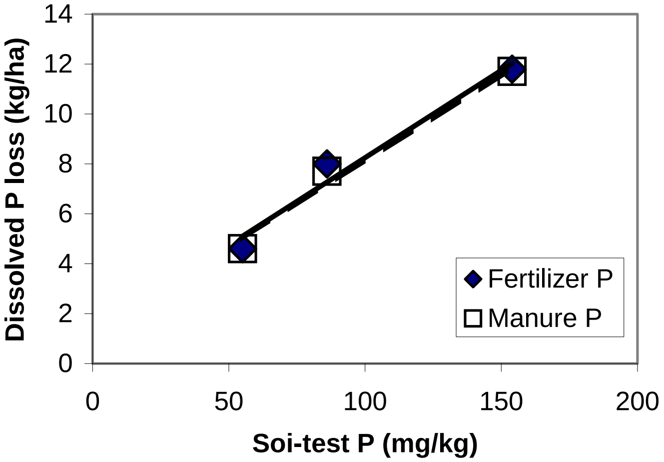

Figure 2. Relationship between total dissolved P loss in runoff and soil test P (7.5-cm depth) after topdressing of aged manure or fertilizer P on perennial grass over two growing seasons (Gaudreau et al., 2002).

Soil tests must be interpreted with some caution. Repeated manure applications can increase exchangeable soil calcium, which reduces the portion of soil P that is soluble in water and susceptible to dissolution in runoff (Sharpley et al., 2004). Although insoluble in water, the calcium phosphate reaction products are extracted during Mehlich-3 or acidified NH_4OAc-EDTA soil-test procedures. The extraction of water-insoluble P forms in soil-tests could overestimate potential P loss in runoff or leachate and limit the utility of soil-tests alone as environmental indicators (Sharpley et al., 2004). After two additional years of manure application on the plots shown in Fig. 2, the relationship between acidified NH_4OAc-EDTA extracts of soil sampled to the 7.5-cm depth and dissolved P loss in runoff was no longer linear (Fig. 3). Although soil Ca concentrations were not quantified, the results suggest linear relationships between soil-test P and runoff loss for short-term manure P applications cannot be extrapolated to long-term manure P applications that increase soil-test P substantially.

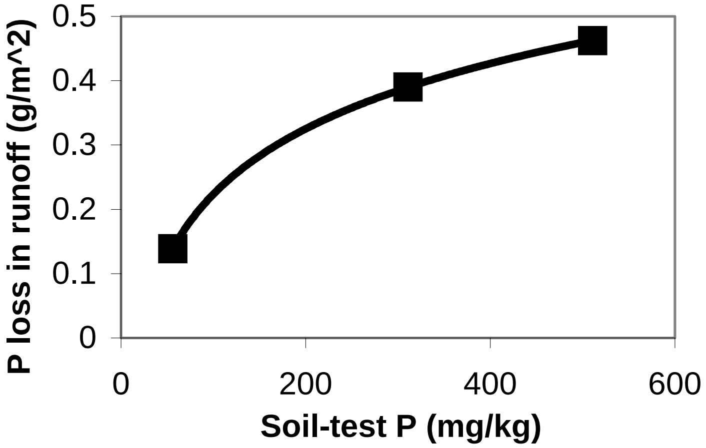

Figure 3. Relationship of dissolved P runoff loss to soil-test P during five rain events after four annual surface applications of aged manure on perennial grass (Vietor et al., 2002).

Several soil characteristics affects interpretation of soil-test P in relation to runoff and leaching loss. Soil pH, surface area of soil particles (texture), water content, and concentrations of aluminum, iron, calcium, and magnesium are among the soil traits that affect P solubility and potential loss in runoff or leachate (McDowell et al., 2001, Turner et al., 2004). A portion of the P is adsorbed to clay particles, especially aluminum and iron hydrous oxides and organic matter complexes. When a soil is supplied with increasing rates of manure or wastewater P, adsorption sites of constituents can become saturated and concentrations of somewhat soluble P forms in the soil solution can increase (McDowell et al., 2001). Soil- and site-specific information about soil aluminum and iron can be measured and used to interpret and improve relationships between soil-test P and runoff concentrations and losses of P (Schroeder et al., 2004). In addition, the ratio of extractable P to extractable iron and aluminum can be measured to represent the soil P sorption saturation (Kleinman et al., 2002b). Soil P sorption saturation can be highly correlated with soil-test P and used as an environmental indicator of potential runoff loss of P from soil.

Water-extractable P in soil or applied manure provides an alternative to agronomic soil tests as indicators of P loss through runoff or leaching (Kleinman et al., 2002a, 2002b; Sharpley and Moyer, 2000). Fractionation of P in raw and composted manures indicated more than 60% of total P was inorganic. In addition, 80% of the inorganic P was water-soluble. The utility of measurements of water-extractable P was demonstrated during simulated rain applications on layers of varied manure sources (Sharpley and Moyer, 2000). The total P in leachate was highly correlated with water-extractable inorganic and organic P in the manure sources. Water-extractable P in manure can similarly be related to dissolved reactive P runoff from manure-amended soil (Kleinman et al., 2002a). Variation of water-extractable P in manure-amended soil accounted for 95% of variation of soluble reactive P in runoff. Yet, a large percentage of dissolved reactive P in the total P collected in runoff indicated manure was the principal P source in manure-amended soil (Kleinman et al., 2002a). Similar studies of dissolved reactive P and total P loss in runoff during simulated rain applications on high and low P soils indicated recently applied manure was the primary source of P in runoff from manure-amended soil (Kleinman et al., 2002b). Mehlich-3 P was highly correlated with dissolved reactive P concentrations from unamended soil, but poorly correlated with dissolved reactive P in runoff from soil topdressed with manure (100 kg total P ha^{-1}). Most (64%) of the total P lost in runoff from soil topdressed with manure was dissolved reactive P. In contrast, only 9% of TP lost from unamended soil was in the soluble-reactive fraction. Given recent manure applications were the principal source of dissolved reactive P in runoff, concentrations of water-soluble P in manure and dissolved reactive P in runoff were linearly related across different soil types and manure sources. The water-soluble P content of manure was an effective indicator of nonpoint-source loss of surface-applied P sources in runoff (Kleinman et al., 2002b).

Mixing of manure with soil can reduce runoff loss of dissolved reactive P compared to surface application. Dissolved reactive P accounted for only 9% of total P in runoff after manure was incorporated and simulated rain applied for 30 min on indoor boxes (Kleinman et al., 2002b). The total P in runoff after mixing of manure with soil was only 37% of that lost from surface-applied manure. In contrast to the surface-applied treatment, suspended solids were highly correlated with total P concentration in runoff after manure was mixed with soil. A best management practice is evident in observations of less total P loss in runoff for manure mixed with soil than for manure topdressed on soil. For example, incorporation of broiler litter reduced reactive P concentrations in runoff of simulated rain by 97% and P mass in runoff by 88% compared with surface applications (Tarkalson and Mikkelsen, 2004).

The monitoring and reporting services available to feedyards contribute to the first objective of this project and to self-assessment of manure P management in the feedlot industry. Previous research concerning source factors affecting P loss in runoff or leachate provide a basis, as stated in our second objective, for interpreting current sampling and reporting services provided to feedyards.

Objective 1. Quantify P amounts and forms in soil, manure, and wastewater samples collected during monitoring of feedyards and associated land.

Objective 2. Interpret P amounts and forms in sample analyses from Texas High Plains In relation to current and previous research relating soil and manure P to runoff and leaching losses.

Manure and soil analyses

The analyses of P in manure, wastewater, and soil from feedyards provide the basic information needed to manage total P applications and evaluate potential nonpoint-source losses of P in runoff or leachate from grassland and cropland. The soil test P provides an agronomic measure of plant-available soil P for comparison to anticipated crop needs and regulatory upper limits for soil P. In addition, the soil-test P concentrations can be indicative of the source factors affecting water quality. The studies reviewed previously in the introduction indicate soil-test P can be directly related to particulate and dissolved fractions of P in runoff. It is noteworthy that previous research demonstrates increases in potential runoff or leaching loss of P even when soil-test P concentrations range well below the regulatory upper limit of 200 mg P kg^{-1} soil established for impaired Texas watersheds. Soil-test P needs to be a key element of nutrient management planning, including decisions about manure and wastewater management, before soil-test P reaches regulatory upper limits. Although Mehlich-3 and other soil test data are useful for nutrient management planning, use of soil-test values as an environmental indicator can overestimate potential P loss in runoff if repeated manure applications increase calcium concentrations in soil. In addition, the relationship between soil-test P and runoff or leaching loss will vary among soil types surrounding feedyards in the Texas High Plains.

Analysis of total P in manure and wastewater is clearly useful for computing and budgeting total P additions in relation to soil tests and crop requirements. In addition, rates of total P applied in manure can be related to potential runoff loss of dissolved P during the months after application (Fig. 1). Yet, the portion of total manure P available to plants and susceptible to runoff or leaching varies among sources of manure and composted manure (He et al., 2004). Analyses of water-extractable P for diverse sources of raw, aged, and composted manure prior to surface application on grassland or cropland could be used to indicate environmental impacts. The studies reviewed above illustrated direct relationships between water extractable P of diverse manure sources and runoff and leaching losses of soluble reactive P. Shaking 1 g of fresh manure (dry-weight equivalent) with 200 mL of distilled water for 60 minutes, followed by centrifuging and filtering, can provide water-soluble P concentrations related to P loss through runoff or leaching (Kleinman et al., 2002a).

Water-extractable P of manure-amended soil can similarly be an environmental indicator of dissolved reactive P loss in runoff. The use of water instead of soil-test extraction solutions could improve the consistency of relationships between extractable P and runoff and leaching losses among diverse manure sources and soil types. Yet, distilled water can disperse clay particles in soil during extraction of samples removed from the 0 to 15-cm depth and overestimate the soil P susceptible to dissolution and transport in soil percolate or runoff (Koopmans et al., 2005). Dilute (10 mM) calcium chloride solution may be preferred over distilled water for the soil extraction procedure (Vietor et al., 2003). The dilute calcium chloride solution can extract soluble P without dispersing soil aggregates, but contributes to analytical problems for soils low in P (Koopmans et al., 2005). Yet, it must be remembered that dissolution of soil P during rainfall occurs within an effective depth of interaction between surface soil and rain “water” (Sharpley, 1985). Dispersal of soil particles within the surface layer of soil only a few mm thick will likely occur during rainfall, particularly if rainfall is intense and falls on tilled soil in which manure is mixed.

Objective 3. Use monitoring data from feedyards and associated land to establish
realistic inputs of soil and management information for simulation
modeling of the fate of manure P applied on grassland and cropland.

Transport factors

Both manure and soil analyses are indicators of source factors affecting water quality on the Texas High Plains. Yet, the relationship of source factors to water quality depends on factors affecting transport of water, sediment, and nutrients from the edge of fields or feedyards to water bodies. The basic transport factors comprise runoff or percolation of excess rainfall or irrigation, which carries nutrients and sediment over or through soil (Sharpley et al., 1993). Slope, soil drainage class, crop vegetation or residue, distance from the edge of field to water bodies, and tillage practices affect the basic transport factors. Conventional wisdom suggests low annual rainfall on the Texas High Plains minimizes transport of water, sediment, and nutrients from fields and feedyards, which limits potential nonpoint-source P loading of mineral and organic P in streams and rivers. In addition, the flat topography dotted with playa basins surrounding many feedyards limits water and nutrient transport to networks of major streams and rivers. Moreover, clay layers in bottoms and sealing effects of runoff constituents from feedyards reportedly prevent seepage into groundwater beneath playas and runoff catchments near feedyards (Clark, 1975, Stewart et al., 1994). Groundwater sampling near feedyards indicated NO_3-N, which is transported in soil percolate more readily than inorganic P forms, was not elevated in samples of water wells proximate to feedyards (Sweeten et al., 1995).

Phosphorus Index

The Texas P index provides one method for integrating source and transport factors in evaluations of the conventional wisdom about P loss through runoff on the Texas High Plains (NRCS, 2000). Separate indexes are available for West and East Texas. The index provides a screening tool for ranking the vulnerability of fields as nonpoint-sources of P for surface waters. Transport and source factors controlling P loss in surface runoff are identified and ranked. Site characteristics representing each factor are weighted according to effects on potential P loss. The site characteristics comprise soil-test P, fertilizer P rate, organic P rate, fertilizer application method and timing, organic P application method and timing, field proximity to a stream, runoff class, and soil erosion rating. Each site characteristic is given a weighting factor that is multiplied times the numerical rating (0, 1, 2, 4, or 8) recorded for that characteristic. The sum of products between weighting factor and rating for the eight site characteristics yields the total index points or P index.

Two contrasting examples will illustrate the importance of transport factors and application of the index in evaluations of site vulnerability to P loss in surface runoff. In addition, the P index can be used to identify management options for reducing P loss in surface runoff to streams. The P index was 20 points greater for site 2 due to an increase in slope of grassland to 5%, moderate erosion, and proximity to a water body (excluding playa basins) (Table 1). These transport factors contributed to manure P transport from the field to water body on site 2, which increased the P runoff potential from Medium to Very High. The increase of P index from Medium to Very High runoff potential between sites 1 and 2 scales down the recommended upper limits for soil-test P in non-impaired watersheds from 400 to 200 mg P kg^{-1} soil. In short, less manure can be applied on the grassland of site 2. Lack of surface pathways and transport of water, sediment, and P to water bodies from site 1 allows greater flexibility in management of P at the source, including greater organic P rates and upper limits for soil-test P. In addition to reduced P application on site 2, management of both source and transport factors will need attention. At the source, P in forage produced on the grassland can be harvested. Among transport factors, increased density of grass plants could reduce soil erosion from the field site. In addition, barriers to sediment and nutrient transport across the strip of land between the field and water body could be added or improved.

Table 1. Comparison of P index for West Texas between manure application sites on grasslands that differ with respect to transport factors.

Site Characteristic	Weighting factor	Site 1 Distant from stream			Site 2 Near stream		
		Rating	Factor	Points	Rating	Factor	Points
Soil-test P	1.0	Very High	8	8	Very high	8	8
Fertilizer P rate	0.75	None	0	0	None	0	0
Organic P rate	0.75	>150 lb/ac P_2O_5	8	6	>150lb/ac P_2O_5	8	6
Fertilizer P method/timing	0.5	None	0	0	None	0	0
Organic P method/timing	0.5	Surface applied	4	2	Surface applied	4	2
Proximity to water body	1.25	>2000 feet	0	0	< 100 feet	8	10
Runoff class	1.0	1% slope curve # 80	1	1	5% slope curve # 83	8	8
Soil erosion	1.5	< 1 ton/ac	0	0	3-5 ton/ac	2	3
				17			37
P runoff potential				Medium			Very high

Simulation models.

Simulation models provide another option for integrating source and transport factors in evaluations of conventional wisdom about runoff and leaching loss from fields and feedyards on the Texas High Plains. The simulation models provide an alternative to costly, lengthy, and labor-intensive field studies (Sharpley et al., 1993). Yet, a major limitation of simulation models is the lack of data for inputs and model calibration and validation. Version 2000 of the Soil and Water Assessment Tool (SWAT) model was previously calibrated and validated for the Upper North Bosque River Watershed in central Texas (Stewart et al., 2003). The model was used to evaluate water quality changes at the watershed outlet due to implementation of manure best management practices. Soil and manure analyses from feedyards on the Texas High Plains were used to develop inputs for SWAT simulations on a watershed in Deaf Smith and Randall counties (Fig. 4). Deaf Smith ranks first among Texas counties in the number of beef cattle on feed. The watershed drains into the Upper Prairie Dog Town Fork (UPDTF) of the Red River.

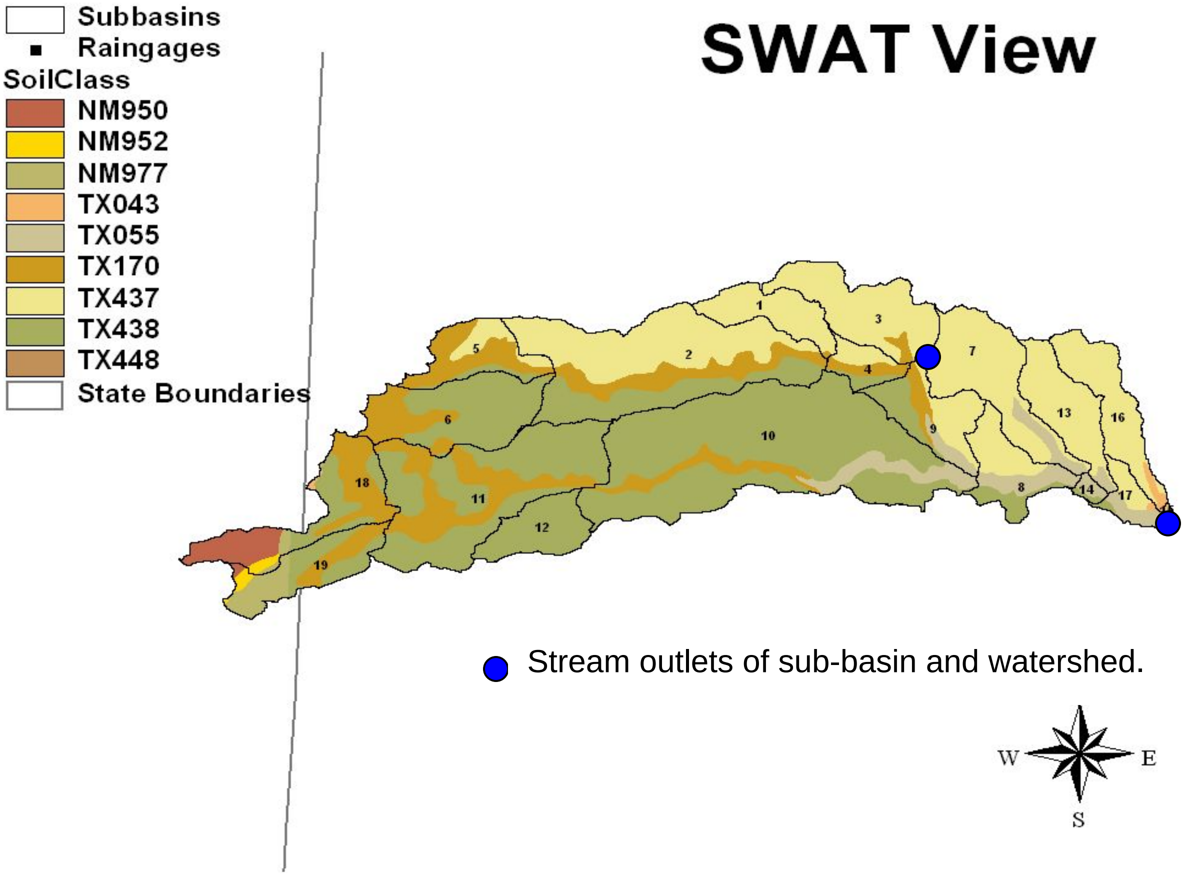

Figure 4. Map of sub-basins within watershed in Deaf Smith and Randall counties for SWAT simulations of flow and loading at outlet points.

Impacts of annual manure applications on water quality in stream outlets of sub-basin 3 and the entire watershed above the Upper Prairie Dog Town Fork (UPDTF) of the Red River were simulated. Jeff Arnold and colleagues at the USDA Agricultural Research Service at Temple, Texas developed the SWAT model. It is a physically based, semidistributed model that runs on a variable continuous time step. The model is optimized to efficiently simulate large and complex watersheds within reasonable time frames. The SWAT model is part of the EPA's Better Assessment Science Integrating Point and Non-point Sources (BASINS) software package. The model simulates surface and ground water hydrology, erosion and sedimentation, plant growth and management, nutrient cycling, and other watershed processes. In addition, the model accommodates spatial variability of soil types, land uses, weather, and topography. Apart from manure and soil-test data available from feedyards, inputs were derived from data layers of geographic information systems (GIS) through the BASINS pre-processor. This GIS interface expedites model setup, enhances accuracy, and minimizes human error during the data input process. Although most inputs are derived from GIS layers using the BASINS interface, inputs for initial watershed conditions, manure composition, chemical and physical properties of surface soil layers, and management operations can be manually formatted and entered directly into the model. Topography, soil, and land use data sets were loaded into the BASINS pre-processor as raster or vector GIS layers for this study.

Although site-specific data were not available for feedyards and associated land areas within the sub-basins and watershed used for simulations, digitized data were available from national and regional databases. Topographical data of the watershed above the outlet to the UPTDF was downloaded from the USGS National Map Seamless Data Distribution System, which is part of the National Elevation Dataset (NED). These data were processed through a Digital Elevation Model (DEM) in BASINS (1:24,000 scale) to create a grid with elevations in meters above Mean Sea Level. The elevations of the watershed above the UPTDF were processed through BASINS to create sub-basins for the SWAT simulations (Fig. 4). The State Soil Geographic (STATSGO) database was used to provide information for the GIS layer of soil information used in simulations. In addition, the National Land Cover Dataset (1992) was obtained from the USGS to provide land use information (Fig. 5). This dataset is a 1:24,000 scale grid derived primarily from Landsat Imagery as part of the Multi-Resolution Land Cover project.

The SWAT model provides a method for evaluating impacts of manure applications on a watershed scale over long-term periods. Both source and transport factors can be integrated in simulations that test assumptions about rainfall and topographic effects on potential runoff loss of P after manure applications. Assuming a population of 0.5 million cows on feed in Deaf Smith county, annual P excretion in manure totals about 7.5 million kg. If feedyard manure is applied on 20% of the land area within the county, the annual rate of manure P on 76,000 ha is approximately 100 kg ha^{-1}. For this study, manure was applied annually to supply 200 kg P ha^{-1} on the area of Pullman soils within sub-basin 3, which makes up 22% of the land area, from 1990 through 2003. A manure P concentration of 7000 mg kg^{-1} was estimated from previous feedyard data for annual manure applications over 13 yr. The land area on which manure was topdressed was established to grassland. The manure P rate was designed to create a range of soil-test phosphorus over the 13-year simulation period that spanned the range of soil-test P in samples collected from the 0 to 15-cm depth of fields surrounding feedyards. The build-up of soil-test P throughout the simulation period coincided with year-to-year variation of rainfall. The BASINS package used the land cover database in combination with the soils database to create Hydrologic Response Units (HRUs) within sub-basins of the watershed. Default SWAT settings for initial soil nutrient concentrations for the various land covers, including the Pullman soils established to grassland, were used to simulate baseline conditions without manure application. The baseline conditions were contrasted to the scenario of 13 yr of annual manure applications on the Pullman soils within sub-basin 3 of the watershed (Fig. 4).

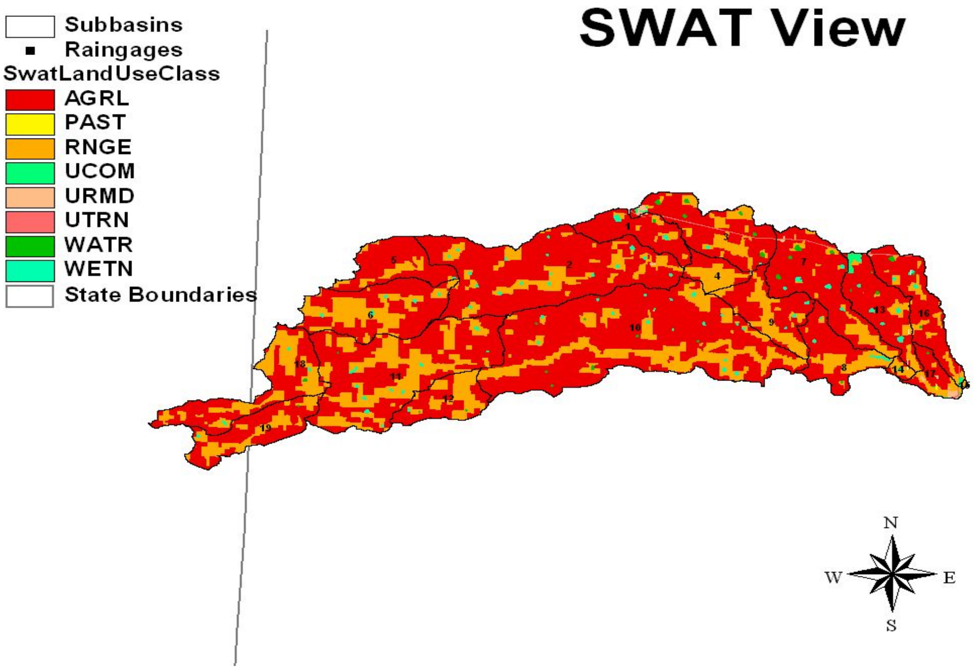

Figure 5.The National Land Cover Dataset (1992) was obtained from the USGS to provide land use information for the watershed within Deaf Smith and Randall counties.

Rainfall data from weather stations managed by The National Climatic Data Center (NCDC, 2003) were incomplete for the simulation period from 1990 to 2003. The SWAT weather generator was used to simulate daily weather conditions in lieu of the historical weather data (Fig. 6). Mean temperature and precipitation inputs for the weather generator were adjusted to generate mean annual precipitation amounts 60% greater than the long-term mean (503 mm) for the watershed. In this study, SWAT simulations allowed evaluation of potential impacts of a range of soil-test P in combination with above-average annual precipitation.

Simulations for sub-basin 3 indicated stream flow and sediment and organic P loads in the watershed outlet were not changed in relation to baseline conditions during 13 yr of manure application. In contrast, manure application on Pullman soils established to grassland did increase simulated mineral P loads in the stream outlet compared to baseline conditions (Fig. 7). The mineral P loads in the sub-basin outlet increased substantially after just three years of manure application (1992) during above average rainfall. The results of the sub-basin simulation are consistent with plot-scale observations of P loss in runoff after topdressings of manure on perennial grass (Figs. 2 and 3). The predictions indicated the margin of difference between scenarios with and without manure applications increased with each successive year of annual manure application during years of above average rainfall throughout the 13-yr period.

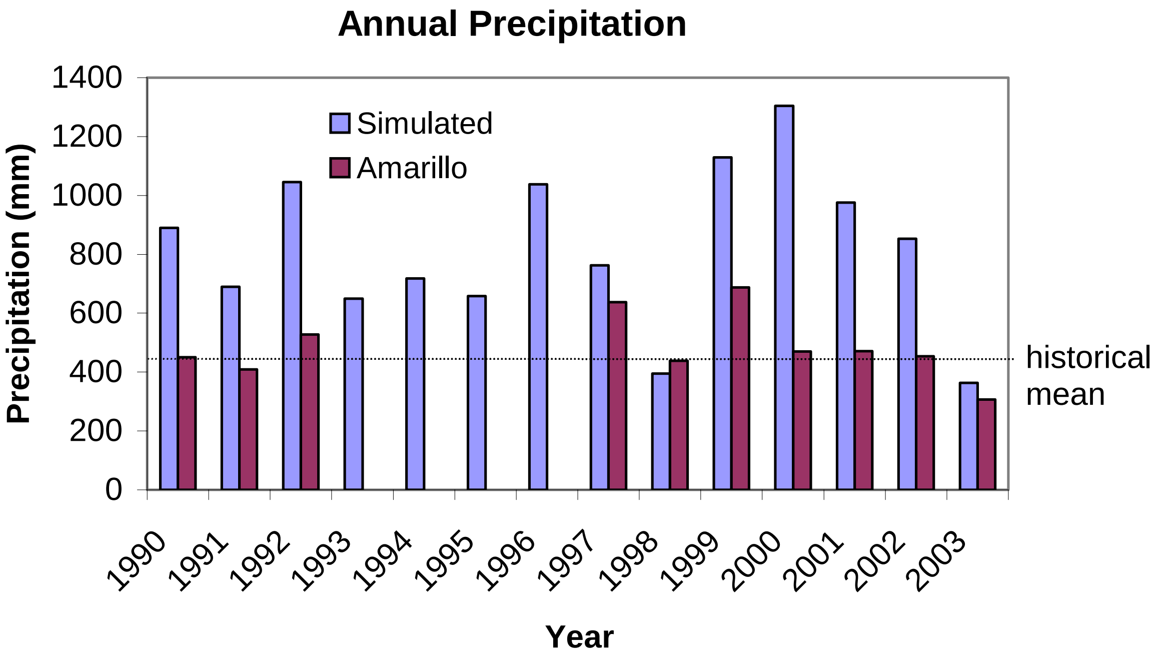

Fig. 6. Comparison of SWAT-generated mean annual precipitation to historical weather data for sub-basin 13 and watershed in Deaf Smith and Randall counties.

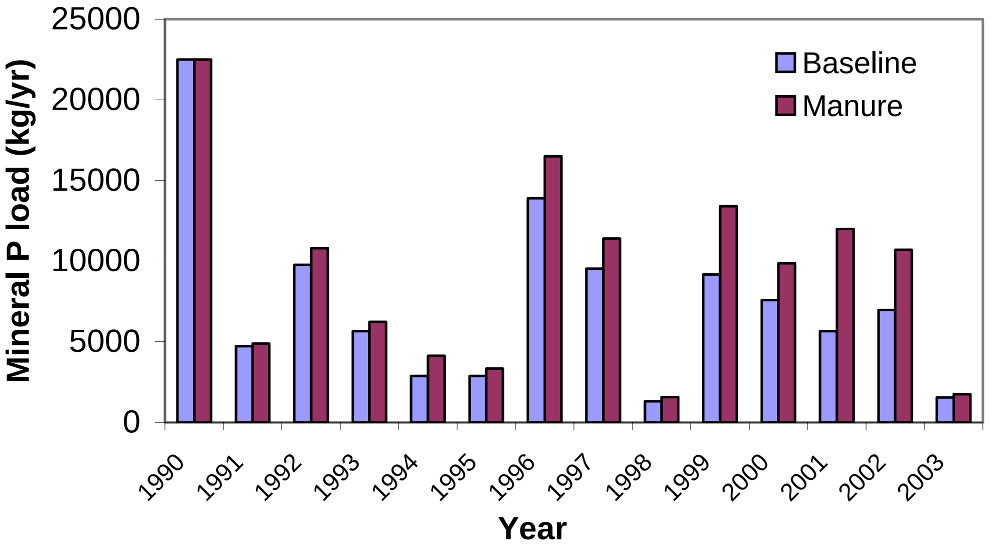

Fig. 7. SWAT simulation of mineral P load in the stream outlet of sub-basin 3 with and without annual applications of 200 kg ha^{-1} of manure phosphorus.

Both the simulations for sub-basin 3 and the runoff data for replicated plots indicated repeated annual manure application can affect water quality if rainfall and water runoff are sufficient to transport dissolved mineral P to streams.

The dilution effect of rainfall runoff from land areas without manure was illustrated in SWAT simulations of water quality at the outlet for the entire watershed (Fig. 8). Simulations indicated annual stream loads of soluble P at the outlet of the entire watershed were changed little due to manure applications on 22% of the land area in sub-basin 3. Although above-average rainfall can increase transport of dissolved P from land areas on which manure P accumulates, the large volumes of runoff from land areas without manure can mitigate the potential impact of manure P on stream TMDLs at the outlet of the entire watershed.

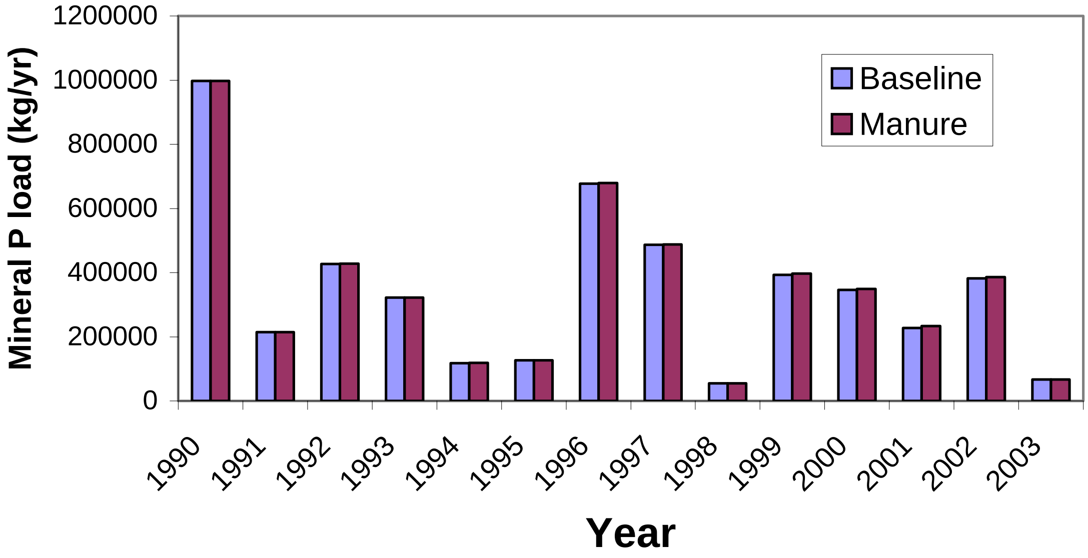

Fig. 8. Predicted stream loads of mineral P at the outlet of the entire watershed for simulations with and without aged manure applications on 22% of the land area within sub-basin 3.

Summary and Conclusions.

The sampling and analysis of manure and of soil at 0 to 15 and 15 to 60 cm provides the basic information needed for environmental compliance and nutrient management on grassland associated with beef feedyards. In addition, soil-test phosphorus is among data needed to estimate source factors in a P index. Soil-test P ranging above concentrations needed to meet agronomic requirements of crops (~50 mg phosphorus kg^{-1} soil) and surface applications of manure P greater than 73 kg P ha^{-1} contribute large point subtotals for source factors in the P index for West Texas. Similarly, plot-scale studies indicate dissolved P loss in runoff is directly related to soil-test P at concentrations above 50 mg P kg^{-1} soil. Both the source factor ratings of the P index and plot-scale studies suggest potential runoff loss of dissolved P in runoff can occur at soil-test P concentrations well below regulatory upper limits in the range of 200 to 500 mg P kg^{-1} soil.

Current research literature suggests water-extractable P in manure is a better indicator of dissolved P loss in runoff than total manure P. Although analysis of total P enables computations of manure application rates, the portion of total P susceptible to runoff from surface applications varies among manure sources and may not be related to runoff loss. Although manure mixing with soil substantially reduces dissolved P loss in runoff compared to surface application, water extractable P of manure-amended soil is similarly closely related to dissolved P runoff loss.

Both the phosphorus index and SWAT simulations revealed an element of truth in conventional wisdom that low rainfall, flat topography, and long distances to streams will minimize water quality impacts of high values for P source factors. As indicated in the SWAT simulations, repeated annual manure applications caused little change in mineral P loads in the stream outlet of sub-basin 3 during years of low rainfall. Conversely, member feedyards need to evaluate source factors with a keen eye during years of high rainfall on fields that contribute runoff to streams. Recognition of the direct relationship between soil-test P or water-extractable P and potential P loss to runoff is particularly important for fields and feedyards as transport pathways and factors amplify the water quality impacts of source factors.

Although manure and soil analyses were often related to leaching loss, neither the P index nor SWAT simulations evaluated potential P transport through soil. Again, conventional wisdom suggests low rainfall and water percolation through soil will minimize P transport through the Pullman, Olton, and other fine-textured soils on the High Plains. Yet, manure application on sandy soils and macropore flow through fine textured soils could contribute to both nitrate and P transport through soil (Johnson et al., 2004). Both need to be considered in future studies.

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