IMPROVING PHOSPHORUS LOSS ASSESSMENT WITH THE APEX MODEL AND PHOSPHORUS INDEX

by

AMMAR B BHANDARI

B.Sc. (Honors), HICAST, Purbanchal University, 2007
M.S. South Dakota State University, 2011

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2016

ABSTRACT

Agricultural fields contribute phosphorus (P) to water bodies, which can degrade water quality. The P index (PI) is a tool to assess the risk of P-loss from agricultural fields. However, due to limited measured data, P indices have not been rigorously evaluated. The Agricultural Policy/Environmental Extender (APEX) model could be used to generate P-loss datasets for P index evaluation and revision. The objectives of the study were to i) determine effects of APEX calibration practices on P-loss estimates from diverse management systems, ii) determine fertilizer and poultry litter management effects on P-loss, iii) evaluate and update the Kansas PI using P-loss simulated by APEX and iv) determine appropriate adsorption isotherms with advection-dispersion equation with column leaching experiment. Runoff data from field studies in Franklin and Crawford counties were used to calibrate and validate APEX. Poultry litter and inorganic fertilizer application timing, rate, method, and soil test P concentration effects on P loss were analyzed using location-specific models. A column leaching laboratory study was also conducted to test the adsorption isotherms. Location-specific model satisfactorily simulated runoff, total P (TP) and dissolved P (DP) loss meeting minimum model performance criteria for 2/3 of the tests whereas management-specific models only met the criteria in 1/3 of the tests. Applying manure or fertilizer during late fall resulted in relatively lower TP loss compared to spring applications before planting. The Kansas-PI rating and the APEX simulated P-loss were correlated with r^2 of 0.40 ($p<0.001$). Adjusting the weighting factors for Prate, soil test P, and erosion improved the correlation ($r^2 = 0.46$; $p<0.001$. Using a component PI structure and determining the weighting factors by multiple linear regression substantially improved the correlation between the PI and TP loss ($r^2 = 0.69$; $p<0.001$). In the P-leaching experiment, both

the linear and nonlinear adsorption isotherms did not fit the experimental data. A multi-reactional advection-dispersion model that better describes all the P processes and complexities in soils should be included in the future. These procedures can provide a roadmap for others interested P transport in soils and using computer models in evaluation, and modifying their PI.

IMPROVING PHOSPHORUS LOSS ASSESSMENT WITH THE APEX MODEL AND PHOSPHORUS INDEX

by

AMMAR B. BHANDARI

B.Sc. (Honors), HICAST, Purbanchal University, 2007
M.S. South Dakota State University, 2011

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2016

Approved by:

Major Professor
Nathan O. Nelson

ABSTRACT

Agricultural fields contribute phosphorus (P) to water bodies, which can degrade water quality. The P index (PI) is a tool to assess the risk of P-loss from agricultural fields. However, due to limited measured data, P indices have not been rigorously evaluated. The Agricultural Policy/Environmental Extender (APEX) model could be used to generate P-loss datasets for P index evaluation and revision. The objectives of the study were to i) determine effects of APEX calibration practices on P-loss estimates from diverse management systems, ii) determine fertilizer and poultry litter management effects on P-loss, iii) evaluate and update the Kansas PI using P-loss simulated by APEX and iv) determine appropriate adsorption isotherms with advection-dispersion equation with column leaching experiment. Runoff data from field studies in Franklin and Crawford counties were used to calibrate and validate APEX. Poultry litter and inorganic fertilizer application timing, rate, method, and soil test P concentration effects on P loss were analyzed using location-specific models. A column leaching laboratory study was also conducted to test the adsorption isotherms. Location-specific model satisfactorily simulated runoff, total P (TP) and dissolved P (DP) loss meeting minimum model performance criteria for 2/3 of the tests whereas management-specific models only met the criteria in 1/3 of the tests. Applying manure or fertilizer during late fall resulted in relatively lower TP loss compared to spring applications before planting. The Kansas-PI rating and the APEX simulated P-loss were correlated with r^2 of 0.40 ($p<0.001$). Adjusting the weighting factors for Prate, soil test P, and erosion improved the correlation ($r^2 = 0.46$; $p<0.001$. Using a component PI structure and determining the weighting factors by multiple linear regression substantially improved the correlation between the PI and TP loss ($r^2 = 0.69$; $p<0.001$). In the P-leaching experiment, both

the linear and nonlinear adsorption isotherms did not fit the experimental data. A multi-reactional advection-dispersion model that better describes all the P processes and complexities in soils should be included in the future. These procedures can provide a roadmap for others interested P transport in soils and using computer models in evaluation, and modifying their PI.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

My deep gratitude to Dr. Nathan O. Nelson, my major advisor for his outstanding guidance, encouragement and mentoring throughout the study. He is a role model for me both in teaching and research, and without his scholastic and technical guidance, It would be difficult to complete this research. I thank my committee members, Drs. Daniel W. Sweeney, Aleksey Y. Sheshukov, and Dorivar Ruiz Diaz, for their candid suggestions and advices throughout the course of this research work.

The research would not have been possible without the funding through a grant from Kansas Water Resource Institute (KWRI), United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Conservation Innovation Grant (CIG) so would like to thank all those funding Agencies.

I would like to thank Dr. Gerard J. Kluitenberg for his support during the study. I am also thankful to Donald Gastineau, NRCS soil scientist for his help and expertise in profile soil sampling from the study sites and providing his unpublished data. I am grateful to fellow graduate students, David Able, Nate Dorsey and James Coover for their help both in soil sampling and in the laboratory analysis. I would also like to thank all my family members for supporting me throughout my entire study. Last, but not least, I would like to thank my wife Mira GCBhandari for her outstanding support and encouragement during the entire course of this study. I am grateful to my loving son Aaayan Surath Bhandari, for the joy he brings every day into my life.

DEDICATION

This PhD dissertation is dedicated to my parents, mother Mrs. Narmati Bhandari and father Mr Surath B. Bhandari. I would also like to dedicate to my late grandmother Mrs. Harikala Bhandari.

THESIS STATEMENT

Decreasing phosphorus (P) loss from agricultural fields is an important environmental and agricultural priority. When P enters surface water, it promotes algal growth and leads to eutrophication, which is a major cause of water quality degradation in the US (U.S Environmental Protection Agency, 2002; Sharpley and Wang, 2014). High P concentrations can also promote toxin production from harmful algal blooms (HAB) (Hudnell, 2010). In 2011, there were 34 reports of human or animal illness from HABs in Kansas, resulting in two people being hospitalized and five animal deaths (KDHE, 2012). Agricultural fields are an important source of P enrichment to water bodies. Excess P application from nitrogen-based manure management has resulted in P accumulation in many agricultural soils. High soil erosion and runoff, especially when coincident with high soil test P or high P applications, results in excessive P loss to surface water. Although environmentally significant P losses may not have an immediate impact on agricultural production, permitting excessive P loss from agriculture is the unwise management of a limited natural resource. Furthermore, failure to control P export from agriculture may promote the creation of regulations that restrict P fertilizer use. It is in the best interest of agriculture and environmental protection to reduce P loss from agricultural fields.

Reduction of P loss from agricultural production requires accurate estimates of how management practices impact P loss relative to soils, landscape position, slope, and hydrology. By understanding these complex relationships, producers, and land managers can identify locations in a watershed that are sources of P loss and they can determine the benefits of alternative management strategies for reducing P loss. Simplified models, such as the P index, can be used for estimating the impact of management practices and soil properties on P loss (Lemunyon and Gilbert, 1993). However, there are concerns about the accuracy of P indices in ranking the risk of P loss from different management practices and many components of P indices have not been justified or validated, (Drewry et al. 2011; Nelson and Shober, 2012; Sharpley et al. 2012). Consequently, questions have been raised about the effectiveness of P-indices in improving water quality (Environmental Protection Agency, 2010; Sharpley et al. 2012). Processed-based computer models are alternative method of estimating P loss from fields with different management. Nevertheless, these models are very difficult to use (Saleh et al. 2011) and have not been adequately tested (Nelson and Shober, 2012). Although tools have been developed, these tools do not currently produce results with the desired level of confidence. Therefore, current methods to estimate agricultural management practice effects on P loss must be improved. Improved phosphorus management tools will assist researchers and conservationists to better estimates P loss, identify critical source areas of P export, and target conservation practices more effectively and efficiently, thus addressing water quality concerns associated with agricultural fields.

Chapter 1. Impact of Agricultural Phosphorus (P) Loss to Water Resources and Methods of Improving P loss Estimation: A Literature Review

1.1 Eutrophication

Contamination of surface waters with nutrient losses from agricultural fields is a major threat to drinking water, recreational resources, and aquatic ecosystems. Nutrient enrichment of water resources can accelerate biological productivity, promote algal growth and eutrophication, and lead to general water quality degradation (Carpenter et al. 1998; U.S Environmental Protection Agency, 2002; Sharpley and Wang 2014). Eutrophication propelled by P loading to freshwater is widespread in the U.S. (Dale et al. 2011) with substantial amounts of P exported from agricultural fields (Dubrovsky et al. 2010). Although nitrogen and carbon also control the growth of aquatic biota, most of the freshwater eutrophication around the world are accelerated by P inputs (Schindler 1977, Sharpley et al. 1995). Therefore, P is often a limiting element and control of P loss from agricultural fields is essential to reduce eutrophication.

Phosphorus is an essential element for plant growth but excessive P inputs accelerate the biological productivity of surface waters resulting eutrophication (Sharpley et al. 2003). High P loading to surface water can promote toxin production from harmful algal blooms (HABs) (Hudnell, 2010; Paerl, 2008) and poses a serious health hazard to human and animals (Burkholder and Glasgow 1997). For instance, excess P has been linked with the outbreaks of the dinoflagellate Pfiesteriapiscidida in Chesapeake Bay tributaries and eastern United States (Sharpley et al. 2003) and neurological damage to people has been linked to these toxic algae (Burkholder and Glasgow, 1997). In addition, P entering to streams, lakes and reservoirs increases the drinking water treatments cost and can also incur billions of dollars in cost every year from lost recreation, and tourism-based economy (Dodds et. al. 2008; Graham et al. 2010; Smith et al. 2015). Therefore, decreasing P loss from agricultural fields is an important environmental and agricultural priority (Sharpley et al. 2001) and improving methods to estimate P loss may play a significant role in limiting P input to water bodies and controlling consequences associated with eutrophication.

1.2 Factors affecting P loss

Spatial variability in soil nutrient concentrations, water holding capacity, topsoil depth, soil hydrology, crop growth, weather conditions, and management practices are important factors affecting P losses. Of these, management practices play a vital role in reducing P loss from agricultural fields. Therefore, quantifying impacts of management practices on soil P content, distribution (chemical forms), and losses (both runoff and leaching) is important as soils are a major source of P losses (McDowell et al. 2003). Tillage practices, methods, rate, the timing of fertilizer and manure application are important management factors that may influence the agricultural P loss in runoff. Furthermore, nitrogen-based manure management practices and P application above crop requirement has forced development of new management options to subdue environmental concerns (Vadas et al. 2012).

Research has shown that controlling both the source and transport mechanisms are important to reduce P loss in agricultural runoff. Critical source areas are defined as the intersection between large P sources and high transport capacities. For instance, sources of P such as high soil test P levels and manure or fertilizer applications are not an environmental risk unless they are transported to sensitive water bodies through leaching, runoff, or erosion.

Therefore, ideal management practices should target the control of P sources (e.g. minimize P build up in soils) and reduce the potential for transport (e.g. reduce surface runoff and erosion) within the critical source areas (Sharpley et al. 2003).

Studies have revealed that minimizing P application rates and incorporating or injecting manure or fertilizers into soils decreases the risk of P loss (Eghball and Power, 1999; Little et al. 2005; Zeimen et al. 2006; Sweeney et al. 2012). So by manipulating management practices, the risk of P loss can be minimized. Understanding the water quality impacts of current management practices as well as potential effects of using alternative management practices to reduce P loss are important for defining agronomic recommendations and environmental policies. Therefore, it is important to accurately assess effects of management practices on soil P content and P loss to water bodies.

1.3 Methods to estimate management effects on phosphorus loss from agricultural fields

Effects of management practices on P loss from agricultural fields can be estimated through three different ways: by measured data from field studies, with the phosphorus index (PI), and by using process-based computer models.

Measurement of P loss with field studies is the most accurate reflection of field conditions and climate complexity. Field studies also provide valuable information about natural variability and illustrate local conditions (Veith et al. 2008). However, comprehensive data collection in complex landscapes and with wide varieties of management practices is time-consuming, expensive, and impractical for field studies. For instance, if we have to test effects of 20 different management combinations with different tillage, fertilizer/manure application rates and soil tests phosphorus (STP) level on P loss, it will make the field study so complex that it becomes impractical. It is also very difficult to find soils with varying degree of STP in one particular location. In addition, field studies are limited with weather scenarios. Weather, especially rainfall is plays a vital role in P loss in runoff from agricultural fields.

The second method to estimate P loss from agricultural fields is with the PI. The PI has source factors (soil test P, P application rates, methods, timings and P source) and transport factors (soil erosion by water, irrigation erosion, soil runoff class, and field's distance to surface water bodies). Each source and transport factor in PI is assigned a rating value and weighting factor based on its relative contribution to total P loss (Lemunyon and Gilbert 1993; Sonez et al. 2009). The Kansas PI is based on the multiplicative formulation and total P loss rating is calculated by multiplying the summed transport factors with the summed source factors (Sonez et al. 2009). The PI is easy to use, user-friendly and can also assess location specific P loss contributing factors (Sharpley et al. 2011). The disadvantages the PI is that it only predicts relative assessment of risk and neither quantifies an amount of P lost nor simulates soil P dynamics over time. It is also not easily adjusted towards short-term time scale or expanded beyond the edge of the field. Hence, provides only one option for producers, if the ratings are high producers are required to reduce or stop applying P applications. Therefore, additional information is still required on use, impacts and evaluation of P indices to reduce P loss from agricultural fields (Nelson and Shober, 2012). In addition, the Natural Resources Conservation Service (NRCS) mandated that the P-index tool must be calibrated to standardize the P loss risk categories across regional, state and watershed boundaries (USDA-NRCS, 2012). Thus, there is a need to evaluate and update the Kansas PI, so it can be used as a tool to accurately estimate P loss, recommend alternative BMPs, and minimize P loss from agricultural fields to water resources.

The third method to estimate P loss from agricultural fields is by using process-based computer models. The process-based computer models are designed to simulate effects of management practices (e.g. tillage, fertilizer application, and cropping systems) on many different natural processes occurring in fields; such as crop growth, evapotranspiration, infiltration, runoff, leaching, erosion, nutrient cycling etc. Therefore, computer models help to assess the impact of management practices on P loss and have emerged as key tools to analyze wide range of management practices (Gassman et al. 2007; Yin et al. 2009; Gassman et al. 2010; Wang et al. 2012; Santhi et al. 2014; Francesconi et al. 2015).

The advantages of using computer models are that they are relatively more feasible than measurement of P loss over large geographic areas to identify critical source area and assess the impact of BMPs (Gburek and Sharpley et al. 1998; Green et al. 2006; Wang et al. 2008; Mudgal et al. 2010; Tuppad et al. 2010; Nelson and Shober, 2012). Computer models are not restricted to treatment comparisons and weather scenarios. Further, computer models help to extend the application of field studies data. For instance, field studies runoff data can be used to calibrate and validate a model such as the APEX. The fully calibrated and validated model then could then be used to test the impact of different BMPs on P loss and develop the BMPs database. Such a database could be further used to evaluate and standardize P-indices as mandated by the United States Department of Agriculture-Natural Resources Conservation Service (NRCS) nutrient management policy instruction 590 (USDA-NRCS, 2011a).

The disadvantages of using computer models are that they require field studies data to calibrate and validate models before using them. Furthermore, computer models have complex subroutines and hence require rigorous training to understand the subroutines or even operate the model software (Saleh et al. 2011). In addition, it is difficult to design a computer model to accurately represent all the processes influencing P loss in a landscape. A fully mechanistic model would describe all the processes with physically and chemically based mathematical expressions. This makes a very complex model. Most models use simplifying relationships in place of these processes based expressions. The simplifications introduce error.

In spite of the disadvantages process-based computer models have been widely used to assess the impact of management practices on P loss and develop BMPs (Plotkin et al. 2013; Francesconi et al. 2014). For instance, the APEX model has been used in the Conservation Effects Assessment Project (CEAP) to assess the benefits of USDA conservation program at the national level (Mausbach and Dedrick, 2004; Wang et al. 2009). It has also been promoted for use with limited data for calibration or even without calibration Gassman et al. 2010). However, models must be tested (calibrated and validated) adequately before simulating BMPs and must be robust enough to accurately simulate water quality parameters of interest (example P loss). Moreover, using the simulation model data to evaluate PI requires accurate P loss estimation for unknown scenarios and computer models must be rigorously validated (Nelson and Shober et al. 2012). Therefore, further testing and scrutiny of the APEX model’s robustness and accuracy in simulating P loss with a wide range of management practices are necessary before using the data for PI evaluation.

1.4 Phosphorus loss pathways from agricultural fields

Phosphorus loss from agricultural fields is a complex process and depends on both the source (P application rate, soil test P, application timings etc.) and transport factors (erosion, runoff, distance to water bodies etc.) (Sharpley et al. 2001). P sorption kinetics, soil properties, and management practices also play vital role in P loss from agricultural fields (Johnes and Hodgkinson, 1998). The primary processes of P loss from agricultural fields occur through three different ways; sediment bound P loss with soil erosion, DP loss in surface water runoff and DP loss in leachate through soil profile (Sharpley et al. 1985a; Heathwaite and Dils, 2000). The P accumulation on the soil surface due to over application of inorganic fertilizer or manure increases the risk of P loss in sediment, surface runoff, and leaching. Therefore, P loss from agricultural fields depends on soil physio-chemical properties, management practices, erosion, surface runoff, and leaching loss and it is necessary to apply remedial measures targeting all the P loss pathways to minimize the overall P loss. Brief descriptions of how different factors affect these pathways of P loss are listed below.

1.4.1 Management practices

Management practices such as tillage, methods of application, application rate and timing of fertilizer and manure are important factors that influence soil P content, P distribution (chemical forms), and losses in runoff, sediment and leaching (Bhandari et al. 2011; McDowell et al. 2003). Studies have indicated P accumulation, P stratification and elevated loss to water resources especially when manure and fertilizer P was applied above crop requirements (Stone et al. 2001; Gachter et al. 2004). Phosphorus accumulation in surface layer increase the risk of P loss with eroded soil particles while in soil profile increase the risk of P loss to surface or sub-surface pathways by decreasing the P sorption capacity of the soils (Sharpley et al. 1984, Sims et al. 1998; Sharpley et al. 2004; Glaesner et al. 2011).

The interaction between top 3-5 cm (1-2 inch) surface soil and rainfall or irrigation water is crucial to release P from soils (Sharpley, 1985a). The detachment of soil particles as an interaction of the soil types, weather and landscape position resulted in sediment bound P loss. The sediment bound P is a dominant mechanism of P loss in tilled agricultural systems (Sharpley et al. 2001). The erosion removes finer-sized soil particles first that has higher soil P content increasing the P enrichment ratio in water (Haygrath and Sharpley, 2002). The release of P from manure, fertilizers, plant and materials, resulted in DP loss in runoff and is a dominant mechanism in no-till systems (Sharpley et al. 2001).

Therefore, ideal management practices should target the control of P sources (e.g. minimize P build up in soils) and reduce the potential for transport (e.g. reduce surface runoff and erosion) within the critical source areas (Sharpley et al. 2003). Thus, by manipulating management practices (crop rotation, application rates, methods etc.) risk of P loss can be minimized.

1.4.2 Soil chemical properties

Soil chemical properties are important factors that determine the P loss. Depending on parent materials, soil type and management practices total P in topsoil (0-15 cm) ranges from 50-3000 mg Kg-1 (Foth and Ellis, 1997). Phosphorus in mineral soils (50-75%) is inorganic in nature. In acidic soils, P is associated with Aluminum (Al) and Iron (Fe) and in alkaline, calcareous soils with calcium (Ca). Primary minerals, secondary minerals (formed by precipitation of P with Al, Ca and Fe), P adsorbed in the surface of clay minerals, Fe, and Al oxy-hydroxides or carbonates are the major source of inorganic P in soils. The dissolved P in soil solution present as primary (PO_4^{3-}) or secondary (HPO_4^{2-}, $H_2PO^-_4$) orthophosphates is in dynamic equilibrium with inorganic and organic forms of P but may vary with relative concentrations as a functions of soil pH. At lower pH (4-5.5) $H_2PO^-_4$ and at pH > 8 HPO_4^{2-} is the dominant ortho-phosphate species (Sims and Pierzynski, 2005). Therefore, presence of Al, Ca, Fe, clay minerals, soil types, parent materials, weathering and soil pH are major soil chemical properties that determine the P availability and loss in agricultural systems.

In addition, the P sorption kinetics; the reversible fast adsorption and irreversible slow desorption process occur simultaneously in soils and affect the concentration of P in solution and solid phase (McGechan and Lewis, 2002). Phosphorus adsorption and desorption parameters in soils are also key to determine the vertical P movement and leaching loss. Phosphorus loading could be problematic in areas with low P adsorption capacities of soils to retain soluble P (Sims et al. 1998; Sharpley et al. 2004; Glaesner et al. 2011). Phosphorus accumulated and saturated in soil is also susceptible to P leaching loss and can be released through desorption. Thus, P adsorption and desorption process is a key to determine the P loss in surface runoff, sediment and leaching loss (Sims and Pierzynski, 2005). Therefore, understanding this basic P chemistry and interactions in soils would be helpful to determine the limitations of different soils and manage P loss more efficiently.

1.4.3 Other soil related factors

P movement in soil also depends on soil mineralogy, presence of macrospores, root channels, spatial variability in soil nutrient concentrations, water holding capacity, top soil depth, soil hydrology, crop growth, and weather conditions etc. Soil inherent variability, specific nature of P release, dominant form of P on soils, texture, aggregate diffusion, organic matter content, and degree of interaction between soil and water, and P sorption capacities are also important factors that determine P loss (Sharpley 1983; 1999). Dominant form of phosphorus (P) on soils, and degree of interaction between soil and water are important parameters that determine P loss from soils (Sharpley 1983; 1999). Therefore, besides management practices and basic soil P chemistry all these factors need to be considered with the basic concept of soil P chemistry in computer models to realistically simulate field conditions in long term P loss studies to reflect more realistic field conditions.

1.5 APEX model brief description

The APEX model was developed to address the gaps that existed to simulate key landscape processes in a farm or small watershed scale (Gassman et al. 2010). Climate, hydrology, erosion, management practices, nutrient cycling, crop growth, carbon cycling, pesticide fate, soil temperature, plant environmental control, subarea/routing and economics are the major components of the APEX model (Gassman et al. 2010; Wang et al. 2009; Williams and Izaurralde, 2006; Williams et al. 2012; Wang et al.2011). The main input data required for driving the APEX model simulations were weather, watershed characteristics, and management practices. Based on those input and components, the model simulates daily water flux, plant growth (including grain yield), nutrient cycling, soil erosion, and nutrient loss (Williams and

Izaurralde, 2006; Williams et al. 2012). The APEX model can simulate wide range of management practices such as tillage, buffer strips, terraces, grass waterways, rotational grazing scenarios, land application of manure or poultry litter etc. (Gassman et al. 2010; Yin et al. 2009).

A computer model must simulate crop growth, runoff, and sediment loss as minimum requirements in order to estimate field-scale P loss. A brief description on how the daily crop growth, runoff volume, sediment, and P loss were described below based on Williams et al. (2012). Besides, the different options available in the APEX for some of the key runoff, sediment, and nutrient loss processes were listed in Appendix A.

1.5.1 Crop growth

The APEX model is capable of simulating growth for approximately 100 different and for both annual and perennial crops (Williams et al. 2012; Gassman et al. 2010). A single model is used in the APEX to simulate all the crops. The annual crops grow from planting date to harvesting date or until the potential heat units equal the accumulated heat units for the crops. Perennial crops may become dormant after frost but maintain their root system throughout the year and start growing when their base temperature was exceeded by average daily temperature (Williams et al. 2012). The model can simulate mixed cropping stands (up to 10 crops) and the phonological development of the crop is based on daily heat unit accumulation. The daily increase in biomass can be estimated as follows based on the equation developed by Monteith, 1977).

$$PIB = .001*PA*(RE-CP*X1) \qquad [1]$$

PA = 0.5*SR*(1.0-exp(-0.65*LAI) [2]

RE = 100.*CO_2/(CO_2+exp(bc1-bc2*CO_2) [3]

X1 = max (VPD-1.-.5) [4]

where PIB is potential increase in biomass in t ha^{-1}.PA is intercepted photosynthetic active radiation in (MJ m^{-2} d^{-1}), RE is the radiation use efficiency factor for converting energy to biomass in (kg ha^{-1})/(MJ m^{-2}), CP is crop parameter relating RE and the vapor pressure deficit (VPD) in kPa, SR is solar radiation (MJ m^{-2} d^{-1}), LAI is leaf area index, bc1 and bc2 are crop parameters determined from two input points on RE-CO_2 curve (Stockle et al. 1992).

1.5.2 Runoff

In general surface runoff is generated when the rate of water application exceed the rate of infiltration. The infiltration rate is very high if the soil is dry but will decrease as the soil becomes wetter. Therefore, if the precipitation rate is higher than infiltration rate, surface runoff will occur. The SCS curve number method is commonly used to estimate surface runoff loss, which requires precipitation, water storage, curve number, and initial abstraction to estimate runoff volume. Hydrologic soil group, cover type, treatment, hydrologic conditions, and antecedent runoff condition are also important in determining runoff curve number.

The runoff volume (Q) was calculated as

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \qquad [5]$$

Where, Q is runoff (in.), P is rainfall (in.), I_a is initial abstraction (in.), S is potential maximum retention after runoff begins (in.).

Initial abstraction (I_a) includes all losses (interception, evaporation, infiltration etc.) before the start of the surface runoff. The value of I_a can be approximated as 0.2S and the equation [5] become-

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad [6]$$

S is a function of the watershed soil and cover, conditions can be written as

$$S = \frac{1000}{CN} - 10 \qquad [7]$$

In addition, information about cover type, hydrologic condition, antecedent moisture condition (AMC) and hydrologic soil group (HSG) are required to determine curve number (SCS 1986).

1.5.3 Sediment loss

The Modified Universal Soil Loss for Small Watersheds (MUSS) equation was commonly used to estimate the sediment loss from field scale small watersheds as follows.

$$\text{MUSS sediment loss} = R \times K \times LS \times C \times P \times D \text{ tons ha}^{-1} \text{ yr}^{-1} \qquad [8]$$

where, R is rainfall and runoff factor, K is soil erodibility factor, LS is slope length and steepness factor, C is cover and management factor, P is erosion control practice factor and D is the coarse fragment factor. The rainfall and runoff actor (R) in the equation 8 was estimated as follows

$$R = 0.79*(Q*q_p)^{0.65}*WSA^{0.009} \qquad [9]$$

where Q is runoff volume (mm), q_p is the peak runoff rate in mm h^{-1} and WSA is the watershed area in hectare (Williams et al. 2012).

1.5.4 Phosphorus loss and description of the P sub-routines

Soil phosphorus (P) in the APEX model is divided into organic and inorganic P pools. The organic P pool is further sub-divided into fresh organic and stable organic P pool. For P leaching the organic part of the P pools are ignored.

The inorganic P pool is sub-divided into stable mineral P, active mineral P and labile P pools (Figure 1.1) and mineral P transferred among these pools. In the inorganic P pools, soil labile P is the major user input that initializes active and stable P-pools in the model and a contributor of dissolved P. Labile P represents easily desorb-able P immediately available for plants or for runoff and leaching loss while active P represents less available not easily desorb-able P that is in equilibrium with labile P (Sharpley et al. 1984). Addition of fertilizer or inorganic P in the soil system disturbs the soil P equilibrium and two reactions occur simultaneously. First, a rapid reversible adsorption of P to surface sites and second, a slow reaction that converts P to a more strongly held non-labile form (Barrow et al. 1981; Javed and Rowell, 2002). Labile P pool can also became stable and move into a non-labile pool depending on time and soil characteristics (Barrow and Shaw 1979).

The relative sizes of the labile P and active P pools at equilibrium is determined by the equation.

$$P_{labile} = P_{active} * PSP / (1 - PSP) \qquad [10]$$

where PSP is the phosphorus sorption coefficient and is the fraction of applied fertilizer that remains labile after six months of incubation with multiple drying and wetting (Jones et al. 1984). P_{labile} and P_{active} is the P content in Kg ha^{-1}. This mass of P (Kg ha^{-1}) can be converted into mg P kg^{-1} soil by multiplying the P_{labile} and P_{active} with {1/[(10*bulk density* depth(m) of soil layer]}.

The labile P in the APEX model can be partitioned into solid and solution phase P. Based on the following equation the relationship between the labile P and active P is linear.

$$k_d = Q_{labile}/C \qquad [11]$$

Where Q_{labile} is the concentration of labile P in solid phase (mg kg^{-1}), C is the concentration of P in solution phase (mg L^{-1}) and k_d is estimated as a function of clay content (Williams, 1995).The relationship between Q_{labile} and C is also linear with a slope of $1/k_d$.

The rate of P transfers between labile and active P pools (P-sub routines) in the APEX is significant to determine the P loss in runoff and leaching. When the labile P pool becomes large then P moves from labile to active P pool to re-establish equilibrium (daily) and the mineral P flow rate (MPR) in kg ha^{-1} d^{-1} between labile and active P pools is given by the following equilibrium relationship –

$$MPR = \lambda \{P_{labile} – (P_{active} *[PSP/ (1-PSP)])\} \qquad [12]$$

where $\lambda = 0.1$ is both the sorption and desorption rate factor depending on the size of labile P pool. There have been a few different suggested values for λ. Furthermore, some models adjust λ depending on the direction of P flux. Therefore, equation [12] can also be rewritten to determine mineral flow rate (MPR) based on amount of labile P as-

$$MPR = \lambda_f \{P_{labile} - (P_{active} *[PSP/ (1-PSP)])\}; \text{ if } P_{labile} > (P_{active} *[PSP/ (1-PSP)]) \qquad [12_a]$$

and,

$$MPR = \lambda_b \{P_{labile} - (P_{active} *[PSP/ (1-PSP)])\}; \text{ if } P_{labile} < (P_{active} *[PSP/ (1-PSP)]) \qquad [12_b]$$

Where λ_f is the sorption rate factor and λ_b is the desorption rate factor.

Initially, Jones et al. (1984) suggested $\lambda_f = 0.1\ d^{-1}$ when P moves from labile to active P pool but there are concerns about this value. Vadas et al. (2006) indicated $\lambda_f = 0.1$ over-predicted labile P especially at early incubated time and soils with higher clay where P transfer from labile to active P was higher. So, models that are using the EPIC P sub-routines (same are used in APEX) with the constant rate of $\lambda_f = 0.1$ would over-estimate dissolved P of 36 % for soils with higher clay content. However, they found that for long term simulations using $\lambda_f = 0.1$ made no difference.

Vadas et al. (2006) also reported that using the dynamic sorption rate factor predicted labile P better than the constant value of $\lambda_f = 0.1$. The dynamic sorption rate factor can be estimated as-

$$\lambda_f = (A) (\text{Time [days]}^B) \qquad [13]$$

Where $A = 0.918e^{-4.603*PSP}$ and $B = - 0.238 \text{ Ln}(A) - 1.126)$

Likewise, after labile P is used as plant uptake, lost to runoff or leaching, P from active pool transfer to labile P pool to simulate soil P buffering (Vadas et al. 2006) but at a slow rate.

Whenever P_{labile} is less than {P_{active} *[PSP/ (1-PSP)]}, P moves from active to labile pool and is estimated by multiplying equation [12_b] with desorption rate factor, $\lambda_b = 0.1$ (Jones et al. 1984). But Vadas et al. (2006) reported that using this desorption rate factor of $\lambda_b = 0.1$ greatly under-estimated P transfer (desorption) from active to labile P. They also found that changing the λ_b to 0.6 or estimated as dynamic rate factor (range from 0.44 to 0.69) improved the prediction of P transfer from active to labile P with the later one predicting more accurately. Therefore, with the modified desorption rate factor (λ_b) of Vadas et al. (2006) equation [12_b] can be written as-

$$MPR = 0.6 \{P_{labile} - (P_{active} * [PSP/(1-PSP)])\} \text{ if } P_{labile} < (P_{active} * [PSP/(1-PSP)]) \quad [14]$$

Further, the dynamic desorption rate factor can also be estimated to use instead of 0.6 desorption rate factor as follows-

Desorption rate factor (λ_b) = (Base) (Time [days]$^{-0.29}$)

where Base = -1.08 (PSP) + 0.79

In addition, based on the APEX model's theoretical document at equilibrium the stable P pool is four times greater than the active P pool.

$$P_{stable} = 4 * P_{active} \quad [15]$$

P_{stable} is in kg ha^{-1} (can be converted to mg kg^{-1} soil for each layer as P_{labile}). The flow rate between stable and active P pool in Kg ha^{-1} d^{-1} is determined with the following equation.

$$ASPR = bo * (4 * P_{active} - P_{stable}) \quad [16]$$

where ASPR is the flow rate between active and stable mineral P pools and bo is the flow coefficient (d^{-1}). The flow reverses when $P_{stable} > 4^* P_{active}$ and is multiplied by 0.1 when ASPR is negative. Flow coefficient bo is determined as

$$bo = \exp(-1.77*PSP-7.05) \qquad [17_a]$$

for non-calcareous soils and

$$bo = 0.0076 \qquad [17_b]$$

for calcareous soils (Jones et al. 1984)

Thus, based on the APEX theoretical documentation and literature, the rate coefficient (parameter 84) that regulates P flux between labile and active P-pool should be set as 0.1 in the APEX model and that was the value recommended in the original paper on phosphorus cycling and transport by Jones et al. (1984). Likewise, the rate coefficient that determines the P flux between active and stable P pool (parameter 85), should be set as 1.0 that is consistent with the original expression of the equation by Jones et al. (1984). However, differences in P flux between stable and active pools will likely have negligible impacts on P loss due to the very slow rates of transfer between these pools.

In addition, labile P that initializes the active and stable P-pools estimated using a STP and a user-defined input (soil file) in APEX model. The PSP, that determines the relative sizes of the labile P and active P pools at equilibrium soil and calculated as a function of the chemical and physical properties of the soils and also a user-defined input (soil file) (Jones et al., 1984). The soluble P runoff coefficient (parameter 8) determines the P concentration in runoff as a function of the P concentration in the soil. And soluble phosphorus leaching (Kd) (parameter 96) that defines a ratio of concentration of P in soil with concentration of P in water are the important parameters in the P-subroutines that affects overall for P loss simulations with the APEX model (Williams et al 2012).

1.6 Steps in computer models/Modeling methods:

The model set up, sensitivity analysis, calibration, and validation are the important steps before the process-based model can be used extensively. The first step in the model development starts with setting up an uncalibrated model using standard or default datasets and input parameter values. However, parameters can be redefined based on the information available and best professional judgment of the study sites (Baffaut et al. 2015).

Sensitivity analysis is done to identify the most sensitive parameters, which can then be adjusted during the calibration process. Sensitivity analysis is not readily transferable and is essential to determine for each management practices (Griensven et al. 2006; Moriasi et al, 2007). Therefore, sensitive parameters should be closely assessed to define its practical meaning and relationships with regard to the soils and management practices. Detail description and function of different model parameters in the model were discussed by Williams et al. (2012) and Steglich and Williams (2013).

Model calibration is the process of selecting appropriate model options, adjusting influential model parameters and inputs within their reasonable ranges based on sensitivity analysis, experience, site information, literature and expert opinions. Model calibration is necessary to minimize the margin of error compared to observed data (Winchell et al. 2011).

Model calibration also provides greater accuracy in simulation data and serves as a reference to help other users with their calibration processes (Wang et al. 2012). Model validation compares and evaluates the accuracy of model predictions with independently observed data (Wang et al. 2012). In general, model inputs are unchanged during validation. The purpose of the model validation is to make sure that the model is not over parameterized during the calibration process and yet capable of adequately simulating the impact of management practices as that of independent datasets. Overall, model calibration and validation help to increase the confidence in model predictions (Wang et al. 2009). Thus, a computer model must be calibrated and validated before extrapolating management practices implications to water quality and generate P loss datasets (Nelson and Shober et al. 2012).

1.7 Phosphorus index (PI)

The PI helps to identify site vulnerability and risk of P loss from agricultural fields by accounting for major source and transport factors that control P movement (Lemunyon and Gilbert, 1993). Research and extension efforts across the US have led to the creation of a unique PI in each state. Currently, 48 states in the US have adopted the PI as a P loss assessment tool and every state has their own PI based on the soil types, weather conditions, P loss pathways etc. (Sharpley et al. 2003).

1.7.1 Different Phosphorus Index formulations

Currently, there are three general structures of P-indices commonly used in the US; additive model, multiplicative model, and a component P index model.

The original phosphorus index (PI_o) model formulation was additive and was developed based on 8 different possible P loss parameters (P fertilizer application rate, P fertilizer application method, organic P source application rate, organic P source application method, runoff, soil test P, soil erosion, and irrigation erosion) multiplied by their respective weighting factors (β) (equation 1) (Lemunyon and Gilbert, 1993).

$$PI_o = \sum_{k=1}^{n} \beta_{\mathrm{k}} S_k \tag{13}$$

The P loss parameters (S) used in the model were categorical values and ranged from 0 (none) to 8 (very high). The weighting factors (β) ranged from 0.5 to 1.5. Each possible S was multiplied by the respective β and products summed to determine the final P index rating. The additive PI was simple and input values were easily obtainable. However, the drawback was that the categorical values for S and arbitrary values for β were not backed by any scientific research (Nelson and Shober et al. 2012).

With the advancement in P loss research and understandings, scientists have modified and made changes to the PI_o and develop different versions such as a multiplicative PI model (PI_m). The PI_m is divided into a group of source parameters (soil test P, P application rate, application methods etc.) and transport parameters (soil erosion, runoff class, distance from surface water body), and the sum of index values for source and transport are multiplied to give the final PI rating (equation 2) (Gburek et al. 2000).

$$PI_m = \left[\sum_{k=1}^{n} \beta_{\mathrm{k}} I_k \right] \left[\sum_{l=1}^{m} \lambda_1 J_l \right] \tag{14}$$

where there are n and m number of source (I) and transport (J) factors respectively. β_k is the weighting factor for *k*th source factor and λ_l is the weighting factor for the lth transport factor. Some of the categorical variables of the PI_o such as P application rates, and erosion loss were changed into continuous variables in PI_m. The PI_m formulation better represents the P loss processes than the PI_o but yet separating the source and transport parameters did not reflect the actual P loss processes as described in field P loss models (Bolster et al. 2012).

The component model (PI_c) is the further modification of the PI_m. Each individual parameter contributing to P loss was calculated as a product of both source and transport factors. The PI_c better reflects the P transport pathways and mechanisms of P loss that occur in the field and are simulated in process-based P loss models (Nelson and Shober, 2012; Bolster et al. 2012).

$$PI_o = \sum_{k=1}^{n} \sum_{l=1}^{m} \beta_{kl} I_k J_l \qquad [15]$$

where there are n and m number of source (*I*) and transport (*J*) factors respectively with β_{kl} as the weighting factor for the interaction of the *k*th source factor (I) and *l*th transport factor (J).

Readers are referred to the following sources for additional detail information on P-Index structure and development; Drewry et al. (2011); Gburek et al. (2000); Sharpley et al. (2009, 2011, 2012); Nelson and Shober (2012).

1.7.2 The Kansas phosphorus index (KS-PI)

The KS-PI a multiplicative P risk assessment tool. The source and transport factors in KS-PI are multiplied to determine the PI rating (Somez et al. 2009). The general form of the multiplicative KS-PI can be written as follows.

KS-PI rating (risk) = P source factor x transport factor [16]

Or, KS-PI = $(\beta_1 STP + \beta_2 P\ rate + \beta_3 AM) \times (\beta_4 Ero + \beta_5 RO + \beta_6 DWB + \beta_7 IrrEro + \beta_8 IrrRO)$ [17]

Where, STP = soil test P, Prate = P additions as organic or inorganic fertilizer, AM = application method and timing, Ero = erosion losses, RO = runoff risk, DWB = distance to a water body, IrrEro = irrigation erosion, IrrRO = irrigation runoff. The β_1-β_8 are the weighting factors (coefficients) that determine relative contribution to TP loss. The values of β_1 to β_8 used in the KS-PI are 1, 0.1, 1, 2, 1, 1, 1, and 1, respectively.

Ideally, weighting factors should be obtained from long-term measured P loss data. For the P-index accuracy, the determination of weighting factor are critical and significant, but, due to limited scientific data, most of the PI weights have been based on the professional judgment of developers (Bolster et al. 2012). Studies have reported improvement in P-index rating and P loss by adjusting the weighting factors. For instance, Sonmez et al. (2009) reported improvement in the correlation between KS-PI rating and measured P loss data by modifying weighting factors for STP and erosion. Nelson and Shober et al. (2012) indicated that use of improved weighting factors is one of the potential way to improve and evaluate the P indices. However, there is still a lack of standard procedure to determine PI weighting factors and further research is needed (Nelson and Parsons, 2012). Thus, this study will help to set a procedure to determine improved PI weighting factors to evaluate P indices.

In addition, the PI should accurately predict P loss risk due to changes in management practices. However, there are concerns about the use of P indices due to development disparity among P-indices across the country (Bennings and Wortmann, 2005; Osmond et al. 2006), poorly justified and arbitrary selection of some weighting factors (Drewry et. al. 2011; Nelson and Shober et al. 2012), and ineffectiveness in improving water quality (Environmental Protection Agency, 2010; Sharpley et al. 2012). Further, the Natural Resources Conservation Service (NRCS) released the nutrient management policy instruction (title 190 national part 302), PI assessment criteria in 2012 and highlighted that the PI tool must be calibrated to standardize the P loss risk categories across regional, state and watershed boundaries (USDA-NRCS, 2011b). Therefore, there is a need to evaluate and update Kansas PI to accurately estimate and minimize P loss from agricultural fields to water resources and also to meet the NRCS P index assessment criteria.

1.8 Summary and research need:

Reducing agricultural P loss to water bodies is a significant priority to protect surface water quality. The Kansas PI is a tool that helps producers to determine the risk and give options to minimize the risk of P loss from agricultural fields. Ideally, long-term measured P loss data are used to evaluate P-indices to reflect the actual field conditions and avoid experimental or climatic biases. However, due to limited P loss, runoff field studies data across the United States, process-based computer models such as the APEX have been proposed to extend the field studies, estimate management practices impact on P loss and develop P loss datasets needed to evaluate and update the P-indices. Further, the model should be tested (calibrated and validated) to determine its ability to adequately simulate P loss for a wide range of best management practices (BMPs). Once calibrated and validated, the model can be used to generate management practices implication on P loss dataset for an unknown sequence of weather, varying degree of soil test P levels, and crop-management practices. Therefore, it is necessary to test the effectiveness of the APEX model to simulate P loss with a wide array of management practices. Thus, developing the management practices database to update and evaluate Kansas PI by taking advantage of the tested APEX model will provide an updated robust PI tool for future guidance to producers on BMPs to minimize agricultural P loss.

The hypotheses of this research were

1. Calibrated and validated APEX model will accurately simulate P loss with constant management practices.
2. Calibrated and validated APEX model will accurately simulate the P loss with changing management practices.
3. High soil test P coupled with high P application rates result in greater TP loss in runoff.
4. Nitrogen based turkey litter application does not increase the long-term annual average TP loss if P inputs are balanced over the entire rotation.
5. Runoff TP loss will be linearly correlated with PI risk rating value.
6. Revised multiplicative Kansas PI will be better correlated to TP loss.
7. Component Kansas PI will be better correlated to TP loss than multiplicative Kansas PI

1.9 The objectives of this research were to

1. Determine the ability of APEX to accurately simulate runoff, sediment, total phosphorus (TP) and dissolved P (DP) losses with constant management practices.

2. Evaluate and assess the ability of APEX to simulate effects of changing management practices on runoff, sediment, TP and DP loss
3. Determine the optimal timing, rate, and frequency for poultry litter applications in no-till by surface broadcasting and conventional tillage to incorporate the litter in different cropping systems in Southeast Kansas.
4. Assess the impact of inorganic P fertilizer application methods, application timings, and application rates on TP loss with different cropping systems in the East central Kansas.
5. Evaluate, and update the Kansas PI using datasets generated with the calibrated and validated APEX model.
6. Determine appropriate P adsorption isotherm with advection-dispersion equation using experimental data from column leaching experiment.

1.10 REFERENCES

Barrow, N.J., J.W. Bowden, A.M. Posner, and J.P. Quirk. 1981. Describing the adsorption of copper, zinc and lead on a variable charge mineral surfaces Aust J. Soil Res 19 : 309-321.

Barrow, N. J., and T. C. Shaw. 1979. Effects of solution:soil ration and vigour of shaking on the rate of phosphate adsorption by soil. J. Soil. Sci. 30: 67-76.

Benning J., and C. Wortmann. 2005. Phosphorus indexes in four Midwestern states: An evaluation of the differences and similarities. J. Soil Water Conserv. 60:221-227.

Bhandari, A.B., R. A. Gelderman, D. Todey, and D. A. German. 2011. Managing manure applications to limit nutrient runoff from agricultural fields. Plant Science Department, South Dakota State University. MS. Thesis.

Bolster, C.H., P.A. Vadas, A.N. Sharpley and J.A. Lory. 2012. Using a phosphorus loss model to evaluate and improve phosphorus indices. J. Environ. Qual. 41:1758-1766.

Burkholder, J., and H. B. Glasgow Jr. 1997. Pfiesteria piscicida and other pfiesteria-like dinoflagellates: Behavior, impacts, and environmental controls. Limnol. Oceanogr. 42:1052-1075.

Baffaut, C., N. O. Nelson, G.M.M.M.A. Senaviratne, A. Bhandari, M.V. Liew, and J. Lory. 2015. Multi-evaluation of APEX for crop and grazing land in the Heartland region of the US. SWAT proceeding, Brazil.

Breeuwsma, A., and S. Silva. 1992. Phosphorus fertilization and environmental effects in the Netherlands and Po region (Italy). Report 57, Dienst Landbouwkundig Onderzoek. The Winard Staring Center, Wageningen, the Netherlands.

Butler, J.S., and F.J. Coale. 2005. Phosphorus leaching in manure amended Atlantic coastal plain soils. . J. Environ. Qual. 34: 370-38.

Carpenter S.R., D.L. Caraco, R.W. Correll, A.N. Howarth, V.H. Sharpley and Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559-568.

Dale, A.W., S. Sommer, L. Bohlen, T. Treude, V.J. Bertics, H.W. Bange, O. Pfannkuche, and T. Schorp. 2011. Rates and regulation of nitrogen cycling in seasonally hypoxic sediments during winter (Boknis Eck, SW Baltic Sea): Sensitivity to environmental variables. Estuarine, Coastal and Shelf Science. 2011;95:14–28. doi: 10.1016/j.ecss.2011.05.016.

Drewry, J.J., L.T.H. Newham and R.S.B. Greene. 2011. Index models to evaluate the risk of phosphorus and nitrogen loss at catchment scales. J. Environ. Manage. 92:639-649.

Dodds, W.K., J.L. Bouska, T.J. Eitzmann, K.L. Pilger, A.J. Pitts, J.T. Riley, D.J. Schloesser and Thornbrugh. 2009. Eutrophication of U.S. freshwaters: Analysis of potential economic damages. Environ. Sci. Technol. 43:12-19.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. H. K.J. Hitt, D.K. Mueller, M.D. Munn, B.T. Nolan, L.J. Puckett, M.G.Rupert, T.M. Short, , N.E. Spahr, L.A. Sprague, W.G. Wilber, 2010. The quality of our Nation’s waters—Nutrients in the Nation’s streams and groundwater, 1994 - 2004, http://water.usgs.gov/nawqa/nutrients/pubs/circ1350.

Eghball, B., and J. Power. 1999. Composted and non composted manure application to conventional and no-tillage systems: Corn yield and nitrogen uptake. Agron. J. 91:819-825.

Francesconi, W., D.R. Smith, G.C. Heathman, X. Wang and C.O. Williams. 2014. Monitoring and apex modeling of no-till and reduced-till in tile-drained agricultural landscapes for water quality. Transactions of the ASABE 57:777-789.

Francesconi, W., D.R. Smith, G.C. Heathman, J.M. Gonzalez and M.M. Benage. 2015. Application of a calibrated/validated agricultural Policy/Environmental eXtender model to assess sediment and nutrient delivery from the wildcat creek Mississippi river basin initiative-cooperative conservation partnership initiative. J. Soil Water Conserv. 70:23-35.

Gachter, R., S.M. Steingruber, M. Reinhardt M. and B. Wehrli. 2004. Nutrient transfer from soil to surface waters: differences between nitrate and phosphate. Aquatic Sci 66: 117-122.

Gassman, P.W., J.R. Williams, X. Wang, A. Saleh, E. Osei, L.M. Hauck, R.C. Izaurralde and J.D. Flowers. 2010. The agricultural Policy/environmental extender (apex) model: An emerging tool for landscape and watershed environmental analyses. Transactions of the ASABE 53:711-740.

Gassman P.W., M.R. Reyes, C.H. Green and J.G. Arnold. 2007. The soil and water assessment tool: Historical development, applications, and future research directions. Trans. ASABE 50:1211-1250.

Gassman, P. W., E. Osei, A. Saleh and L. Hauck. 2002. Application of an environmental and economic modeling system for watershed assessments. J. Am. Water Resour. Assoc. 38:423-438.

Gburek, W., and A. Sharpley. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. J. Environ. Qual. 27:267-277.

Glaesner, N., Kjaergaard, C. Rubek, G.H. and magid, J. 2011. Interactions between soil texture and placement of dairy slurry application: II. Leaching of phosphorus forms. J. Environ. Qua. 40: 344-351.

Graham J.L., M.T. Loftin, A.C. Meyer and Ziegler. 2010. Cyanotoxin mixtures and taste-and-odor compounds in cyanobacterial blooms from the midwestern united states. Environ. Sci. Technol. 44:7361-7368.

Green, C. M., Tomer, M. Di Luzio and J. Arnold. 2006. Hydrologic evaluation of the soil and water assessment tool for a large tile-drained watershed in iowa. Trans. ASAE 49:413-422. Heathwaite, A.L. and R. M. Dils. 2000. Characterizing phosphorus loss in the surface and sub-surface hydrological pathways. Sci Total Environ. 251-252:523-538.

Heathwaite A., and R. Dils. 2000. Characterising phosphorus loss in surface and subsurface hydrological pathways. Sci. Total Environ. 251:523-538.

Haygarth, P., M. and A. N. Sharpley. 2000. Terminology for phosphorus transfer. J. Environ. Qual. 29, 10–15.

Hudnell, H.K. 2010. The state of U.S. freshwater harmful algal blooms assessments, policy and legislation. Toxicon 55:1024-1034.

Lemunyon, J., and R. Gilbert. 1993. The concept and need for a phosphorus assessment-tool. J. Prod. Agric. 6:483-486.

Javid, S., and D.L. Rowell. 2002. A laboratory study of the effect of time and temperature on the decline in Olsen P following phosphate addition to calcareous soils. Soil Use Manag. 18:127-134.

Jones, C.A., C.V. Cole, A.N. Shaarpley, and J.R. Williams. 1984. A simplified soil and plant phosphorus model: I. Documentation. SSSA J. 48: 800-805.

Johnes P., and R. Hodgkinson. 1998. Phosphorus loss from agricultural catchments: Pathways and implications for management. Soil use Manage. 14:175-185.

Kansas Department of Health and Environment. 2012. 2011 harmful algae bloom overview. Kansas Department of Health and Environment, Bureau of Environmental Health, Topeka, KS.Available at http://www.kdheks.gov/algae-illness/download/HABsummary2011.pdf.

Koopmans, G. F., R.W. McDowell, W.J Chardon, O. Oenema, and J. Dolfing. 2002. Soil phosphorus quantity-intensity relationships to predict increased soil phosphorus loss to overland and sub-surface flow. Chemosphere 48:679-687.

Kovzelove, C., T. Simpson, and R. Korcak. 2010. Quantification and implications of surplus phosphorus and manure in major animal production region of Maryland, Pennsylvania, and Virginia. Water Stewardship, Annapolis, MD. http://watershedstewardshipinc.org/downward/P_PAPER_FINAL_2-9-10.pdf (assessed 12 Dec 2015).

Little, J.L., D.R. Bennett and J.J. Miller. 2005. Nutrient and sediment losses under simulated rainfall following manure incorporation by different methods. J. Environ. Qual. 34:1883-1895. Maguire, R. O. and J.T Sims. 2002. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Melich 3. SSSA J. 66 (6): 2033-2039.

Mausbach, M., and A. Dedrick. 2004. The length we go - measuring environmental benefits of conservation practices. J. Soil Water Conserv. 59:96A-103A.

McDowell, R.W., R.M. Monaghan, and J. Morton. 2003. Soil phosphorus concentrations to minimize potential P loss to surface waters in Southland. New Zeal. J. Agric. Res. 40 46:239-253.

McGechan, M.B., and D.R. Lewis. 2002. Sorption of phosphorus by soil, part 1: principles, equations and models. Biosyst. Eng. 82:1-24

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50:885-900.

Mudgal A., C. Baffaut, S.H. Anderson, E.J. Sadler and A.L. Thompson. 2010. Apex model assessment of variable landscapes on runoff and dissolved herbicides. Transactions of the ASABE 53:1047-1058.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Bratain. Phil. Trans. Res. SOc. London Ser. B. 281:277-329.

Nelson, N.O., and A.L. Shober. 2012. Evaluation of phosphorus indices after twenty years of science and development. J. Environ. Qual. 41:1703-1710.

Osmond, D.L., M.L. Cabrera, S.E. Feagley, G.E. Hardee, C.C. Mitchell, P.A. Moore Jr. R.S. Mylavarapu, J.L. Oldham, J.C. Stevens, W.C. Thom, F. Walker and H. Zhang. 2006. Comparing ratings of the southern phosphorus indices. J. Soil Water Conserv. 61:325-337.

Paerl H. 2008. Chapter 10: Nutrient and other environmental controls of harmful cyanobacterial blooms along the freshwater-marine continuum. Adv. Exp. Med. Biol. 619:217-237.

Plotkin, S. X., Wang, T.L. Potter, D.D. Bosch, J.R. Williams, E.S. Hesketh and J.K. Bagdon. 2013. Apex calibration and validation of water and herbicide transport under us southern Atlantic coastal plain conditions. Transactions of the ASABE 56:43-60.

Santhi, C. M., White, J.G. Arnold, L. Norfleet, J. Atwood, R. Kellogg, N. Kannan, X. Wang, M. Di Luzio, J.R. Williams and T. Gerik. 2014. Estimating the effects of agricultural conservation practices on phosphorus loads in the Mississippi-atchafalaya river basin. Transactions of the ASABE 57:1339-1357.

Saleh, A., O. Gallego, E. Osei, H. Lal, C. Gross, S. McKinney and H. Cover. 2011. Nutrient tracking tool-a user-friendly tool for calculating nutrient reductions for water quality trading. J. Soil Water Conserv. 66:400-410.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. Science 195:260–262.

Sharpley, A. N. 1985a. Depth of surface soil-runoff interaction as affected by rainfall, soil slope, and management. Soil Sci. Soc. Am. J. 49, 1010–1015.

Sharpley, A. N. 1995. Identifying sites vulnerable to phosphorus loss in agricultural runoff. J. Environ. Qual. 24:947-951. Doi:10.2134/jeq1995.00472425002400050024x

Sharpley, A.N., C.A.jones, C.Gray, and C.V. Cole. 1984. A simplified soil and plant phosphorus model:2 Prediction of labile, organic, and sorbed phosphorus. SSSA J. 48(4): 805-809.

Sharpley, A.N., R. McDowell, J. Weld and P. Kleinman. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. J. Environ. Qual. 30:2026-2036.

Sharpley A. N., R. McDowell and P. Kleinman. 2001. Phosphorus loss from land to water: Integrating agricultural and environmental management. Plant Soil 237:287-307.

Sharpley, A. N., P.J.A. Kleinman, R.W. McDowell, M.Gitau, and R.B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. J. soil and water conserv. 57 (6): 425-439.

Sharpley, A. N., P. Kleinman, R. McDowell, M. Gitau and R. Bryant. 2003. Modeling phosphorous transport in agricultural watersheds: Processes and possibilities (vol 57, pg 425, 2003). J. Soil Water Conserv. 58:127-127.

Sharpley, A. N., R.W. McDowell, and P.J.A. Kleinman. 2004. Phosphorus loss in agricultural drainage: historical perspective and current research. J Environ Qual 27: 277-293.

Sharpley, A. N., D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond and , P. A. Vadas. 2012. Phosphorus indices: Why we need to take stock of how we are doing. J. Environ. Qual. 41:1711-1719.

Sharpley, A. N., and X. Wang. 2014. Managing agricultural phosphorus for water quality: Lessons from the USA and china. J. Environ. Sci. 26:1770-1782.

Sims, J.T., T.R. Simard, and B.C. Joren, 1998 Phosphorus loss in agricultural drainage: Historical prospective and current research. J. Environ. Qual. 27 (2): 353-360.

Smith, D.R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker and A.N. Sharpley. 2015. Surface runoff and tile drainage transport of phosphorus in the Midwestern United States. J. Environ. Qual. 44:495-502.

Sonmez, O., G.M. Pierzynski, L. Frees, B. Davis, D. Leikam, D.W. Sweeney and K.A. Janssen. 2009. A field-based assessment tool for phosphorus losses in runoff in Kansas. J. Soil Water Conserv. 64:212-222.

Sorensen, P., and G.H. Rubek. 2011. Leaching of nitrate and phosphorus after autumn and spring application of separated solid animal manures to winter wheat. BSSS Soil use and Mgmt. 28: 1-11.

Steglich, E. M., and J.R. Williams. 2013. Agricultural Policy/Environmental eXtender Model: User’s manual. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX.

Stockle, C.O., J.R. Williams, N.J. Rosenberg, and C.A. Jones. 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I-Modification of the EPIC model for climate change analysis. Agric. Systems. 38:225-238

Sweeney, D.W., G.M. Pierzynski and P.L. Barnes. 2012. Nutrient losses in Watershed -scale surface runoff from claypan soil receiving turkey litter and fertilizer. Agriculture Ecosystems & Environment 150:19-26

Tuppad, P. C., Santhi, X. Wang, J.R. Williams, R. Srinivasan and P.H. Gowda. 2010. Simulation of conservation practices using the apex model. Appl. Eng. Agric. 26:779-794.

U. S. Environmental Protection Agency, 2002. Nutrient water quality criteria, summary Table for the nutrient criteria documents. http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/.

U. S. Environmental Protection Agency, 2010. Guidence for federal land management in the Chesapeak bay watershed. Chapter 2: Agriculture. Rep. EPA841-R-10-002. USEPA, Non point Source Pollution, Officer of Wetlands, Oceans, and Watershed, Washington, DC. http://www.epa.gov/nps/Chesbay502/pdf/chesbay_chp02.pdf (Assessed 12 Oct, 2015).

USDA NRCS (USDA Natural Resources Conservation Service). 2009. Conservation Effects Assessment Project (CEAP). Washington, DC available at: www.nrcs.usda.gov/Technical/nri/ceap/ .

Vadas, P.A., T.Krogstad, and A.N. Sharpley. 2006. Modeling phosphorus transfer between labile and non-labile soil pools. Updating the EPIC model. SSSA J. 70(3): 736-743.

Vadas, P.A., and M.J. White. Validating soil phosphorus routines in the SWAT model. 2010. Trans. ASBAE 53(5): 1469-1476.

Vadas, P.A., B. C. Joern, and P. A. Moore, Jr. 2012.Simulating soil phosphorus dynamics for a phosphorus loss quantification tool. J. Environ. Qual. doi:10.2135/jeq2012.0003

Van Es, H.M. Schindelbeck, R.R. and W.E. Jokela. 2004. Effect of manure application timing crop and soil type on phosphorus leaching. J. Environ. Qual. 33: 1070-1080.

Van Griensven, A. T. Meizner, S. Grunwald, T. Bishoop, M. Diluzio, and R. Srinivasan. 2006. A single global sensitivity analysis tool for the parameters of multi-variable catchment models, J. Hydrol, 324:10-23. Doi:10.1016/j.jhydrol.2005.09.008

Veith, T.L., A.N. Sharpley and J.G. Arnold. 2008. Modeling a small, northeastern watershed with detailed, field-level data. Transactions of the ASABE 51:471-483 ER. Wang X. P.W.

Wang, X., J. R. Williams. J. D. Atwood. M. L. Norfleet. and A. D. King. 2011. APEX model upgrades, data inputs, and parameter settings for use in CEAP cropland modeling. Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014165(accessed 10/24/2014).

Wang, X., D. W. Hoffman, J. E. Wolfe, J. R. Williams, and W. E. Fox. 2009. Modeling the effectiveness of conservation practices at shoal creek watershed, Texas, using apex. Transactions of the ASABE 52 (4): 1181-92.

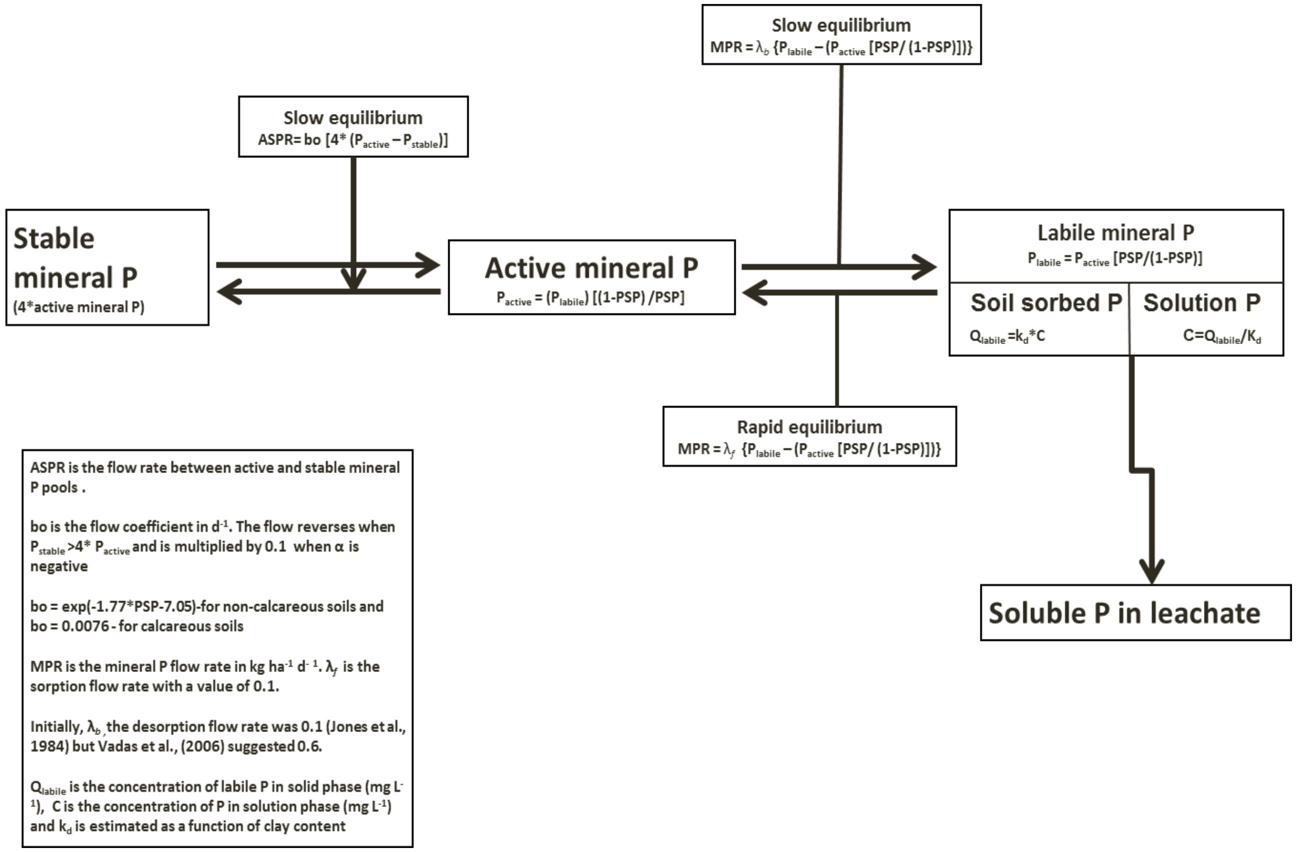
Wang, X., J. R. Williams, P. W. Gassman, C. Baffaut, R. C. Izaurralde, J. Jeong, and J. R. Kiniry. 2012. Epic and apex: Model use, calibration, and validation. Trans of the Asabe 55 (4): 1447-62.

Williams, J.W., R.C. Izaurralde, and E.M. Steglich. 2008. Agricultural policy/environmental extender model. Theoretical Documentation. BREC Report # 2008-17.

Williams, J.R., R.C. Izaurralde, and E.M. Steglich. 2012. Agricultural Policy/Environmental eXtender Model: Theoretical documentation. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX.

Yin, L. X., Wang, J. Pan and P.W. Gassman. 2009. Evaluation of apex for daily runoff and sediment yield from three plots in the middle Huaihe river watershed, china. Transactions of the ASABE 52:1833-1845.

Zeimen, M.B., K.A. Janssen, D.W. Sweeney, G.M. Pierzynski, K.R. Mankin, D.L. Devlin, D.L. Regehr, M.R. Langemeier and K.A. McVay. 2006. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. J. Soil Water Conserv. 61:258-267.



ASPR is the flow rate between active and stable mineral P pools .

bo is the flow coefficient in d^{-1}. The flow reverses when $P_{stable} > 4^* P_{active}$ and is multiplied by 0.1 when α is negative

bo = exp(-1.77*PSP-7.05)-for non-calcareous soils and bo = 0.0076 - for calcareous soils

MPR is the mineral P flow rate in kg ha^{-1} d^{-1}. λ_f is the sorption flow rate with a value of 0.1.

Initially, λ_b, the desorption flow rate was 0.1 (Jones et al., 1984) but Vadas et al., (2006) suggested 0.6.

Q_{labile} is the concentration of labile P in solid phase (mg L^{-1}), C is the concentration of P in solution phase (mg L^{-1}) and k_d is estimated as a function of clay content

Figure 1.1. Inorganic phosphorus pools in APEX model (adopted from Williams et al. 2012)

Chapter 2. Simulation of Runoff, Sediment, and Phosphorus Loss Using the APEX Model under Varying Management Practices

ABSTRACT

Process-based models have been proposed as a tool to generate data required for P-index assessment and development. Although models are commonly used to simulate phosphorus (P) loss from agriculture using management practices that are different from the calibration data, this use of models has not been fully tested. The objective of this study is to determine if the Agricultural Policy Environmental eXtender (APEX) model can accurately simulate runoff, sediment, total P (TP), and dissolved P (DP) loss from agricultural fields with management practices that are different from the calibration. The APEX model was parameterized and calibrated with field-scale data from eight different management systems (management-specific models) at two locations. The calibrated models were then validated with either the same management (tillage, nutrient source, rate etc.) used for calibration or with different management. Location-specific models were also developed by calibrating APEX with data from all the management practices. The management-specific models resulted in satisfactory performance when used to simulate runoff, TP and DP within their respective management systems, with $r^2 > 0.50$, Nash-Sutcliffe efficiency > 0.30, and bias within ±35% for runoff or ±60% for TP and DP. When applied outside the calibration management, the management-specific models only met the minimum performance criteria in 1/3 of the tests. The location specific models had better model performance when applied across all management systems than did the management-specific models. We recommend that models are applied within the

managements used for calibration and further suggest including as many management systems as possible in the calibration process.

2.1 INTRODUCTION

Agricultural Watersheds export substantial amounts of phosphorus (P) to water resources (Sharpley et al. 2003), which can accelerate biological productivity, promote algal growth and eutrophication, and lead to general water quality degradation (Carpenter et al. 1998; U.S Environmental Protection Agency, 2002; Sharpley and Wang 2014). Changes in agricultural management can increase or decrease P loss, thereby influencing the associated water quality impairments. Land managers need accurate information on the effects of management practices on P loss so they can choose practices that reduce P loss and protect water quality. However, there is a general lack of data on P loss from the various and complex managements.

Field studies can provide valuable data on the water quality impacts of agricultural management systems. These studies can reveal unknown and unforeseen treatment effects and interactions that occur within complex physical, chemical, and biological settings. However, some draw-backs of these studies include the limited number of treatment comparisons due to physical and economic constraints, limited duration of generally 3 to 5 years, and results that are highly influenced by the weather patterns that occur during the study.

Process-based computer models have the potential to provide data on management practice effects on water quality and can be used as tools to assess the impact of complex managements on P loss (Yin et al. 2009; Gassman et al. 2010; Wang et al. 2012). Models can extend the application of data from field studies. Models are advantageous because they are not restricted to a limited number of treatment comparisons, duration, or weather scenarios. For instance, a database of estimated P losses from various management systems could be developed using a calibrated and validated process-based computer model. The data could then be used to evaluate and update more simplified management tools used for conservation planning, such as phosphorus indices (Nelson and Shober, 2012). Disadvantages of using computer models include rigorous parametrization process that often requires assumptions for parameters that are difficult to measure, extensive data requirements, potential errors from simplifications in the mathematical descriptions of complex processes, and limited availability of field study data required to calibrate and validate models (Saleh et al. 2011).

Despite these disadvantages computer models have been widely used to asses impacts of management practices on P loss (Plotkin et al. 2013; Francesconi et al. 2014) and to guide water resource policy, management, and regulation (Ford et al. 2015). For instance, the APEX model has been used in the Conservation Effects Assessment Project (CEAP) to assess the benefits of the USDA conservation program at a national level (Mausbach and Dedrick, 2004; Wang et al. 2009). Models have also been promoted for use with limited data for calibration or even without calibration (Gassman et al. 2010). However, models must be tested (calibrated and validated) over a wide range of management practices to assure that they are robust. Model testing decreases margins of error compared to the measured data and also helps to minimize uncertainties related to model parameters (Winchell et al. 2011; Wang et al. 2009). Therefore, testing model’s robustness with different management practices is needed before using it for assessing management practice effects on P loss.

Most models are validated with the same management practices as were used during calibration (Ramanaryan et al. 1997; Gassman et al. 2002; Williams et al. 2006; Yin et al. 2009; Gassman et al. 2010; Mudgal et al. 2010, Kumar et al. 2011; Wang et al. 2012; Senavirante et al. 2013; Francesconi, 2014). This could create issues if these models are applied to management practice scenarios not included in the calibration dataset. Although models have been used to simulate P loss from agriculture using management practices that are different from the management practices of the calibration data, studies evaluating this use of models are strikingly absent from published literature. Thus, some management specific and sensitive parameters may be ignored during the model testing if the model is calibrated and validated with a single set of management practices and then used to simulate water quality impacts of different and complex management practices. This could produce inaccurate estimations and lead to faulty conclusions. This has significant impact if process based models are used to develop datasets for evaluation of P-indices as suggested by the NRCS P-index assessment criteria (USDA-NRCS, 2012).

The primary objectives of this study were to determine if APEX can accurately simulate runoff, sediment , total P and dissolved P losses from management practices that are i) similar to the calibration data (i.e. constant management practices), and ii) different from the calibration data (i.e. changing management practices). Because APEX has not been calibrated and validated for P loss from cropland receiving poultry litter, a secondary objective of this study was to parameterize the APEX model and evaluate its ability to simulate the effects of poultry litter applications on P loss from small cropland watersheds.

2.2 MATERIALS AND METHODS

Measured runoff and water quality data from two field-scale watershed studies were used to calibrate and validate the APEX model. The Franklin site was located in Franklin County, Kansas (38° 25’ N, 95° 7’ W). All soils on the site were Summit soil series (Summit fine, Smectitic, Thermic Oxyaquic Vertic Argiudolls) in NRCS hydrologic soil group C, as confirmed by an on-site investigation (Donald Gastineau, unpublished data, 2013) with average slope of 4-7 %. The study site was terraced, thus creating 6 drainage areas ranging from 0.4 ha to 1.5 ha. The study was initiated in 1998 to investigate the effect of tillage and fertilizer application method on water quality for a soybean-grain sorghum rotation. We used data from the 2001 to 2004 cropping years with management systems listed in Table 1.1. Additional details of the site and data collection are described by Zeimen et al. (2006), Mankin et al. (2010), and Maski et al. (2008).

The Crawford runoff study was located in Crawford County, Kansas (37° 30’ N, 94° 59’ W). The soil series was Parsons Silt loam (fine, mixed thermic Mollic Albaqualf), which is a claypan soil in NRCS hydrologic group D, as confirmed by an on-site investigation (Donald Gastineau, unpublished data, 2013). There were 10 adjacent small watersheds 133m by 31m (0.40 ha) in size with an approximate slope of 1%. Each watershed was separated on all sides by a soil berm to isolate runoff, with berms on the downslope end of the watershed angled toward a weir. The study was initiated in 1998 to investigate the effect of tillage fertilizer application method on water quality for a grain sorghum-soybean rotation. The site was then used to evaluate P loss from continuous grain sorghum amended with poultry litter in 2005-2007 and 2011-2013. The site was planted to continuous soybean with no litter application from 2008-

2010. The data used in this study were from 2011- 2013 in a continuous grain sorghum cropping system with management systems listed in Table 1.1. Additional details on site characteristics and data collection procedures are available in Sweeney et al. (2012) and Zeimen et al. (2006).

Runoff at both sites was monitored from April through October or November. Runoff was not monitored during the winter months due to complications associated with freezing temperatures. Runoff volume was measured at each watershed outlet with a 90 degree v-notch weir, instrumented with ISCO 6700 samplers (ISCO, Lincoln, Nebraska). Water quality data included runoff volume, sediment loss, total nitrogen (TN) loss, total P (TP) loss, and dissolved P (DP) loss based on flow-weighted composite samples for each runoff event, with some events including multiple days. Because detailed hydrograph data were not available, event durations were defined based on the onsite precipitation records, where days with continuous precipitation were regarded as a single event. Measured data were reviewed for quality control and events with inexplicable data (i.e. runoff: rainfall ratio > 0.9) were omitted from the analysis.

2.2.1 APEX model and input data acquisition

The APEX model is a farm to small watershed scale, daily time-step, process-based model. Primary inputs are geo-spatial characteristics of the watershed, physical and chemical properties of soils, agricultural management (or cultivation) practices, and daily weather data. Based on these inputs, the model simulates daily water flux, plant growth (including grain yield), nutrient cycling, soil erosion, and nutrient loss (Wang et al. 2009; Williams and Izaurralde, 2006; Williams et al. 2012; Wang et al.2011). Watersheds can be divided into multiple sub-areas that have similar soils, slopes, and management practices. APEX routes water, sediment and nutrients from one subarea to next and to the watershed outlet (Steglich and Williams et al. 2013).

Different options are available in APEX, which allows users to select equations for simulation of major processes, such as erosion or potential evapotranspiration (Gassman et al. 2010; Williams et al. 2012). The curve number is the primary method used to simulate runoff in APEX and infiltration is estimated as the difference between effective precipitation and surface runoff (Baffaut et al. 2013). Management related inputs include as land use, crop type, planting date, tillage processes and dates, fertilizer or manure application rates and dates, and harvesting date. The APEX model is written in Fortran with an open source code that is available from the model developers. APEX version 0806 compiled in August 2015 was used for this study.

There are models that would better simulate hydrology, crop growth and P loss with extensive sub-routines such as Root Zone Water Quality Model (RZWQM), Decision Support System for Agrotechnology Transfer (DSSAT), annual phosphorus loss estimator (APLE), respectively. However, none of the models is perfect to simulate all the filed process together. The watersheds used in this study were very small ranging from approximately 0.40 - 1.50 hectare in size with mostly a single subarea except in one. Therefore, the APEX model was selected for this study because it has the capability to route water, sediment, nutrients, and pesticides between the subareas and has the most comprehensive routing capabilities available in current landscape models that better represents our watersheds (Srivastava et al. 2007; Gassman et al. 2010).

2.2.1.1 Weather file

Both sites had on-site, daily precipitation data collected during the months where runoff was monitored. Precipitation data from nearby weather stations (National Climatic Data Center) were used to fill in winter precipitation, missing precipitation data during the growing season, and daily temperature data. Long-term (25+ years) weather data from the nearby weather stations were also used to develop monthly weather files for the APEX model, including characteristics of monthly temperature, relative humidity and wind speed. Weather stations used to supplement on-site weather data were the Ottawa (38.6132°, -95.2808°) and Garnett (38.28, -95.2177) weather stations for the Franklin site and the Parsons (37.3677, -95.2891) and Girard (37.508, -94.8391) weather stations for the Crawford site. During the data collection periods, annual precipitation ranged from 617 to 1121 mm at Franklin and from 763 to 1342 mm at Crawford.

2.2.1.2 Development of site-specific soils data

The soil data inputs for the model were as follows (for each layer) the depth to bottom of the layer, soil texture, total nitrogen percentage, organic carbon percentage, and anion exchange extractable phosphorus, available water, hydraulic conductivity, and bulk density for each soil series. Measurement of some sensitive soil inputs to the APEX model, such as available water, hydraulic conductivity, and bulk density is very difficult, time consuming, and expensive. Therefore, site-specific soil file was developed by combining data from the Natural Resource Conservation Service (NRCS) Soil Characterization database and measured on-site data.

2.2.1.3 Frankin soil data

Archived soil samples collected at 0-5 cm and 5-15 cm deep from each watershed in the year 2000 were analyzed for total carbon (TC), total nitrogen (TN), total P (TP), and Bray P (Appendix B). The anion exchangeable phosphorus (AEP) was determined using regression equation (Mallarino and Atta, 2005). The soil phosphorous sorption coefficient (PSP) was back calculated as PSP = 1/ ([(total phosphorus - organic phosphorus)/ (5*labile Phosphorus)] + 4/5) (Nelson and Parsons, 2006).

Three soil cores were collected down to 1m from each watershed in the fall of 2012 and segmented according to pedogenic horizons. The resulting soil samples were air dried ground and sieved to 2mm and analyzed for particle size (sand, silt and clay), total nitrogen (TN), and total carbon (TC) for each horizon (Appendix B). Although the soils of all watersheds were in within the Summit series, there were differences in horizon number and depth. Therefore, unique soil files were developed for each watershed. Measured soil characteristics were similar to those of pedon 09N0906 (User pedon ID S09KS20700) from the National Cooperative Soil Survey (NCSS) characterization database (Donald Gastineau, personal communication, 2013). Therefore, soil properties that were not measured (i.e. bulk density, field capacity, wilting point, and cation exchange capacity) were entered based on data from layers in pedon 09N0906 with corresponding depth, texture, and TC. Saturated hydraulic conductivity (k-sat) were estimated based on soil texture and bulk density using the Rosetta model (*Http://www.Ars.Usda.Gov/News/Docs.Htm?Docid=8953)*.

2.2.1.4 Crawford soil data

Soil samples were collected on spring 2011 before the initiation of the runoff study and were analyzed for TN, TC, TP, Bray P. The AEP and soil PSP was determined using the same procedure as for the Franklin site.

Three soil cores were collected down to 1m from six watersheds in the spring of 2013 and segmented according to pedogenic horizons. The resulting soil samples were air dried, ground and sieved to 2mm and analyzed for particle size (sand, silt and clay), TN, and TC for each horizon (Appendix B). The watershed profiles were similar enough that the lab data were averaged across to develop a single soil file. Measured soil characteristics were similar to pedon 11N0042 (User pedon ID S2011KS021001) from the national cooperative soil survey (NCSS) characterization database (Donald Gastineau, personal communication, 2013). Therefore, soil properties that were not measured (i.e. bulk density, field capacity, wilting point, and cation exchange capacity) were entered based on data from layers in pedon 11N0042 with corresponding depth, texture, and TC. Measured saturated hydraulic conductivity (K-sat) values from representative Parsons Silt loam soils were obtained from the NRCS (Donald Gastineau, unpublished data, 2013).

2.2.1.5 Management file

Site specific management data such as tillage, fertilization/poultry litter rates, application methods, date of planting, date of harvesting etc. were manually entered based on farm records following the APEX0806 operation file format to develop management file in each watersheds.

2.2.1.6 Watershed characterization

Each field was considered as a watershed and each watershed represents a single drainage area in both locations. The watersheds in the Franklin site were delineated using ArcAPEX interface and 2m digital elevation data (http://kansasgis.org/catalog/index.cfm?data_id=1921&show_cat=5). The average upland slope (SLP), average upland slope length (SPLG), mainstream channel slope (CHS) and channel slope of routing reach (RCHS) were adjusted based on site characteristics and measured data (Keith A. Janssen, unpublished data, 2000). Watersheds in the Crawford site were defined using win-APEX and assessing each parameters based on the site information. At the Crawford site, 2m digital elevation data were not available (at the time of the model set up) therefore, win-APEX was used.

Control and parameter file inputs

The APEX control file defines the different equations used for specific processes in the model. The parameter file includes process threshold values, and equation coefficients. The control file and parameter file inputs were based on Conservation Effects Assessment Project (CEAP) cropland study (Wang et al. 2011). Some of the control, and model parameter inputs were redefined based on the site information and professional judgment of the sites (Baffaut et al. 2015). For additional description of the APEX model, model inputs, and nutrient sub-routines, the reader is referred to Gassman et al. (2010), Wang et al. (2012), and Williams et al. (2012).

2.2.2 Data analysis and model evaluation

Model estimates of runoff, sediment, total phosphorus (TP) and dissolved phosphorus (DP) from the daily watershed outlet (.DWS) file were compared to measured data for each event. The coefficient of determination (r^2), Nash-Sutcliff model efficiency (NSE) (Nash and Sutcliffe, 1970), and percentage bias (PBIAS) (Gupta et al. 1999) were used to evaluate model performance during calibration and validation. The NSE and p-bias were calculated as follows:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y_{mean}^{obs})^2} \right] \qquad [1]$$

$$\text{P-bias} = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n} (Y_i^{obs})} \right] \qquad [2]$$

where Y_i^{obs} =i$^{\text{th}}$ observation, Y_i^{sim} = i$^{\text{th}}$ simulated value, Y_{mean}^{obs} = mean of observed data and n = total number of observations.

Researchers have considered different acceptable ranges for these statistics depending on the time scale of the measured data, type of measured data, and objective of the study. For instance Ramanarayan et al. (1997) considered r^2 >0.5 and NSE >0.40 as satisfactory for surface water quality for monthly values with the APEX model. Chung et al. (2002) used r^2 > 0.5 and NSE > 0.3 as satisfactory for monthly tile flow and NO_3-N loss with EPIC model. Wang et al. (2008) indicated r^2 > 0.5 and NSE > 0.4 as acceptable for monthly runoff and nutrient concentrations using the APEX model. Moriasi et al. (2007) suggested NSE > 0.5 with P-bias ±25% for streamflow, ±55% for sediment and ±70% for nitrogen and phosphorus for monthly values. They also indicated that NSE values can be relaxed for shorter time steps (daily events). Yin et al. 2009 reported NSE for event based runoff and sediment between 0.41-0.84 and r^2 between 0.55 - 0.85. Mudgal et al. (2010) regarded r^2 > 0.5 and NSE > 0.45 as threshold for satisfactory calibration and validation with event data. Considering the variability in literature and the objectives of the current study, the threshold values for acceptable model performance statistics for runoff were set at 0.50, 0.30 and ±35% for r^2, NSE, and P-bias respectively and for sediment, TP, and DP loss the threshold values were set at 0.50, 0.30 and ±60% for r^2, NSE, and P-bias, respectively.

2.2.3 Management specific sensitivity analysis, model calibration and validation

Sensitivity analysis is not readily transferable (Griensven et al. 2006) and is essential to determine which parameters need to be calibrated (Moriasi et al, 2007). In this study, manual sensitivity analysis was conducted by testing all the options in control and range of values in parameter files to identify sensitive parameters for each management. The sensitive parameters in the parameter file were divided into four categories based on the impact on runoff, sediment, TP and DP loss (Table 2.2). Identified sensitive parameters were assessed to define their practical meaning and relationships with regard to the soils and management in each watershed. Biological mixing efficiency (parameter 29), soluble phosphorus runoff coefficient (parameter 8), soil biological activity parameters coefficient adjusts microbial activity function in the top soil layer (parameter 69), and microbial decay rate coefficient (parameter 70) were the most important and critical parameters. Parameters that were sensitive and differ from one management to another are described in greater detail in Appendix B.

Management-specific models were developed by independently calibrating APEX for each management system. The models were manually calibrated by changing options in the control file and by adjusting sensitive parameter values identified in Table 2.2 that maximize the model performance (maximize r^2 and NSE and result in a p-bias nearest to 0). The inputs in the soil, management, or watershed files were not considered for calibration as those were carefully determined during model set up.

To test objective i. management-specific models were validated by comparing model output to independently measured data from a watershed with management that was identical to the calibration data. Validation was completed without changing the calibrated parameters, i.e. control and parameter values used during validation were identical to the calibrated values. To test objective ii. the management-specific models were used to simulate runoff, sediment, and nutrient loss from watersheds where the management practices were different from the management used for model calibration. The model output was then compared to the measured data to assess model performance as previously described. The same management data from two watersheds were combined together to evaluate model performance for the objective ii.

2.2.4 Location specific model development

A location-specific model was developed for each site by considering the same 20 sensitive parameters identified during the management-specific calibration process (Table 2.2). The location specific calibration was completed by first identifying average parameter values for each location based on the management-specific models. Second, highly sensitive model parameters were manually adjusted to maximize model performance criteria for data from all management systems at that location. The location specific models were then validated for all management practices listed in table 2.3.

2.2.5 Aggregated model performance assessment

Data from all management systems (watersheds) and locations were aggregated to assess overall model performance. For instance, event-based measured data from 3 watersheds at the Franklin location and 4 watersheds at the Crawford location were compared to the event-based model estimates and used to compute the correlation coefficient, NSE and PBIAS for the entire dataset, thereby assessing model performance across management systems and locations. A similar process was followed for the validation datasets. The crop yields were also aggregated for all watersheds in each location and the model performance was evaluated with p-bias.

2.3 RESULTS AND DISCUSSION

2.3.1 Crop yields

The model simulated yield for crops were in very good agreement with the measured data at both sites. The PBIAS for the calibrated model was -22% and validated model was -7 % for grain sorghum at Crawford location. Likewise, the aggregated p-bias for soybean and grain sorghum yield at the Franklin location was -5% and -2% with the calibrated and validated model.

2.3.2 Franklin Site

2.3.2.1 Runoff calibration and validation

The runoff simulated loss with the uncalibrated model did not meet the model performance threshold criteria for NSE and r^2 for any three managements but the p-bias criteria were met (Table 2.5). The calibration improved model performance statistics for runoff in all three managements exceeding the minimum performance criteria. Similarly, all the managements were validated with statistics above acceptable threshold criteria for runoff. Other studies have reported similar statistics for runoff calibration and validation (Gassman et al. 2010; Kumar et al. 2011; Senaviratne et al. 2013; Francesconi et al. 2014). The overall model simulated runoff was 25 - 38 % and 23 - 32 % greater in no-till management practices (NTSA and NTDB) compared to CONV-T management for calibration and validation datasets respectively. The trend of simulated runoff loss was in good agreement with the measured loss (Zeimen et al. 2006). Potentially greater soil moisture and compaction in no-till may have resulted in greater runoff loss as compared with conventional tillage (Mickelson et al. 2001a; Myers et al. 1995).

2.3.2.2 Sediment loss calibration and validation

The uncalibrated model simulated sediment loss was 662 to 2038 % greater than measured data and did not meet the model performance threshold criteria (Table 2.5). Although sediment loss simulation was greatly improved after calibration, only the CONV-T management met all the model performance criteria. The NTSA management did not meet the criteria for r^2 and the NTDB management practice did not meet criteria for either r^2 or NSE. Similarly, the no-till management practices (NTSA and NTDB) did not meet the performance criteria for the validation while the CONV-T management met the criteria (Table 2.5).

The poor calibration for the no-till management practices is likely a result of the low overall sediment loss from these management practices. The maximum measured sediment loss during a single event was 0.94, 0.24 and 0.52 Mg ha^{-1} with CONV-T, NTDB and NTSA management practices respectively during calibration. Likewise, the total measured sediment losses over the simulation period were 4.23, 1.93 and 2.95 Mg ha^{-1} and model simulated losses were 3.98, 1.66 and 1.84 Mg ha^{-1} with CONV-T, NTDB and NTSA management practices respectively during the entire 4-yr study period. Though the model performance criteria for NSE and r^2 were not meet with NTDB (watershed 7) management during calibration, the measured (1.93 Mg ha^{-1}) and model simulated (1.66 Mg ha^{-1}) sediment loss during the entire study were very similar. Further, the overall model simulated sediment loss was in agreement with the measured data with highest loss from CONV-T management followed by the NTDB and NTSA managements (Zeimen et al. 2006). The range of measured sediment loss was greater in CONV-T (watersheds 5 and 6) management that passed calibration and validation criteria indicating the model performance may improve when used to simulate management practices with wider ranges of sediment loss.

2.3.2.3 Phosphorus loss calibration and validation

Overall, total P loss with the uncalibrated model did not meet the model performance criteria for r^2, NSE and p-bias (Table 2.5). The calibration improved the model simulation in all three management practices and met the threshold criteria for r^2, NSE and p-bias. Likewise, all the three management-specific models met the performance criteria for validation datasets that had the same management system as the calibration datasets (Table 5).

The model simulated TP loss was greater with NTSA followed by NTDB and the lowest with CONV-T management practices for 2003 and 2004. These differences in TP loss with different management practices were similar to those of measured loss (Zeimen et al. 2006). Perhaps, the deep band application of P as in NTDB management and incorporation and mixing of P fertilizer with chisel/disk operation as in CONV-T management reduced P loss compared to the no-till surface application (NTSA) management practice. The management specific TP loss followed the similar trends during validation. Overall, the model simulated TP loss was under-predicted during calibration and validation by 16 to 47%.

None of the uncalibrated models met all performance criteria for simulation of DP loss (Table 2.5). The uncalibrated model for NTSA (watershed 8) management met the threshold criteria for NSE and r^2, however, this is of little consequence because the uncalibrated model did not pass threshold criteria for runoff. The model performance criteria for DP loss simulated by the calibrated NTSA model exceeded the threshold criteria for both calibration (watershed 8) and validation (watershed 4) datasets. For the NTDB management, the calibrated model NSE (0.34) and p-bias (+16%) passed the threshold criteria and r^2 (0.48) was only slightly less than acceptable. However, the DP simulation for NTDB model did not pass threshold criteria for validation. Furthermore, the CONV-T management model did not meet the performance criteria for DP loss in either calibration or validation.

The difficulty in calibration and validation of DP loss with CONV-T management might be due to very low measured DP loss with conventional tillage. The overall DP loss from CONV-T (watershed 6) management during the entire 4 year study period was approximately 5% (0.18 Kg ha^{-1}) of the measured total P loss (3.44 Kg ha^{-1}). Likewise, measured DP loss was 28% of TP loss from NTDB (watershed 7) and 45% from NTSA (watershed 8) managements. The trends of DP loss were similar with 4%, 19% and 44% of the total measured TP loss with treatments CONV-T, NTDB, and NTSA (Watershed s 5, 2 and 4) respectively for the validation dataset. So, if the measured DP loss is very low such as 4-5% of TP, as in CONV-T management it would be difficult for the model to simulate the loss according to our performance indicators. But if the DP loss is near 50% of the total P loss, the model can accurately simulate the loss as seen with

NTSA management practices. The overall model simulated DP loss was greater with NTSA (1.10 kg ha^{-1} yr^{-1}) followed by NTDB (0.36 kg ha^{-1} yr^{-1}) and lowest with CONV-T (0.06 kg ha^{-1} yr^{-1}) management during calibration and followed the similar trends during validation. The model simulated results were consistent with the measured data (Zeimen et al. 2006).

2.3.3 Crawford Site

2.3.3.1 Runoff calibration and validation

The runoff loss with the uncalibrated model met the model performance threshold criteria for r^2, NSE and p-bias (Table 5) in all managements. Calibration improved the model performance for simulated runoff loss, exceeding the minimum threshold criteria for both calibration and validation datasets (Table 2.5).

2.3.3.2 Sediment loss calibration and validation

The uncalibrated model simulated sediment loss was approximately 662 to 2038 % greater than measured data and did not meet the minimum threshold criteria (Table 2.5). The sediment loss was greatly improved after calibration but only the model for FERTC management practices met the performance criteria. The p-bias for sediment loss was within the acceptable criteria for all managements. However, CONT, TLPC and TLNC management practices did not meet the criteria for either r^2 or NSE. Overall, the sediment loss was under-predicted during the calibration by 6 to 60 %. But the validated model over-predicted sediment loss by 48 to 200 % (Table 2.5) and none of the managements met the sediment loss performance criteria.

The plausible reason for difficulty in model calibration and validation with sediment loss might be due to low slope (approximately 1%) resulting in very low measured sediment transport. Several studies have indicated the similar difficulty in calibration and validation of the APEX model with sediment loss especially when the measured loss is very low (Kumar et al.2011; Mudgal et al.2012; Senavirante et al.2013) They also indicated the APEX model algorithms might need to be improved to address the low sediment loss.

Although sediment calibration and validation was poor, the simulated sediment loss followed the observed trend of lower loss simulated from systems with no-till management (CONT) and higher from systems with conventional tillage management practices (FERTC, TLNC and TLPC). The trends were similar during validation. Therefore, despite the poor event-based model performance statistics, the model simulated average annual losses were very similar to the measured data and accurately reflected the difference between no-till and conventional tillage.

2.3.3.3 Phosphorus loss calibration and validation

Out of 4 management practices, only 2 models (FERTC and TLPC) met the performance criteria for TP loss without calibration. In models for the other 2 management practices (CONT and TLNC), the TP loss was over predicted by 62 to 196 % compared to measured loss (Table 2.5). Management-specific models for all 4 management systems met the model performance threshold criteria except for r^2 in CONT model during calibration (Table 2.5). Similarly, all 4 management-specific models met the performance criteria (Table 2.5) for TP loss during validation.

For DP loss, none of the uncalibrated models met performance criteria. Except for r^2 of the model for CONT, all 4 management-specific calibrated models exceeded the performance criteria for DP loss (Table 2.5). Likewise, all 4 management-specific calibrated models met the performance criteria for DP loss for validation within their respective management systems.

The overall average annual measured DP loss was higher with TLNC followed by FERTC, TLPC and CONT managements. As expected, the measured dissolved P loss was approximately 72% of the TP loss with TLNC treatment and lowest with FERTC (53%), a commercial fertilizer application treatment. The model simulated DP loss showed similar trends.

2.3.4 Aggregated model performance assessment

Performance of the management-specific models across managements and locations was assessed by combining observed and simulated data from all management systems at both locations for computation of aggregated statistics. The results showed that the uncalibrated models met the threshold criteria for runoff, but not for sediment, TP and DP loss (Figure 2.1). Nevertheless, as expected, the runoff, TP and DP loss simulated by the calibrated model exceeded the threshold criteria when data were aggregated from both sites (Figure 2.1). The sediment loss performance was greatly improved with NSE and p-bias meeting the threshold criteria, but did not pass the criteria for r^2. Similarly, the aggregated runoff and TP loss simulated during the validation period exceeded the minimum threshold criteria. The NSE and p-bias for DP loss were above the minimum threshold but r^2 was slightly lower than the minimum criteria. The p-bias for sediment loss met the model performance criteria but the r^2 and NSE did not (Figure 2.1). Therefore, aggregated model performance results indicate that, when calibrated for specific management practices, the APEX model is able to satisfactorily simulate runoff total P, and dissolved P loss across multiple locations and management practices. However, the uncalibrated model could not satisfactorily simulate P loss. Although calibration greatly improved simulation of sediment loss, APEX did not satisfactorily simulate sediment loss, perhaps because of the relatively low loss from these management practices in the tested locations.

2.3.5 Testing the APEX model to simulate effects of changing management systems

Water quality models are often used to compare the impact of new or changing management systems on sediment and P loss. However, in many cases the models are calibrated and validated within a single management system as has been previously described (Yin et al. 2009; Gassman et al. 2010; Senavirante et al. 2013; Francesconi, 2014). This could result in errors if the calibration is management-specific. Our second objective was to determine if APEX can simulate P loss from agricultural management systems that are different than the management used for model calibration. This was tested by using the previously calibrated and validated management-specific models to simulate runoff, sediment, and P loss for validation data sets with contrasting management practices.

2.3.5.1 Franklin site-testing Phosphorus (P) fertilizer placement and tillage

The ability of the APEX model to simulate changes in P placement was determined by using a model calibrated and validated for surface applied P fertilizer (NTSA, watershed 8) to simulate P loss when the fertilizer is sub-surface applied (NTDB, watersheds 2 and 7). The reverse was also tested. The model was successful at simulating a change from sub-surface to surface placement of P fertilizer, but not the reverse (Table 2.6). Using the NTSA model to simulate P loss from NTDB managements resulted in a low r^2 for TP loss and values outside the thresholds for all DP performance criteria. Likewise, the ability of APEX to simulate effect of tillage and P placement was also tested using the model calibrated and validated for conventional tillage (CONV-T) to simulate P loss from no-till management systems (NTDB and

NTSA). The reverse was also tested. On both cases the simulated runoff, sediment, TP and DP loss did not pass the minimum threshold criteria (Table 2.6). Overall, sediment, TP and DP losses were under-predicted.

The results indicated that when the tillage is similar, the model is capable of effectively simulating runoff, and TP. But if the tillage is changed, the APEX model was unable to accurately simulate sediment, TP or DP losses. Therefore, if the model is calibrated and validated with one management and used to simulate water quality impacts for different management practices (especially with a change in tillage) the resulting model estimates of P loss will not be quantitatively correct. Hence, this may lead to incorrect information and misguide policy makers when simulating long term water quality loss assessments for best management practices (BMPs).

2.3.5.2 Crawford site-testing nutrient source, rate, and tillage

The ability of the APEX model to simulate effects of different nutrient sources on P loss was tested by using a model calibrated with data from conventional tillage-P based poultry litter application (TLPC) system to simulate the P loss from conventional tillage-P based commercial fertilizer (FERTC) management. The runoff, TP and DP loss all met the model performance threshold criteria (Table 2.6) indicating the fully calibrated and validated APEX model is capable of simulating this change in fertilizer source with same tillage. However, the sediment loss did not pass the threshold criteria potentially due to low sediment loss as described earlier.

The ability of the APEX model to simulate the effect of P application rate on P loss was also tested. The initial model was calibrated and validated with data from a conventionally tilled system for which poultry litter was applied at a rate that satisfies nitrogen crop requirement (TLNC). The management-specific model was then used to simulate P loss when the application rate was reduced to meet the phosphorus crop requirement (TLPC) and when commercial fertilizer was applied at agronomic rates (FERTC). The results indicated that while performance criteria were met for runoff, this was not the case for sediment, TP or DP loss (Table 6). Likewise, the ability of the APEX model to simulate effects of changing nutrient source, rate and tillage was tested using a fully calibrated and validated CONT management model to simulate P loss from conventional tillage high P rate (TLNC), conventional tillage low P rate (TLPC) poultry applications, and conventional tillage P rate commercial fertilizer application (FERTC) management systems. The runoff, TP and DP loss with P based nutrient applications (i.e. TLPC and FERTC) exceeded the model performance criteria but the sediment loss was over-predicted by 100 to 333 %. Although the CONT management-specific model satisfactorily simulated P loss from systems that had low P (TLPC and FERTC), simulated TP and DP loss did not pass the threshold criteria when poultry litter was applied a the N-based rate (TLNC).

The model performance statistics reflected that if only the nutrient source was different with same tillage and with low P rate like in TLPC and FERTC, the model was capable of simulating change in fertilizer source. The results indicated that if a model calibrated and validated for conventional tillage and high N-rate poultry litter application (TLNC) was used to simulate P loss from management systems with no-till and low P rates (such as CONT, FERTC and TLPC), the model did not pass the minimum threshold criteria. The effect of tillage was not sensitive in this location perhaps due to low slope (approximately 1%) and very low sediment loss. But if the change in P rate was large the model was unable to simulate the TP loss accurately. Perhaps, there are some model parameters that are different for high and low P poultry litter application management practices such as soluble phosphorus runoff coefficient (Parameter- 8) that need to be examined closely when simulating TP and DP loss.

Overall, the runoff, TP, and DP loss performance criteria for management-specific models applied outside the management used for calibration were met for only 1 management system at the Franklin location (out of 6) and 4 management systems at the Crawford location (out of 12) (Table 2.6). These results showed that management-specific models can accurately simulate effects of changing management on P loss < 30 % of the time. The results also reflected that APEX models perform better with smaller changes in management. For instance, a difference in P loss due to P placement in a no-till management practices (NTSA and NTBD) was well simulated at the Franklin location. Likewise, the effects of changing P source on P loss was accurately simulated with the management-specific models. This study also indicated that extra caution is required if the change in management includes extremely high or low P application rates, high soil test P level, and change in tillage systems. Therefore, scientists and policy makers need to be aware of this deficiency and over a 70% chance of failure to quantitatively predict effects of changing management systems on P loss when a computer model was calibrated and validated with one management system and used to simulate P loss with a different management system.

2.3.6 Location specific model

Because a management-specific calibrated and validated model failed to accurately simulate P loss >70 % of the time when applied to different management systems, a location specific model was developed by using data from multiple management systems for calibration at each location (Franklin and Crawford). The method of selecting the model parameters and the final parameter values for the location-specific models are listed in Table 2.7.

At Franklin, the simulated runoff and TP loss exceeded the threshold criteria for both calibration and validation datasets in all three management systems with a location-specific model (Table 8). The simulated sediment loss in CONV-T management also met the model performance criteria for both calibration and validation datasets. However, the DP loss was greatly over-predicted in CONV-T management system (Table 2.8).

At Crawford, the location-specific model was successful at simulating runoff, TP and DP loss and met the performance criteria for all the management systems except CONT management, for which TP and DP simulated results did not meet the r^2 requirements during calibration. Likewise, the model performance criteria for runoff, TP and DP loss for validation datasets were met for all the management practices. However, the sediment loss was over-predicted (Table 2.8).

2.3.7 Simulation of 30 year long term runoff, sediment, TP and DP loss with a location specific model

The location-specific models were used to simulate 30-year average annual loss for runoff, sediment, TP and DP loss from each of the management systems at the respective locations. At Franklin, the simulations indicated that the conventional tillage system (CONV-T) resulted in greater runoff, sediment loss and TP loss compared to no-till management systems (NTDB and NTSA). But the DP loss was higher in no-till surface applied fertilizer management (Table 2.9). The higher sediment loss in CONV-T might have also contributed in greater TP loss.

At Crawford, the location-specific model simulate similar runoff for all management practices, but greater sediment loss with conventional tillage management systems (FERTC, TLPC, and TLNC). The TP loss was extremely high with N-based poultry litter management system (TLNC) followed by FERTC, TLPC and CONT. The DP loss follows the similar trend. The simulated results also indicated that a long term N based poultry litter application (that over applies P) with conventional tillage should not be recommended from water quality stand point. The location specific model simulated average loss for base managements were in good agreement with the measured data in both locations and indicated that, if the model is properly calibrated and validated with multiple management practices, it is robust enough and can be used to simulate long term water quality impacts of multiple management systems.

2.4 CONCLUSIONS

The overall model performance evaluation indicated that management-specific APEX models can accurately simulate runoff, sediment, TP and DP loss within their respective management systems. However, these models have limited ability to simulate P loss from management systems that differ from the management used for the calibration data. The findings of this study have significant implications because, so far, computer models calibrated and validated with one management system have been used to simulate water quality impacts of many different management systems. We caution model users against this practice.

When the datasets from multiple management systems were used to calibrate APEX, results were greatly improved. This illustrates that models calibrated across multiple management systems will be more robust and than those calibrated within a single management system.

Therefore, we encourage model users to include data from multiple management systems in the calibration process for water quality models like APEX.

The APEX model parameters that were critical included biological mixing efficiency (P29), soluble P runoff coefficient (P8) and biological process parameters (P69, P70). These parameters may change based on management practices. The biological mixing processes in the model need to be improved and more information is needed to make better estimates of biological process parameter values. Therefore, scientists and policy makers must exercise caution when using model-estimated P losses to evaluate or promote adoption of management practices if the model used to develop the estimates was not calibrated and validated for all management systems.

2.5 FUTURE RESEAERCH NEED

- The APEX model uses a simple linear approach to estimate P leaching from the top soil layer to the next layer based on P concentration in soil and solution. But, P sorption in soils is non-linear and when P concentration in soil increases the relationship becomes non-linear. Thus, using a linear adsorption model to determine the solution P concentration in the soil will underestimate the solution P concentration. Consequently, the model will underestimate P flux to lower soil horizons and overestimate P concentration in surface soil horizon. Therefore, improving the P sub-routines by accounting vertical P movement and using a nonlinear adsorption model would help to accurately predicting P loss.
- The effect of biological mixing processes in the model need to be improved and more information is required to better estimate biological process parameters.

2.6 REFERENCES:

Baffaut, C., N. O. Nelson. G.M.M.M.A. Senaviratne. A. Bhandari. M.V. Liew. J. Lory. 2015. Multi-evaluation of APEX for crop and grazing land in the Heartland region of the US. SWAT proceeding, Brazil.

Baffaut, C., N. O. Nelson. M,van Liew, J. Arnold, and J. Williams. 2013. SWATing your APEX model: A how to from the trenches. In: Proc. of the 2013 International SWAT Conf. Toulouse, France. 19 July 2013. http://swat.tamu.edu/conferences/international.2013/ (Accessed 12 Jan. 2016)

Carpenter, S.R., D.L. Caraco, R.W. Correll, A.N. Howarth, V.H. Sharpley and Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559-568.

Chung, S.W., P.W.Gassman, R.Gu and R.S.Kanwar. 2002. Evaluation of epic for assessing tile flow and nitrogen losses for alternative agricultural management systems. Trans. ASAE 45:1135.

Douglas-Mankin, K.R., D. Maski, K.A. Janssen, P. Tuppad and G.M. Pierzynski. 2010. Modeling nutrient runoff yields from combined in-Watershed crop management practices using swat. Transactions of the ASABE 53:1557-1568.

Ford, W., M. King, J. Williams and Fausey. 2015. Sensitivity analysis of the agricultural Policy/Environmental eXtender (APEX) for phosphorus loads in tile-drained landscapes. J. Environ. Qual. 44:1099.

Francesconi, W., D.R. Smith, G.C. Heathman, X. Wang and C.O. Williams. 2014. Monitoring and apex modeling of no-till and reduced-till in tile-drained agricultural landscapes for water quality. Transactions of the ASABE 57:777-789.

Gassman, P. W., E. Osei, A. Saleh and L. Hauck. 2002. Application of an environmental and economic modeling system for watershed assessments. J. Am. Water Resour. Assoc. 38:423-438.

Gassman, P.W., M.R. Reyes, C.H. Green and J.G. Arnold. 2007. The soil and water assessment tool: Historical development, applications, and future research directions. Trans. ASABE 50:1211-1250.

Gassman, P.W., J.R. Williams, X. Wang, A. Saleh, E. Osei, L.M. Hauck, R.C. Izaurralde and J.D. Flowers. 2010. The agricultural Policy/environmental extender (apex) model: An emerging tool for landscape and watershed environmental analyses. Transactions of the ASABE 53:711-740.

Gupta, H., V. S. Sorooshian and P.O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrol. Eng. 4:135-143.

Kansas Data Access and Support Center (DASC) http://kansasgis.org/catalog/index.cfm?data_id=1921&show_cat=5

Koopmans G. R., McDowell, W. Chardon, O. Oenema and J. Dolfing. 2002. Soil phosphorus quantity-intensity relationships to predict increased soil phosphorus loss to overland and subsurface flow. Chemosphere 48:679-687.

Kumar, S., R.P. Udawatta, S.H. Anderson and A. Mudgal. 2011. APEX model simulation of runoff and sediment losses for grazed pasture watersheds with agroforestry buffers. Agrofor. Syst. 83:51-62.

Mallarino, A., and A. Atia. 2005. Correlation of a resin membrane soil phosphorus test with corn yield and routine soil tests. Soil Sci. Soc. Am. J. 69:266-272.

Maski, D., K.R. Mankin, K.A. Janssen, P. Tuppad and G.M. Pierzynski. 2008. Modeling runoff and sediment yields from combined in-Watershed crop practices using the soil and water assessment tool. J. Soil Water Conserv. 63:193-203.

Mausbach, M., and A. Dedrick. 2004. The length we go - measuring environmental benefits of conservation practices. J. Soil Water Conserv. 59:96A-103A.

Mickelson, S., S. Anton, J. Baker and S. Ahmed. 2001. Subsurface herbicide application with the modified john deere mulch master. Trans. ASAE 44:807-812.

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50:885-900.

Mudgal, A., C. Baffaut, S.H. Anderson, E.J. Sadler and A.L. Thompson. 2010. Apex model assessment of variable landscapes on runoff and dissolved herbicides. Transactions of the ASABE 53:1047-1058.

Mudgal, A., C. Baffaut, S.H. Anderson, E.J. Sadler, N.R. Kitchen, K.A. Sudduth and R.N. Lerch. 2012. Using the agricultural Policy/Environmental eXtender to develop and validate physically based indices for the delineation of critical management areas. J. Soil Water Conserv. 67:284-299.

Myers, J., M. Wagger and R. Leidy. 1995. Chemical movement in relation to tillage system and simulated rainfall intensity. J. Environ. Qual. 24:1183-1192

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion principles. J. Hydrol. 10(3): 282-290.

Nelson, N.O., and A.L. Shober. 2012. Evaluation of phosphorus indices after twenty years of science and development. J. Environ. Qual. 41:1703-1710.

Nelson, N.O., and J.E. Parsons. 2006. Modification and validation of GLEAMS for prediction of phosphorus leaching in waste-amended soils. Transactions of the Asabe 49:1395-1407.

Plotkin, S., X. Wang, T.L. Potter, D.D. Bosch, J.R. Williams, E.S. Hesketh and J.K. Bagdon. 2013. Apex calibration and validation of water and herbicide transport under us southern atlantic coastal plain conditions. Transactions of the ASABE 56:43-60.

Ramanarayanan, T.S., J.R. Williams, W.A. Dugas, L.M. Hauck and A.M.S. McFarland. 1997. Using APEX to identify alternative practices for animal waste management. part - I: Model description and validation. Paper - American Society of Agricultural Engineers22 pp.-22 pp.

Saleh, A., O. Gallego, E. Osei, H. Lal, C. Gross, S. McKinney and H. Cover. 2011. Nutrient tracking tool-a user-friendly tool for calculating nutrient reductions for water quality trading. J. Soil Water Conserv. 66:400-410.

Senaviratne, G.M.M.M.A., R.P. Udawatta, C. Baffaut and S.H. Anderson. 2013. Agricultural policy environmental eXtender simulation of three adjacent row-crop watersheds in the claypan region. J. Environ. Qual. 42:726-36.

Sharpley, A. N., P. Kleinman, R. McDowell, M. Gitau and R. Bryant. 2003. Modeling phosphorous transport in agricultural watersheds: Processes and possibilities (vol 57, pg 425, 2003). J. Soil Water Conserv. 58:127-127.

Sharpley, A. N., and X. Wang. 2014. Managing agricultural phosphorus for water quality: Lessons from the USA and China. J. Environ. Sci. 26:1770-1782.

Steglich, E. M., and J.R. Williams. 2013. Agricultural Policy/Environmental eXtender Model: User’s manual. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX.

Sweeney, D.W., G.M. Pierzynski and P.L. Barnes. 2012. Nutrient losses in Watershed -scale surface runoff from claypan soil receiving turkey litter and fertilizer. Agriculture Ecosystems & Environment 150:19-26

U.S. Department of Agriculture-Natural Resource Conservation Service, 2012. Title 190-National Instruction (Title 190-NI, Amend . January 2012) Part 302-X.3- Nutrient management policy implementation. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046435.pdf (Accessed 20 Jan. 2016).

U.S. Department of Agriculture – Agricultural Research Service, Salinity Lab. Rosetta V1.0. Riverside, CA. Retrieved from http://www.ars.usda.gov/News/docs.htm?docid=8953 (Accessed 3 July 2013).

U. S. Environmental Protection Agency, 2002. Nutrient water quality criteria, summary Table for the nutrient criteria documents. http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/ (Accessed 15 March. 2013)

van Griensven, A., T. Meixner, S. Grunwald, T. Bishop, A. Diluzio and R. Srinivasan. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. J. Hydrol. 324:10-23.

Wang, X., P.W. Gassman. J. R. Williams. S. Potter. and A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil & Tillage Research 101:78-88.

Wang, X. J., R. Williams. J. D. Atwood. M. L. Norfleet. and A. D. King. 2011. APEX model upgrades, data inputs, and parameter settings for use in CEAP cropland modeling. Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014165(accessed 10/24/2015).

Wang, X., D. W. Hoffman, J. E. Wolfe, J. R. Williams, and W. E. Fox. 2009. Modeling the effectiveness of conservation practices at shoal creek watershed, Texas, using apex. Transactions of the ASABE 52 (4): 1181-92.

Wang, X., J. R. Williams, P. W. Gassman, C. Baffaut, R. C. Izaurralde, J. Jeong, and J. R. Kiniry. 2012. Epic and apex: Model use, calibration, and validation. Trans of the Asabe 55 (4): 1447-62.

Williams, J.R., R.C. Izaurralde, and E.M. Steglich. 2012. Agricultural Policy/Environmental eXtender Model: Theoretical documentation. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX.

Williams, J.R., and Izaurralde, R.C. 2006.The APEX model. Watershed models, V.P. Singh and D.K. Frevert, eds. CRC Press, Boca Raton, FL, 437-482.

Winchell, M.F., R.L. Jones. and T.L. Estes. 2011. Comparison of models for estimating the removal of pesticides by vegetated filter strips. In k. Goh, B. Bret, T.L. Potter and J.Gan (Eds.), pesticide mitigation Strategies for Surface Water Quality (pp. 273-286). ACS Symposium Series Vol. 1075. Washington, D.C.: ACS Publications Retrieved from http://pubs.acs.org/isbn/9780841226579

Yin L., X. Wang, J. Pan and P.W. Gassman. 2009. Evaluation of apex for daily runoff and sediment yield from three plots in the middle Huaihe river watershed, china. Transactions of the ASABE 52:1833-1845.

Zeimen, M.B., K.A. Janssen, D.W. Sweeney, G.M. Pierzynski, K.R. Mankin, D.L. Devlin, D.L. Regehr, M.R. Langemeier and K.A. McVay. 2006. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. J. Soil Water Conserv. 61:258-267.

Table 2.1. Management practices and their abbreviations for watersheds at Franklin and Crawford locations

Location	Watershed	Management Abbreviation	Management practices†	Number of events	Modeling use
Franklin	7	NTDB	No-till; deep band fertilizer application, 7.6-12.7 cm (3-5 inch) depth	32	Calibration
Franklin	8	NTSA	No-till; surface applied fertilizer	33	Calibration
Franklin	6	CONV-T	Fertilizer incorporated; chisel-disk-field cultivate	36	Calibration
Franklin	2	NTDB	No-till; deep band fertilizer application, 7.6-12.7 cm (3-5 inch) depth	36	Validation
Franklin	4	NTSA	No-till; surface applied fertilizer	34	Validation
Franklin	5	CONV-T	Fertilizer incorporated; chisel-disk-field cultivate	34	Validation
Crawford	102	FERTC	Conventional tillage; commercial N and P fertilizers	27	Calibration
Crawford	103	CONT	No-till; without fertilizer/turkey litter application	27	Calibration
Crawford	104	TLPC	Conventional tillage; P based turkey litter + commercial nitrogen application	27	Calibration
Crawford	105	TLNC	Conventional tillage; nitrogen based turkey litter	27	Calibration
Crawford	203	FERTC	Conventional tillage; commercial N and P fertilizers	27	Validation
Crawford	205	CONT	No-till; without fertilizer/turkey litter application	26	Validation
Crawford	204	TLPC	Conventional tillage; P based turkey litter + commercial nitrogen application	27	Validation
Crawford	201	TLNC	Conventional tillage; nitrogen based turkey litter	27	Validation

†Franklin location- management practices-nutrient source and rate
NTDB, NTSA and CONV-T = Liquid urea ammonium nitrate + ammonium polyphosphate; 78 kg N ha^{-1} and 16 Kg P ha^{-1}
Crawford location - management practices-nutrient source and rate
TLNC = 7.5 Mg ha^{-1} turkey litter; 135 kg N ha^{-1} and approx. 180 P kg ha^{-1};
TLPC= 1 Mg ha^{-1} turkey litter + Liquid urea ammonium nitrate; 135 kg N ha^{-1} and 24 Kg P ha^{-1} (crop removal rate)
FERTC = Liquid urea ammonium nitrate + ammonium polyphosphate; 135 kg N ha^{-1} and 24 Kg P ha^{-1}
Conventional tillage is Chisel (15 cm depth) followed by disk (5-10 cm depth)

Table 2.2. APEX model parameters tested during sensitivity analysis, calibration and their selected values at Franklin and Crawford locations

Sensitive parameter†	Range tested‡	Un-calibrated values	Calibrated values selected						
			Franklin management practices			Crawford management practices			
			CONV-T	NTDB	NTSA	FERTC	CONT	TLPC	TLNC
Parameters affecting runoff									
Runoff CN residue adjustment parameter P[15]	0.0-0.3	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Soil evaporation plant cover factor P[17]	0.0-0.5	0.10	0.00	0.10	0.15	0.20	0.15	0.20	0.20
Water stress weighing coefficient P[38]	0.0-1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SCS CN index coefficient P[42]	0.3-2.5	1.00	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Upper limit CN retention parameter P[44]	1.0-2.0	1.50	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Parameters affecting sediment									
Sediment routing coefficient P[19]	0.01-0.05	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01
RUSLE C-factor coefficient residue factor P[46]	0.5-1.5	0.50	0.85	1.05	0.85	0.85	0.85	0.75	1.30
RUSLE C-factor coefficient biomass factor P[47]	0.5-1.5	0.50	0.10	0.10	0.10	0.10	1.50	0.10	0.10
Parameters affecting soil biological activity									
Biological mixing efficiency P[29]	0.1-0.5	0.10	0.10	0.50	0.50	0.20	0.35	0.10	0.50
Maximum depth for biological mixing P[31]	0.1-0.3	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Coefficient adjusts microbial activity P[69]	0.1-1.0	1.00	0.50	0.50	0.50	0.50	0.65	0.50	0.60
Microbial decay rate coefficient P[70]	0.5-1.5	1.00	0.80	0.90	0.50	0.50	0.50	0.50	0.50
Parameters affecting total and dissolved Phosphorus									
Root growth soil strength P[2]	1.0-2.0	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Soluble phosphorus runoff coefficient P[8]	10.0-20.0	15.0	20.0	20.0	10.0	4.0[a]	5.0[a]	5.0[a]	20.0
P upward movement by evaporation coefficient P[59]	1- 20.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Manure erosion equation coefficient P[62]	0.1-0.5	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Manure erosion exponent P[68]	0.1-1.0	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Standing dead fall rate coefficient P[76]	0.0001-0.1	0.01	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Coefficient. regulating P flux between labile and active pool P[84]	0.0001-0.001	0.0001	0.60[a]	0.001	0.001	0.001	0.001	0.001	0.001
Coefficient regulating P flux between labile and active pool P[85]	0.0001-0.001	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Soluble Phosphorus Leaching KD value P[96]	1-15	1.00	5.00	15.00	5.00	15.00	15.00	15.00	15.00

†CN, curve number; SCS, Soil Conservation Service ; RUSLE, Revised Universal Soil Loss Equation; KD, partition coefficient.

‡The parameter ranges specified in the APEX user manual (Steglich and Williams, 2013).

[a] Values outside user manual recommended range.

Table 2.3 Summary of the managements calibrated and validated for objective 1 at Franklin and Crawford runoff study location

location	Management practice	Watershed used for calibration	No of events	Watershed used for validation	No of events
Franklin	CONV-T	Watershed 6	32	Watershed 2	36
Franklin	NTDB	Watershed 7	33	Watershed 4	34
Franklin	NTSA	Watershed 8	36	Watershed 5	34
Crawford	FERTC	Watershed 102	27	Watershed 203	27
Crawford	CONT	Watershed 103	27	Watershed 205	26
Crawford	TLPC	Watershed 104	27	Watershed 204	27
Crawford	TLNC	Watershed 105	27	Watershed 201	27

Table 2.4 Summary of the managements tested for objective 2 at Franklin and Crawford runoff study site

Site	Management practice used to calibrate	Management practice used to test
Franklin	NTDB (Watershed 7)	NTSA (Watersheds 4 & 8)
	NTDB (Watershed 7)	CONV-T (Watersheds 5 & 6)
	NTSA (Watershed 8)	NTDB (Watersheds 2 & 7)
	NTSA (Watershed 8)	CONV-T (Watersheds 5 & 6)
	CONV-T (Watershed 6)	NTDB (Watersheds 2 & 7)
	CONV-T (Watershed 6)	NTSA (Watersheds 4 & 8)
Crawford	CONT (Watershed 103)	FERTC (Watersheds 102 & 203)
	CONT (Watershed 103)	TLPC (Watersheds 104 & 204)
	CONT (Watershed 103)	TLNC (Watersheds 105 & 201)
	FERTC (Watersheds 102)	CONT (Watersheds 103 &205)
	FERTC (Watersheds 102)	TLPC (Watersheds 104 & 204)
	FERTC (Watersheds 102)	TLNC (Watersheds 105 & 201)
	TLPC (Watersheds 104)	FERTC (Watersheds 102 & 203)
	TLPC (Watersheds 104)	TLNC (Watersheds 105 & 201)
	TLPC (Watersheds 104)	CONT (Watersheds 103 &205)
	TLNC (Watersheds 105)	CONT (Watersheds 103 &205)
	TLNC (Watersheds 105)	FERTC (Watersheds 102 & 203)
	TLNC (Watersheds 105)	TLPC (Watersheds 104 & 204)

Table 2.5. Model performance statistics for runoff, sediment, and P loss simulated with APEX for uncalibrated models, management-specific calibrations, and validation within the management system used for calibration at Franklin and Crawford runoff study sites. (Bolded values indicate the model performance that did not meet the threshold criteria.)

Forms of model tested	Management† (Watersheds)	Runoff			Sediment			Total Phosphorus			Dissolved Phosphorus		
		r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias
Franklin runoff study site													
Uncalibrated model	CONV-T (Watershed 6)	**0.39**	**-0.74**	**-18**	**0.33**	**-77**	**-662**	**0.30**	**-14.98**	**-243**	**0.00**	**-22.8**	**-135**
	NTDB (Watershed 7)	**0.40**	**0.01**	**20**	**0.21**	**-543**	**-1428**	**0.35**	**-54.91**	**-415**	**0.17**	**-0.30**	**70**
	NTSA (Watershed 8)	**0.36**	**0.05**	**17**	**0.30**	**-680**	**-2038**	0.55	**-28.86**	**-555**	0.93	0.40	**66**
Calibration	CONV-T (Watershed 6)	0.83	0.72	2	0.66	0.61	17	0.55	0.44	44	**0.11**	**-1.11**	-36
	NTDB (Watershed 7)	0.77	0.58	34	**0.40**	**-0.62**	2	0.61	0.41	46	**0.48**	0.34	16
	NTSA (Watershed 8)	0.78	0.74	13	**0.48**	0.40	38	0.78	0.76	16	0.73	0.71	-33
Validation	CONV-T (Watershed 5)	0.75	0.70	16	0.60	0.46	28	0.58	0.48	38	**0.32**	**-1.03**	-36
	NTDB (Watershed 2)	0.59	0.45	35	**0.42**	0.32	49	0.50	0.36	43	**0.34**	**-0.12**	-52
	NTSA (Watershed 4)	0.78	0.74	14	**0.24**	**-0.20**	-49	0.70	0.56	-14	0.78	0.70	-46
Crawford runoff study site													
Uncalibrated model	FERTC (Watershed 102)	0.83	0.75	33	**0.18**	**-13**	**-375**	0.87	0.80	27	0.61	**0.01**	**85**
	CONT (Watershed 103)	0.65	0.57	1	**0.08**	**-109**	**-966**	0.71	**-0.33**	**-67**	0.37	**-0.29**	**98**
	TLPC (Watershed 104)	0.72	0.65	32	**0.07**	**-33**	**-573**	0.61	0.57	18	0.53	**0.05**	**83**
	TLNC (Watershed 105)	0.72	0.69	20	**0.16**	**-109**	**-913**	0.88	**-5.29**	**-196**	0.81	**-0.89**	**-99**
Calibration	FERTC (Watershed 102)	0.87	0.85	19	0.50	0.45	35	0.77	0.49	53	0.66	0.58	31
	CONT (Watershed 103)	0.78	0.68	-15	**0.22**	**0.03**	15	**0.43**	0.33	45	**0.36**	0.30	31
	TLPC (Watershed 104)	0.79	0.77	18	**0.24**	**-0.34**	3	0.61	0.36	53	0.57	0.41	40
	TLNC (Watershed 105)	0.82	0.80	1	**0.30**	**-0.86**	-6	0.74	0.43	-13	0.60	**-0.60**	-54
Validation	FERTC (Watershed 203)	0.73	0.60	-1	0.81	**-9.22**	**-200**	0.64	0.58	28	0.56	0.54	19
	CONT (Watershed 205)	0.85	0.81	22	**0.28**	**-3.15**	**-82**	0.67	0.44	55	0.51	0.35	56
	TLPC (Watershed 204)	0.65	0.63	12	**0.17**	**-4.50**	**-80**	0.57	0.43	44	0.50	0.42	37
	TLNC (Watershed 201)	0.77	0.76	-14	**0.39**	**-1.73**	-48	0.84	0.38	59	0.82	0.41	54

†CONV-T = Fertilizer incorporated with chisel-disk-field cultivate, NTDB = No-till deep band fertilizer application, NTSA = No-till surface applied fertilizer. FERTC = Conventional tillage commercial N and P fertilizers, CONT = No-till---control without any fertilizer/poultry litter, TLPC = Conventional tillage-P based turkey litter + commercial N, TLNC = Conventional tillage-N based turkey litter.

Model performance threshold criteria for Runoff loss = 0.50, 0.30, ±35 % for r^2, NSE, and PBIAS respectively; Sediment, TP and DP loss = = 0.50, 0.30, ±60 % for r^2, NSE, and PBIAS respectively.

Table 2.6. Model performance statistics for runoff, sediment, and P loss simulated with calibrated and validated management specific APEX model to test changing management i.e. when applied to different management at Franklin and Crawford runoff study sites. (Bolded values indicate the model performance that did not meet the threshold criteria.)

Management used to calibrate†	Management validated	P/F/‡	Runoff			Sediment			Total Phosphorus			Dissolved Phosphorus		
			r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias
Franklin runoff study site														
NTDB	NTSA	P	0.81	0.76	22	**0.21**	**0.09**	20	0.68	0.60	35	0.72	0.54	26
NTDB	CONV-T	F	0.70	0.52	-13	0.63	**0.17**	-18	0.51	**0.13**	-7	**0.21**	**-72.0**	**-462**
NTSA	NTDB	F	0.63	0.55	24	**0.28**	**0.20**	17	**0.41**	0.37	21	**0.24**	**-1.84**	**-83**
NTSA	CONV-T	F	0.66	0.38	-24	0.62	**-1.27**	**-70**	0.50	**-0.99**	-53	**0.16**	**-232**	**-846**
CONV-T	NTDB	F	0.62	0.18	**-52**	**0.12**	**-0.30**	**91**	**0.36**	**-0.56**	89	**0.10**	**-0.39**	**-75**
CONV-T	NTSA	F	0.77	0.45	**49**	**0.06**	**-0.31**	**97**	0.64	**-0.17**	**92**	**0.44**	**-0.01**	**87**
Crawford runoff study site														
CONT	FERTC	P	0.78	0.76	13	**0.27**	**-3.12**	**-135**	0.75	0.62	39	0.66	0.52	41
CONT	TLPC	P	0.69	0.66	14	**0.05**	**-5.71**	**-104**	0.71	0.42	51	0.54	0.37	48
CONT	TLNC	F	0.79	0.79	-2	**0.48**	**-29**	**-333**	0.53	**0.03**	**-112**	0.53	**-0.36**	**-155**
FERTC	CONT	F	0.75	0.74	10	**0.08**	**-0.05**	**67**	**0.36**	**0.25**	48	**0.38**	0.34	33
FERTC	TLPC	P	0.70	0.67	12	**0.10**	**0.01**	**62**	0.56	0.33	55	0.50	0.42	33
FERTC	TLNC	F	0.80	0.80	-4	**0.36**	**-3.68**	**-80**	0.51	**-0.11**	**-135**	0.50	**-1.05**	**-212**
TLPC	FERTC	P	0.79	0.77	11	**0.36**	**0.04**	-17	0.70	0.53	45	0.64	0.56	33
TLPC	TLNC	F	0.81	0.81	-4	**0.37**	**-4.59**	**-96**	0.55	**0.11**	**-116**	0.53	**-0.58**	**-182**
TLPC	CONT	F	0.75	0.75	11	**0.08**	**-0.04**	**67**	**0.40**	**0.27**	51	**0.40**	0.37	38
TLNC	CONT	F	0.72	0.71	6	**0.05**	**-0.09**	**70**	**0.44**	**-0.21**	**88**	**0.38**	**-0.08**	**87**
TLNC	FERTC	F	0.77	0.75	8	**0.32**	**0.28**	26	0.63	**0.05**	**80**	0.70	**0.00**	**82**
TLNC	TLPC	F	0.70	0.67	13	**0.15**	**-1.18**	-38	0.51	**0.07**	**78**	0.94	**-0.18**	**-108**

†NTDB = No-till deep band fertilizer application, CONV-T = Fertilizer incorporated with chisel-disk-field cultivate, NTSA = No-till surface applied fertilizer. FERTC = Conventional tillage commercial N and P fertilizers, CONT = No-till control without any fertilizers/poultry litter, TLPC = Conventional tillage-P based turkey litter + commercial N, TLNC = Conventional tillage-N based poultry litter. Bolded values indicate the model performance that did not pass the threshold criteria.

‡ P = model threshold criteria met for runoff and TP loss; F = model threshold criteria did not met for both runoff and TP loss;

The management specific calibrated and validated model failed approximately 70% of the time when applied to different management systems

Table 2.7. Model parameters and their selected values for a location specific model developed at Franklin and Crawford runoff study sites

Sensitive parameter†	Range tested/ Average used‡	Values selected for a location specific model	
		Franklin site	Crawford site
Parameters affecting runoff			
P[15] Runoff CN residue adjustment parameter	Average	0.02	0.02
P[17] Soil evaporation plant cover factor	0.0-0.5	0.05	0.20
P[38] Water stress weighing coefficient	Average	1.00	1.00
P[42] SCS CN index coefficient	Average	2.50	2.50
P[44] Upper limit CN retention parameter	Average	2.00	2.00
Parameters affecting sediment			
P[19] Sediment routing coefficient	Average	0.01	0.01
P[46] RUSLE C-factor coefficient residue factor	0.5-1.5	0.95	0.90
P[47] RUSLE C-factor coefficient biomass factor	0.5-1.5	0.10	0.50
Parameters affecting soil biological activity			
P[29] Biological mixing efficiency	0.10-0.50	0.30	0.35
P[31] Maximum depth for biological mixing	Average	0.30	0.30
P[69] Coefficient adjusts microbial activity	0.1-1.0	0.65	0.50
P[70] Microbial decay rate coefficient	0.5-1.5	0.70	0.65
Parameters affecting total and dissolved Phosphorus			
P[2] Root growth soil strength	Average	1.50	1.50
P[8] Soluble phosphorus runoff coefficient	10.0-20.0	12.0	8.0
P[59] P upward movement by evaporation coefficient	Average	1.0	1.0
P[62] Manure erosion equation coefficient	Average	0.10	0.10
P[68] Manure erosion exponent	Average	1.0	1.0
P[76] Standing dead fall rate coefficient	Average	0.001	0.002
P [84] Coefficient. regulating P flux between labile and active pool	Average	0.001	0.001
P[96] Soluble phosphorus leaching KD value	1-15	5	10

†CN, curve number; SCS, Soil Conservation Service ; RUSLE, Revised Universal Soil Loss Equation; KD, partition coefficient.

‡The parameter values were selected either based on the parameter ranges specified in the APEX manual (Steglich and Williams, 2013) or by averaging parameter values from management specific model in each location. Thus average means, the average taken from calibrated models in each location as specified in table 4

Table 2.8. Model performance statistics for runoff, sediment, and P loss simulated with location specific APEX model to test changing management i.e. when applied to different management at Franklin and Crawford runoff study sites. (Bolded values indicate the model performance that did not meet the threshold criteria.)

Model tested	Management/ Watershed†	P/ F	Runoff			Sediment			Total Phosphorus			Dissolved Phosphorus		
			r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias
Franklin runoff study site														
Calibration	CONV-T (Watershed 6)	F	0.79	0.54	-15	0.66	0.32	-15	**0.41**	**-0.02**	-8	**0.09**	**-145**	**-724**
	NTDB (Watershed 7)	P	0.78	0.59	34	**0.35**	**0.02**	**68**	0.66	0.37	52	0.50	**-0.21**	-20
	NTSA (Watershed 8)	P	0.83	0.71	32	**0.38**	**-0.10**	**83**	0.80	0.60	48	0.74	0.67	5
Validation	CONV-T (Watershed 5)	F	0.70	0.63	4	0.60	**0.17**	2	0.57	**0.07**	-8	**0.32**	**-175**	**-659**
	NTDB (Watershed 2)	F	0.59	0.38	**43**	**0.43**	**0.04**	**81**	0.47	0.30	49	**0.36**	**-1.02**	**-98**
	NTSA (Watershed 4)	P	0.82	0.70	30	**0.12**	**0.03**	58	0.71	0.68	28	0.75	0.74	-21
Crawford runoff study site														
Calibration	FERTC (Watershed 102)	P	0.87	0.85	19	**0.42**	**-0.78**	-56	0.82	0.52	56	0.76	0.35	60
	CONT (Watershed 103)	P	0.78	0.66	-19	**0.15**	**-0.46**	-13	0.50	0.30	55	**0.33**	**0.23**	53
	TLPC (Watershed 104)	P	0.78	0.76	18	**0.19**	**-4.61**	**-124**	0.52	0.31	56	0.52	**0.21**	**64**
	TLNC (Watershed 105)	F	0.83	0.81	3	**0.35**	**-19.3**	**-259**	0.76	**-7.56**	**-178**	0.60	**-15.0**	**-262**
Validation	FERTC (Watershed 203)	P	0.72	0.57	0	0.73	**-70.2**	**-661**	0.62	0.58	30	0.63	0.40	50
	CONT (Watershed 205)	F	0.76	0.71	25	**0.16**	**-6.7**	**-121**	0.63	**0.23**	**66**	**0.45**	**0.13**	**71**
	TLPC (Watershed 204)	P	0.63	0.60	11	**0.18**	**-23.2**	**-299**	0.57	0.40	49	**0.47**	**0.21**	**64**
	TLNC (Watershed 201)	P	0.78	0.77	-12	0.450	**-32.6**	**-402**	0.82	0.77	-1	0.84	0.80	-9

†CONV-T = Fertilizer incorporated with chisel-disk-field cultivate, NTDB = No-till deep band fertilizer application, NTSA = No-till surface applied fertilizer. FERTC = Conventional tillage commercial N and P fertilizers, CONT = No-till---control without any fertilizers/poultry litter, TLPC = Conventional tillage-P based turkey litter + commercial N, TLNC = Conventional tillage-N based turkey litter. Bolded values indicate the model performance that did not pass the threshold criteria

The location specific model developed using multiple management practices in each location passed approximately 65 % of the time when applied to different management practices

Table 2.9. Long term (30 years) model simulated average annual runoff, sediment, TP and DP loss for base managements with location specific model

Base management†	Runoff loss (mm)	Sediment loss (Mg ha^{-1})	Total P (Kg ha^{-1})	Dissolved P loss (Kg ha^{-1})
Franklin runoff study site (Average of 30 year rotation)				
CONV-T	154	1.11	1.1	0.6
NTDB	132	0.10	0.4	0.4
NTSA	126	0.10	0.7	0.6
Crawford runoff study site (Average of 30 year rotation)				
FERTC	195	2.20	1.6	1.1
CONT	186	0.70	0.3	0.2
TLPC	190	2.17	1.4	0.9
TLNC	178	2.47	11.0	9.2

†NTDB = No-till deep band fertilizer application, NTSA = No-till surface applied fertilizer, CONV-T = Fertilizer incorporated with chisel-disk-field cultivate. FERTC = Conventional tillage commercial N and P fertilizers, CONT = No-till---control without any fertilizers/poultry litter, TLPC = Conventional tillage-P based turkey litter + commercial N, TLNC = Conventional tillage-N based turkey litter.

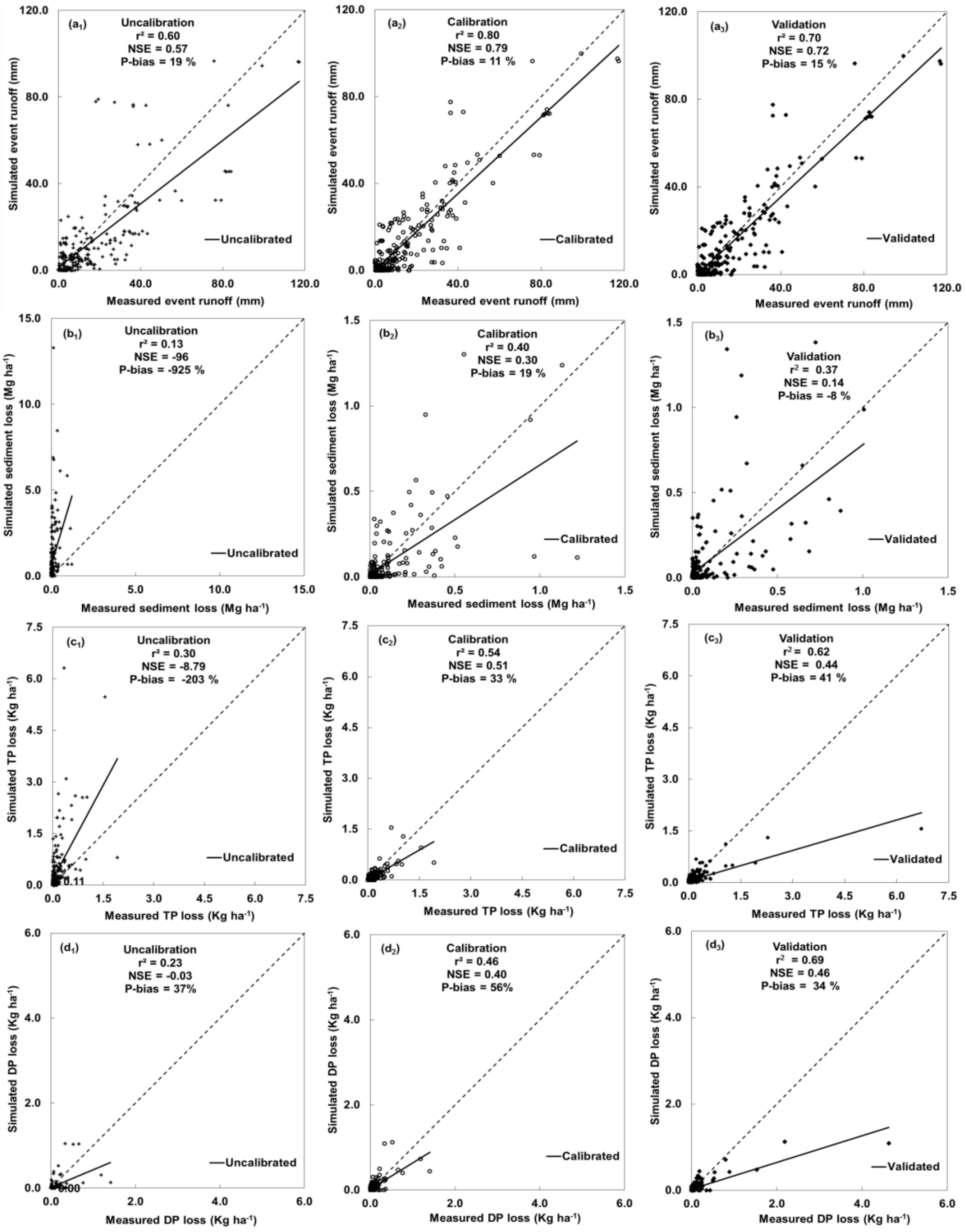


Figure 2.1. Event-based linear regression of measured vs. simulated values with model performance statistics for APEX-simulated runoff, sediment loss, and TP loss for models that were uncalibrated, calibrated for specific management systems, and validated within the management systems used for calibration model with aggregated data from both sites. (a_1) Uncalibrated runoff, (a_2) Calibrated runoff (a_3) Validated runoff; (b_1) Uncalibrated sediment loss (b_2) Calibrated sediment loss (b_3) Validated sediment loss; (c_1) Uncalibrated TP loss, (c_2) Calibrated TP loss and (c_3) Validated TP loss; (d_1) Uncalibrated DP loss, (d_2) Calibrated DP loss and (d_3) Validated DP loss.

Chapter 3. Evaluation of Management Practices to Minimize Phosphorus Loss from Poultry Litter Application Using the APEX Model

ABSTRACT

Phosphorus (P) losses from agricultural fields play a significant role in surface water quality degradation. Applying P at the right time, right rate and at right frequency provide both economic and environmental benefits. However, management options need to be tested prior to recommendations. Simulation models offer an alternative method of field studies to evaluating the management practice performance and are not subject to the time, treatments, or weather constraints of field studies. The objective of the study was to determine the optimal timing, rate, and frequency for poultry litter applications in no-till by surface broadcasting and conventional tillage to incorporate the litter in different cropping systems, using the Agricultural Policy/Environmental Extender (APEX) model. The fully calibrated and validated APEX model was used to evaluate the effect of poultry litter application timing (spring vs. fall), frequencies (1 Mg ha^{-1}every year, 2 Mg ha^{-1} every 2 year, or 4 Mg ha^{-1} every 4 year and 8 mg ha^{-1} every 8 year in an 8-year rotation), cropping systems, and rates on P loss in no-till and incorporation with tillage. The model was used to simulate P loss for 100 different weather scenarios for each combination. Overall, applying poultry litter during late fall resulted in relatively lower total P loss compared to poultry litter applied during spring before planting. Poultry litter should be incorporated, especially if applied in the spring. When soil test P (STP) is below 100 mg kg^{-1} soil test P (STP) application of poultry litter in no-till resulted in approximately 50 % greater TP loss compared to when litter is incorporated by tillage. The results suggest that applying 4 Mg ha^{-1} every other year is the optimal litter rate and frequency

in an eight year P based cropping systems. The 4 Mg ha^{-1} yr^{-1} results in excessive P loss and should be avoided. Corn-winter wheat-soybean double cropping is the best cropping system for poultry litter applications as it reduced the runoff, sediment and TP loss compared to other cropping systems. The results can be used by producers in the region to help them minimize P loss to receiving waters when applying poultry litter.

3.1 INTRODUCTION

Reducing phosphorus (P) loss from agricultural fields is critical to maintaining water quality. Any management practices that reduce P loss in runoff help to protect water quality. Best management practices (BMPs) (also referred to as conservation practices) have been developed to reduce nutrient and sediment loss from agricultural fields and meet the goal of improving water quality (Richardson et al. 2008; Francesconi et al. 2015). For instance, the Conservation Effects Assessment Project (CEAP) was initiated by the United States Department of Agriculture, Natural Resources Conservation services (USDA-NRCS) to quantify the environmental benefits of current cropland BMPs at regional and national levels (Mausbach and Dedrick, 2004; Francesconi et al. 2015; Santhi et al. 2014). Best management practices such as conservation reserve program (CRP), conservation tillage with crop rotations and cover have also been promoted by USDA for decades to protect water resources and improve agricultural production (Richardson et al. 2008).

The impact of best management practices on P loss from agricultural fields can be evaluated either by monitoring water quality in the field or by using process-based computer models (Senaviratne et al. 2013; Santhi et al. 2014; Francesconi et al 2015). Monitoring water quality impacts in fields are time-consuming and labor intensive. The tasks become more cumbersome in large watersheds, multiple locations, with many treatments and are limited with treatment and weather scenarios. Because of such limitation with field studies, process-based computer models can be used an alternative for evaluating BMPs (Gassman et al. 2010). Computer models also help to extend the application of field studies data and have emerged as key tools to analyze BMPs (Gassman et al. 2007), guide water resource policy, management and regulations (Ford et al. 2015) and design future BMPs more effectively (Santhi et al. 2014). Under the CEAP framework computer models were extensively used and were promoted to simulate BMPs. The Agricultural Policy/Environmental eXtender APEX model has been proposed as a tool for evaluating BMPs in CEAP watersheds (Gassman et. al. 2010).

Several studies have indicated APEX's ability to accurately simulate the best management practices on P loss (Gassman et al. 2010; Santhi et al. 2014; Francesconi et al. 2015; Wang et al. 2009; Tuppad et al. 2010). However, none of them have been tested and were used to develop BMPs for poultry litter applications. Utilization of poultry litter as a nutrient source outside the production area reduces spatial concentration and risks to water quality (Liechty et al. 2009). But the impact of poultry litter in those areas which do not have a history of poultry application need to be assessed. Lack of adequate testing has also prompted controversy as producers feel they have been unfairly targeted (Sharpley et al. 2015) and are desperately looking for alternative BMPs. The field scale data to guide management decisions for poultry litter with water quality effects are rare (Harmel et al. 2009). Therefore, calibrated and validated computer model like APEX can be used to develop BMPs for poultry litter applications in such areas where poultry litter has not been applied.

Although Kansas is not a major poultry producer, due to increasing fertilizer price and easily transportable litter from neighboring states, poultry litter application in the southeast region of the state is on the rise. For instance, Herron et al. (2012) reported more than 100,000 tons of poultry litter exported annually from Arkansas and Oklahoma with most of this going to Kansas and central Oklahoma. However, little information exists on BMP options to producers in the region with no poultry litter application history. To overcome the lack of information on the impact of poultry litter application in the region, Sweeney et al. (2012) conducted a field runoff study. However, due to space and logistic restriction, their treatment evaluations were limited. Nonetheless, producers are looking for wide range of options on application timings, rates, and frequencies for poultry litter applications with minimal potential environmental risk. Therefore, we evaluated the impact of multiple rates, application timings, soil test P levels, and frequencies of application using the APEX model to determine optimal timings, rates, and frequencies for poultry litter application in the region. Those management practices were also selected so that the datasets generated in this study could be used for the Kansas phosphorus index evaluation.

The goal of the study was to assess the impact of poultry litter applications on TP loss and determine BMPs option for common cropping systems in the region. The objective of this study was to determine the optimal timing, rate, and frequency for poultry litter applications in no-till by surface broadcasting and conventional tillage to incorporate the litter in different cropping systems,. This was accomplished by using the APEX model calibrated and validated with field study data from poultry litter applications in southeast Kansas.

3.2 MATERIALS AND METHODS

The fully calibrated and validated location specific model developed using multiple managements and watershed characteristics were used to analyze different management scenarios. The management practice scenarios analyzed with the APEX model were focused on STP, application timings, P application rate, and method of P application. Those management practices were selected based on the minimum criteria set by NRCS for state PI assessment of P loss risk from fields (USDA-NRCS, 2012). In addition, a wide variety of management practices evaluated in this study (using the APEX model) would provide information on poultry litter application and potential environmental risk. The poultry litter application, tillage, planting, and harvesting dates were approximated based on the commonly used timings in the region (Dan Sweeney, personal communication, 2015). The combinations of management practices analyzed were listed in Table 1. Additional details on site characteristics and data collection are available in Sweeney et al. (2012).

The STP selected was 25, 50, 100, 200, and 400 mg kg^{-1} and was assumed to be for 0-15cm depth. The five application timings selected were January 15th, April 1st June 5th and November 15th, October 15th. The source of nutrient used in Crawford site was poultry litter and the P application rate selected were 0 (control), 25, 50, 100, and 200 kg P ha^{-1}. The method of application was either no-till surface broadcast or incorporated immediately with chisel, disk and field cultivate. The nitrogen (N) rate (135 kg N ha^{-1}) poultry litter application supply approximately 200 kg P ha^{-1}. The remaining N in other P rate applications (118 kg N ha^{-1} for 1 Mg ha^{-1} of poultry litter, 101 kg N ha^{-1} for 2 Mg ha^{-1} of poultry litter and 68 kg N ha^{-1} for 4 Mg ha^{-1} of poultry litter application) was applied with a commercial fertilizer. The cropping systems used were continuous corn, corn-soybean, grain sorghum-soybean and corn-winter wheat-soybean double cropping. The poultry litter was applied every year in the continuous corn cropping system. However, in other 2-year rotations that had soybeans, the litter was applied only in the first year of rotation cycle.

The model was run for 4 years of warm up (i.e., initial 4 year of model run was not used in the results) and for 1, 2, 4 or 8 years of rotation depending upon the management practices tested. The warmup period had the same management practices as that used in the rotation in each cropping system. During the warmup, inorganic fertilizer was applied on the P-based rate to avoid the P build up in soils. The additional nitrogen (N) fertilizer was applied to minimize the effect of N deficiency on crop yield.

The APEX model was run for 100 different weather scenarios with the APEX weather generator. An automated 'autoapex tool' that was written in FORTRAN was used which automatically updates STP, and management practices file. The autoapex tool averages 100 different weather scenarios to output annual maximum, minimum, mean, standard deviation and median values for runoff, sediment and TP loss for each management combination. The full data of these model runs for runoff, sediment, and TP loss were listed in the APPENDIX C1 - C12.

The average annual TP loss with P-based application rate and frequency of application for poultry litter was also evaluated to determine the optimal rate and frequency of application i.e. whether applying small rate more frequently or a large rate less frequently will result in lower TP loss. In this management evaluation, the poultry litter was applied in an 8-year corn-soybean rotation so that over the 8-year period the sum of the poultry litter applied was same i.e. 8 Mg ha^{-1}. The only difference was in frequency of application such as no P application 0 Mg ha^{-1} every year, 1 Mg ha^{-1} every year, 2 Mg ha^{-1} every other year, 4 Mg ha^{-1} every 4 year and 8 Mg ha^{-1} every eight year (Table 2). In addition, the commonly used poultry litter application rates in the region were also evaluated to determine the optimal rate option for producers (Table 3).

3.3 RESULTS AND DISCUSSION

3.3.1 Average annual TP loss with different cropping systems

The TP loss decreased substantially with corn-winter wheat-soybean double cropping compared to other cropping systems (Figure 3.1d). Perhaps, winter wheat might have acted as a cover crop increasing the nutrient recycling and decreasing the TP loss (Dabney et al. 2001; Singer et al. 2007). The average annual runoff loss decreased by approximately 35 % with corn-winter wheat double cropping compared to other cropping systems. The average annual sediment loss was also reduced by 15-70% in no-till with corn-winter wheat soybean double cropping. Likewise, when the litter was incorporated the sediment loss was reduced approximately by 25% with the corn-winter wheat-soybean rotation compared to continuous corn and by 65% compared to grain sorghum-soybean cropping systems (APPENDIX C). These results are similar to what other researches have reported. For example, Zuazo and Pleguezwelo (2009) in a field study found that continuous soil cover improved infiltration and decreased runoff. Francesconi et al. (2015) reported similar benefits of reduced runoff, sediment, and nutrients loss in runoff with cover crops using the APEX model.

The TP loss with continuous corn was greater compared to other cropping systems due to the application of poultry litter every year (Figure 3.1). The average annual TP loss only in the poultry litter application year with corn-soybean, grain sorghum-soybean, and corn-winter wheat-soybean cropping systems was similar to continuous corn indicating that the poultry litter application resulted in a similar loss in the application year regardless of corn or grain sorghum crops. The average TP losses with other cropping systems were lower because poultry litter was not applied in the soybean (second) year.

3.3.2 Average annual TP loss with application timings

The average annual TP loss was greater with spring (January and April) compared to winter (October and November) applications in a corn-soybean cropping system (Figure 3.1). The trend of TP loss with timings was similar in other cropping systems. The reduced TP loss during winter might be due to more time for the nutrients in the litter interact and be adsorbed to soil particles. For instance, the inorganic P pool in the APEX model is divided into stable mineral P, active mineral P and labile P pools. Soil labile P is the major contributor of both dissolved and sediment P loss in runoff. Labile P represents easily desorb-able P immediately available for plants or for runoff and leaching loss while active P represents less available not easily desorb-able P that is in equilibrium with labile P (Sharpley et al. 1984). Addition of fertilizer or organic P in the soil system disturbs the soil P equilibrium and two reactions occur simultaneously. First, a rapid reversible adsorption of P to surface sites and second, a slow reaction that converts P to a more strongly held non-labile form (Javed and Rowell, 2002). Labile P pool can also became stable and move into a non-labile pool depending on time and soil characteristics (Barrow and Shaw 1979). Therefore, poultry litter applied during October and November have more time to interact with soil particles and potentially some P might have moved to the active or stable P pool reducing the TP loss in runoff as the crop uptake, loss in runoff and leaching are minimal during winter.

3.3.3 Average annual TP loss with soil test P and P application rates

The average annual TP loss trended higher with increased soil test phosphorus (STP) and increased P application rates in all the cropping systems (Figures, 3.1 and 3.2). Both the application rates and STP are important factors that control P loss in runoff. Similar to these model results, the linear relationships between application rates and STP to TP loss in runoff were reported by different studies. For instance, Schroeder et al. (2004) with a rainfall simulation study reported linear relationship between STP and P loss in runoff. Likewise, in a small plot study Tarkalson et al. (2004) reported linear relationship between broiler litter application and TP runoff in runoff.

3.3.4 Average annual TP loss with method of application

The average annual TP loss was higher in no till-surface broadcast compared to incorporation with a chisel, disk and field cultivator regardless of application timings. Incorporation by tillage was found more effective in reducing TP loss during spring (January and April) compared to winter applications (October and November) (Figure 3.1). Likewise, tillage incorporation of poultry litter was found to be more effective in minimizing TP loss at lower STP and with high P application rates (Figure 3.2). Overall, in lower STP (25 ppm and 50 ppm) the TP loss was reduced by approximately 40-50 % when poultry litter was incorporated compared to no-till surface broadcast (Appendix C). Tarkalson et al. (2004) found similar results with approximately 80-90 % reduction in runoff TP loss when broiler litter was incorporated. The effectiveness of incorporation decrease with increase in STP and in some instances resulted in similar or, even more, TP loss than in the no-till surface broadcast (Figure 3.2). This is likely due to greater loss of sediment-bound P when poultry litter was incorporated (Allen and Mallarino, 2008). Though the average annual sediment loss across all cropping system with incorporation was only 0.75 Mg ha^{-1}, it was approximately 800% greater than in no-till surface application (0.09 Mg ha^{-1}) (APPENDIX C).Therefore, the higher sediment loss with incorporation would have increased TP loss substantially equaling or exceeding that from the no till-surface broadcast system. The increased TP loss with high STP (>50 ppm) and higher application rates with incorporation indicated that even the incorporation might not be a viable method to reduce TP loss when STP is high and coincides with higher P application rates (Figure 3.2).

3.3.5 Average annual TP loss with a P-based poultry litter application

In the P-based application, 8 Mg ha^{-1} of poultry litter was applied over an 8-year time period so that the amount of P applied during the 8-year rotation was same. However, poultry litter was applied every year, every other year, every 4 year, or every 8 year to determine optimal frequency for P based management system.

3.3.6 Frequency of P-based poultry litter application and timing

The frequency of poultry litter application did not make a difference in the average annual TP loss, indicating that applying poultry litter in different rates but P based on the P requirements of the crops over rotation years resulted in a similar average annual long-term TP loss (Figure 3.3).

Overall, the March application resulted in slightly higher average annual TP loss compared to November application regardless of rates and frequencies (Figure 3.3). Perhaps, in the November application due to a decrease in rainfall or no rainfall at all, the available phosphorus in the poultry litter has more time to adsorb to the soil sites. However, in the March application, the phosphorus present in the poultry litter would have less time to interact with soil increasing the vulnerability to runoff loss. The 28-year long term average annual rainfall indicated drastic increase in rainfall with the start of March (Figure 3.4) Therefore, rainfall soon after poultry litter incorporation or surface broadcast in March might have resulted in greater average annual TP loss in runoff. Studies have reported a decline in P loss with an increase in time to a runoff with poultry litter in rainfall simulation studies (Westerman and Overcash 1980; Heathman et al. 1995; Sharpley, 1997) and field study (Sistani et al. 2009).

3.3.7 Method of application in a P based systems

Overall, the no-till surface broadcast application of poultry litter resulted in higher average annual TP loss in both the March and November application compared with incorporation with tillage (Figure 3.3). It is because the poultry litter was mixed and incorporated into the soil during incorporation but the surface broadcast exposes the litter and increases the potential loss in runoff (Adeli et al, 2011). Therefore, if poultry litter has to be applied during March then it should be incorporated to minimize TP loss. Researchers reported similar results either in field or rain simulation studies (Sharpley, 1997; Pote et al. 2003; Tarkalson et al. 2004; Torbert et al. 2005; Shah et al. 2004).

3.3.8 Maximum TP loss in a P based systems

The average annual TP loss was little affected when poultry litter was applied at the P-based (crop removal rate) rates regardless of the frequency of application. However, there was a large difference when comparing the maximum amount of TP loss from a higher rate of single application from the 8-year rotation to the loss from lower rates of multiple applications. For instance, the application of 8 Mg ha^{-1} during March in no-till resulted in approximately 29 kg ha^{-1} of TP loss (Figure 3.5). The rainfall events that occurred immediately or within a short period of time after poultry litter was applied on March resulted in such loss. Studies have reported greatest TP loss in the first runoff events after fertilizer application (Kleinman and Sharpley 2003; Vadas et al. 2007), even if the first runoff occurs a long time after fertilizer application (Schroder et al. 2004; Harmel et al. 2009). If the watershed is directly or indirectly connected to environmentally sensitive areas (water resources such as perennial streams, lakes, reservoirs etc.), this amount of TP loss in a single application year can trigger algae blooms. Therefore, weighing the unpredictability of the weather, 8 Mg ha^{-1} every eight years is a very risky scenario and should not be recommended even though the average annual TP loss for 100 weather scenarios had lower TP loss.

The maximum TP loss from a single application in no-till was similar with 1 Mg ha^{-1} every year and 2 Mg ha^{-1} every other year in March. However, maximum TP loss increased by 40% for litter applications of 4 Mg ha^{-1} every 4 years and 80% for litter applications of 8 Mg ha^{-1} every 8 years (Figure 3.5). The maximum annual TP loss with a single application had a similar loss with 1 Mg ha^{-1} yr $^{-1}$, 2 ha^{-1} every 2 yr $^{-1}$, and 4 Mg ha^{-1} every 4 yr $^{-1}$ with a November application. However, the maximum TP loss increased by approximately 50% and 33 % in no-till surface broadcast and incorporation, respectively, when litter was applied at 8 Mg ha^{-1} every 8 years in November. The maximum TP loss was also increased by approximately 35% with both no-till surface broadcast and incorporation when litter was applied at 8 Mg ha^{-1} every 8 years in March compared to November (Figure 3.5).

Overall poultry litter incorporation reduced the average annual TP loss by approximately half Kg ha^{-1} compared to no till-surface broadcast. Hence, based on the average annual TP loss (Figure 3.3) and maximum TP loss (Figure 3.5), 4 Mg ha^{-1} every 4 years and incorporating during November would be the best management practice for P-based poultry litter application from a practical (assuming producers would prefer to apply 4 Mg ha^{-1} at one time due to transportation cost) and environmental standpoint.

3.3.9 Total P loss with commonly used poultry application rates in the region

Due to transportation cost, producers prefer to apply more poultry litter at one time. Therefore, a more commonly used application rates in the region and its impact on P loss in runoff were evaluated (Table 3.3). The 4 Mg ha^{-1} every year results in excessive P loss both in March and November application compared to 4 Mg ha^{-1} every other year and 4 Mg ha^{-1} every 4 years (Figure 3.6). Hence, producers should not be applying 4 Mg ha^{-1} yr^{-1} poultry litter in successive years. The higher TP loss with 4 Mg ha^{-1} every year is due to the more frequent application and the accumulation of P in the soil surface from exceeding the crop removal rate.

The effects of continuous poultry litter application and P accumulation in soils were reported by several studies. For instance, in a field study with a continuous poultry litter applications Sistani et al. (2004) and Mitchel and Tu, (2006) reported increased STP as poultry litter application rates have a linear relationship with soil test P accumulations (Cox and He Hendricks, 2000; Leytem and Sims, 2005). The increase in STP may exceed sorption capacity of surface soils (Liechty et al. 2009) that eventually increases the risk of P loss in runoff.

Poultry litter incorporation reduced the TP loss by approximately 50% compared to no-till management. Changing the poultry litter application rate from 4 Mg ha^{-1} every year to 4 Mg ha^{-1} every other year decreased the annual average TP loss by almost 50% in no-till management systems (Figure 3.6). Similarly, The TP loss with 4 Mg ha^{-1} every other year and 4 Mg ha^{-1} every 4 years was similar when poultry litter was incorporated. Therefore, from practical and economic standpoint applying 4 Mg ha^{-1} every other year is an acceptable management practice if the producer wants to apply poultry litter more frequently. But STP should be tested appropriately to monitor potential STP accumulation. If the soil test P increases to more than 50 mg kg^{-1} the management should be changed from 4 Mg ha^{-1} every other year to P-based application (4 Mg ha^{-1} every four years) to minimize TP loss. The recommendation supports similar findings by Harmel et al. (2011 and 2008) who recommended the application of 4.5 Mg ha^{-1} poultry litter every other year based on runoff water quality and economic returns from a long-term field study.

3.4 CONCLUSIONS

Proper application and management of poultry litter are critical to minimizing TP loss and improve water quality degradation. The model simulated results showed poultry litter applied during late fall had lower TP loss compared to litter applied during spring. No till-surface broadcast increased the TP loss in runoff compared to using tillage to incorporate poultry litter. The increase in STP and litter application rates increase the TP loss linearly both in no till-surface broadcast and incorporation with tillage. The model simulated results were consistent with rainfall simulations and field studies with poultry litter applications. However, model simulated results may vary with other soils, watersheds, and climates; thus, any computer simulation models should be calibrated and validated using the site-specific information before using for BMPs evaluation and recommendations. The results would be helpful for producers, planners, and policy makers in developing and guiding BMPs to minimize TP loss in via agricultural fields.

3.5 RECOMMENDATIONS

- 4 Mg ha^{-1} every other year is an acceptable practice for poultry litter application in continuous corn, corn-soybean, grain sorghum-soybean and corn-winter wheat-soybean cropping systems.

- Apply poultry litter in November or incorporate if applying in March.

- Continuous poultry litter application builds soil test P (STP), so STP must be checked frequently.

- If the STP is greater than 50 mg kg^{-1} avoid poultry litter application or at minimum switch the management to 4 Mg ha^{-1} every 4-year (a P-based poultry litter application).

- Use corn-winter wheat-soybean double cropping if you are applying poultry litter to maximize the benefits and reduce TP loss.

- High application rate of 8 Mg ha^{-1} should be avoided from environmental prospective even if it is only every 8 years.

3.6 REFERENCES

Allen, B.L., and A.P. Mallarino. 2008. Effect of liquid swine manure rate, incorporation, and timing of rainfall on phosphorus loss with surface runoff. J. Environ. Qual. 37:125–137

Adeli, A., M.W. Shankle, H. Tewolde, J.P. Brooks, K.R. Sistani, M.R. McLaughlin and D.E. Rowe. 2011. Effect of surface incorporation of broiler litter applied to no-till cotton on runoff quality. J. Environ. Qual. 40:566-574.

Barrow, N. J., and T. C. Shaw. 1979. Effects of solution:soil ration and vigour of shaking on the rate of phosphate adsorption by soil. J. Soil. Sci. 30: 67-76.

Cox, F., and S. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Dabney, S. G., Wilson, K. McGregor and G. Foster. 2004. History, residue, and tillage effects on erosion of loessial soil. Trans. ASAE 47:767-775.

Duran, Zuazo V.H., and C.R. Rodriguez Pleguezuelo. 2008. Soil-erosion and runoff prevention by plant covers. A review. Agron. Sustain. Dev. 28:65-86.

Ford, W., M. King, J. Williams and Fausey. 2015. Sensitivity analysis of the agricultural Policy/Environmental eXtender (APEX) for phosphorus loads in tile-drained landscapes. J. Environ. Qual. 44:1099.

Francesconi, W., D.R. Smith, D.C. Flanagan, C. Huang and X. Wang. 2015. Modeling conservation practices in APEX: From the field to the watershed. J. Great Lakes Res. 41:760-769.

Gassman, P.W., M.R. Reyes, C.H. Green and J.G. Arnold. 2007. The soil and water assessment tool: Historical development, applications, and future research directions. Trans. ASABE 50:1211-1250.

Gassman, P.W. J.R. Williams, X. Wang, A. Saleh, E. Osei, L.M. Hauck, R.C. Izaurralde and J.D. Flowers. 2010. The agricultural Policy/environmental extender (apex) model: An emerging tool for landscape and watershed environmental analyses. Transactions of the Asabe 53:711-740.

Harmel, R.D., B. Harmel and M.C. Patterson. 2008. On-farm agro-economic effects of fertilizing cropland with poultry litter. J. Appl. Poult. Res. 17:545-555.

Harmel, R.D., D.R. Smith, R.L. Haney, and M. Dozier. 2009. Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. Journal of Soil and Water Conservation 64(6):400-412.

Harmel, R.D., R.L. Haney and D.R. Smith. 2011. Effects of annual turkey litter application on surface soil quality of a texas blackland vertisol. Soil Sci. 176:227-236.

Heathman, G.C., A.N. Sharpley, S.J. Smith, and J.S. Robinson. 1995. Land application of poultry litter and water quality in Oklahoma, U.S.A. Fert. Res. 40:165–173.

Herron, S., A. N. Sharpley, S Watkins, and M. Daniels. 2012. Poultry Litter Management in the Illinois River Watershed of Arkansas and Oklahoma. Cooperative Extension Service, Division of Agriculture, University of Arkansas. Fact Sheet FSA9535. 4pages.

Javid, S., and D.L. Rowell. 2002. A laboratory study of the effect of time and temperature on the decline in Olsen P following phosphate addition to calcareous soils. Soil Use Manag. 18:127-134.

Kaiser, D.E., A.P. Mallarino, M.U. Haq and B.L. Allen. 2009. Runoff phosphorus loss immediately after poultry manure application as influenced by the application rate and tillage. J. Environ. Qual. 38:299-308.

Kleinman, P., and A. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072-1081.

Leytem, A., and J. Sims. 2005. Changes in soil test phosphorus from broiler litter additions. Commun. Soil Sci. Plant Anal. 36:2541-2559.

Liechty, H.O., M.A. Blazier, J.P. Wight, L.A. Gaston, J.D. Richardson and R.L. Ficklin. 2009. Assessment of repeated application of poultry litter on phosphorus and nitrogen dynamics in loblolly pine: Implications for water quality. For. Ecol. Manage. 258:2294-2303.

Mausbach, M., and A. Dedrick. 2004. The length we go - measuring environmental benefits of conservation practices. J. Soil Water Conserv. 59:96A-103A.

Mitchell, C., and S. Tu. 2005. Long-term evaluation of poultry litter as a source of nitrogen for cotton and corn. Agron. J. 97:399-407.

Pote, D.H., K.L. Kingery, G.E. Aiken, F.X. Han, P.A. Moore, Jr. and K. Buddington.2003. Water-quality effects on incorporating poultry litter into perennial grassland soils. J. Environ. Qual. 32:2392–2398.

Santhi, C. N., Kannan, M. White, M. Di Luzio, J.G. Arnold, X. Wang and J.R. Williams. 2014. An integrated modeling approach for estimating the water quality benefits of conservation practices at the river basin scale. J. Environ. Qual. 43:177-198.

Schroeder, P. D., Radcliffe, M. Cabrera and C. Belew. 2004. Relationship between soil test phosphorus and phosphorus in runoff: Effects of soil series variability. J. Environ. Qual. 33:1452-1463.

Senaviratne, G.M.M.M., R.P. Udawatta, C. Baffaut and S.H. Anderson. 2013. Agricultural policy environmental eXtender simulation of three adjacent row-crop watersheds in the claypan region. J. Environ. Qual. 42:726-36.

Shah, S., M. Shamblin, H. Boone, S. Gartin and D. Bhumbla. 2004. Runoff water quality impacts of different turkey litter application methods. Appl. Eng. Agric. 20:207-210.

Sharpley, A.N., C.A.jones, C.Gray, and C.V. Cole. 1984. A simplified soil and plant phosphorus model:2 Prediction of labile, organic, and sorbed phosphorus. SSSA J. 48(4): 805-809.

Sharpley, A.N. 1997. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. J. Environ. Qual. 26:1127–1132.

Sharpley A.N., M. Daniels, L. Berry, C. Hallmark and J. Hesselbein. 2015. Arkansas discovery farms: Documenting water quality benefits of on-farm conservation management and empowering farmers. Acta Agric. Scand. Sect. B-Soil Plant Sci. 65:186-198.

Singer J.W., and S.M. Nusser. 2007. Are cover crops being used in the US corn belt? J. Soil Water Conserv. 62:353-358.

Sistani K.R., H.A. Torbert, T.R. Way, C.H. Bolster, D.H. Pote and J.G. Warren. 2009. Broiler litter application method and runoff timing effects on nutrient and escherichia coli losses from tall fescue pasture. J. Environ. Qual. 38:1216-1223.

Tarkalson, D., and R. Mikkelsen. 2004. Runoff phosphorus losses as related to phosphorus source, application method, and application rate on a piedmont soil. J. Environ. Qual. 33:1424-1430. Torbert H. R. Harmel, K. Potter and M. Dozier. 2005. Evaluation of some phosphorus index criteria in cultivated agriculture in clay soils. J. Soil Water Conserv. 60:21-29.

Tuppad, P., C. Santhi, X. Wang, J.R. Williams, R. Srinivasan and P.H. Gowda. 2010. Simulation of conservation practices using the apex model. Appl. Eng. Agric. 26:779-794.

Vadas, P.A., W.J. Gburek, A.N. Sharpley, P.J.A. Kleinman, P.A. Moore Jr. M.L. Cabrera and R.D. Harmel. 2007. A model for phosphorus transformation and runoff loss for surface-applied manures. J. Environ. Qual. 36:324-332.

Wang, X., D.W. Hoffman, J.E. Wolfe, J.R. Williams and W.E. Fox. 2009. Modeling the effectiveness of conservation practices at shoal creek watershed, texas, using apex. Transactions of the Asabe 52:1181-1192.

Westerman, P.W., T.L. Donnelly, and M.R. Overcash. 1983. Erosion of soil and poultry manure: A laboratory study. Trans. ASAE 26:1070–1078.

Table 3.1 Best management scenarios for poultry litter applications at Crawford study site

Cropping systems	Application timings	Soil test P levels (ppm)	Phosphorus application rates (Kg P ha^{-1})	Application methods	Total model runs
Continuous-Corn (C-C)	April 1st October 15th November 15th January 15th	5 (25, 50, 100, 200 and 400)	5 (0, 25, 50, 100, and 200)	2 i) No-till-Surface broadcast ii) Surface broadcast and incorporated	200
Corn-Soybean (C-S)	April 1st October 15th November 15th January 15th	5	5	2	200
Grain sorghum-Soybean (GS-S)	April 1st June 5th October 15th November 15th January 15th	5	5	2	250
Corn-Winter wheat-Soybean (C-WW-S)	April 1st October 15th November 15th January 15th	5	5	2	200

Table 3.2 hosphorus-based poultry litter application rates and treatments

Treatments	Application rates	Application frequency	Sum over 8-year rotation	Application methods
0x Annual P based application	0 Mg ha^{-1}	Once every year	0 Mg ha^{-1}	i) No-till-Surface broadcast ii) Surface broadcast and incorporated
1x Annual P-based application	1 Mg ha^{-1}	Once every year	8 Mg ha^{-1}	‘’
2x Annual P-based application	2 Mg ha^{-1}	Once every 2 years	8 Mg ha^{-1}	‘’
4x Annual P-based application	4 Mg ha^{-1}	Once every 4 years	8 Mg ha^{-1}	‘’
Nitrogen rate (8x P based) application	8 Mg ha^{-1}	Once every 8 years	8 Mg ha^{-1}	‘’

Table 3.3. Common rates and frequency of poultry litter applications in Southeast Kansas

Application rates	Application frequency	Sum over 4-year rotation	Application methods
0 Mg ha yr^{-1}	None	0 Mg ha yr^{-1}	i) No-till-Surface broadcast ii) surface broadcast and incorporated
4 Mg ha yr^{-1}	Once every year	16 Mg ha yr^{-1}	ʺ
4 Mg ha yr^{-1}	Once every 2 year	8 Mg ha yr^{-1}	ʺ
4 Mg ha yr^{-1}	Once every 4 year	4 Mg ha yr^{-1}	ʺ

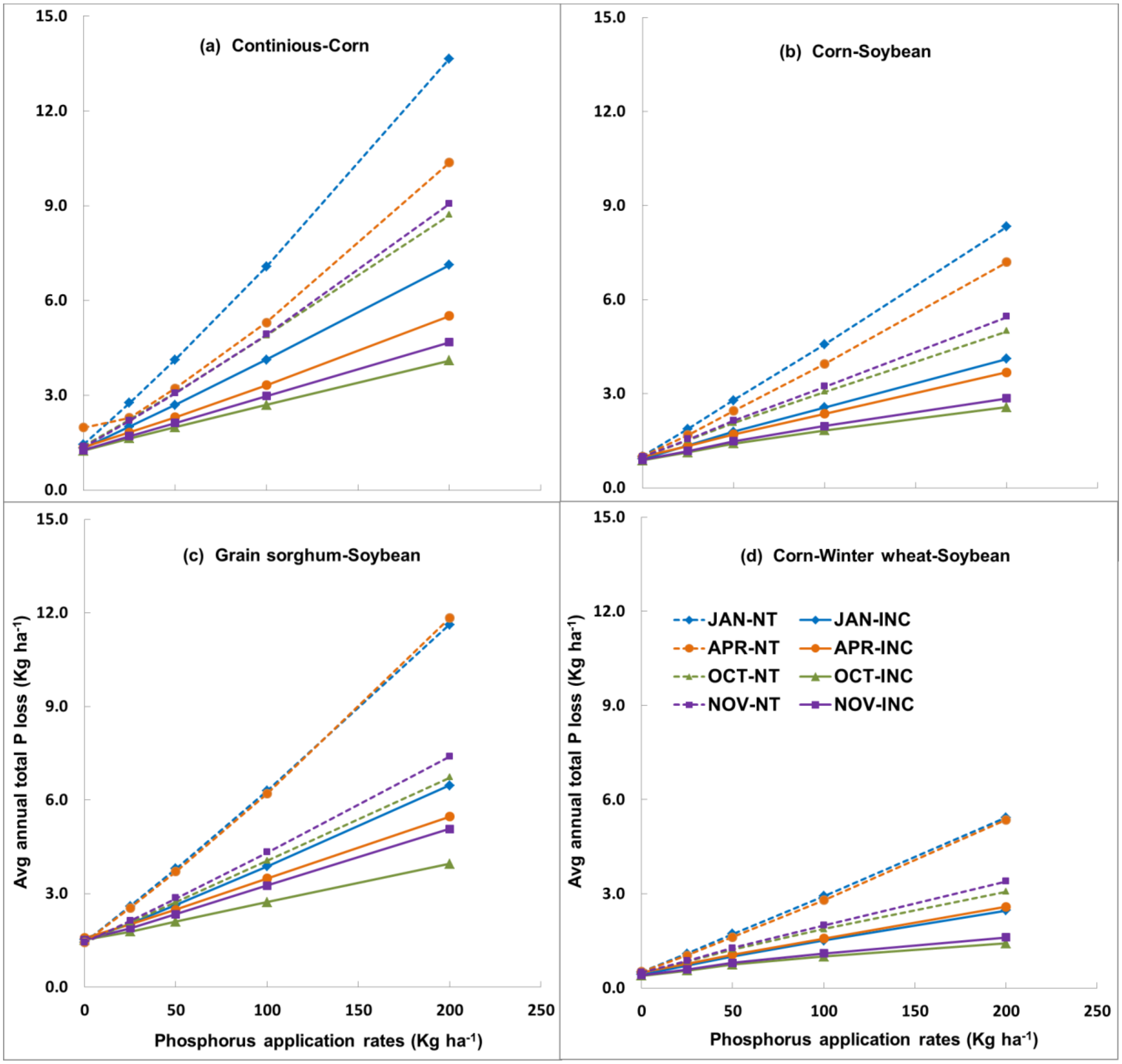


Figure 3.1. The model simulated average annual total phosphorus (TP) loss for different cropping systems and timings with 25 mg kg^{-1} soil test phosphorus (STP).a) Continuous corn; b) Corn-soybean; c) Grain sorghum-soybean d) Corn-winter wheat -Soybean double cropping. NT = no-till surface broadcast; INC = fertilizer incorporated with tillage; JAN = January, APR = April application, OCT = October application and NOV = November application.

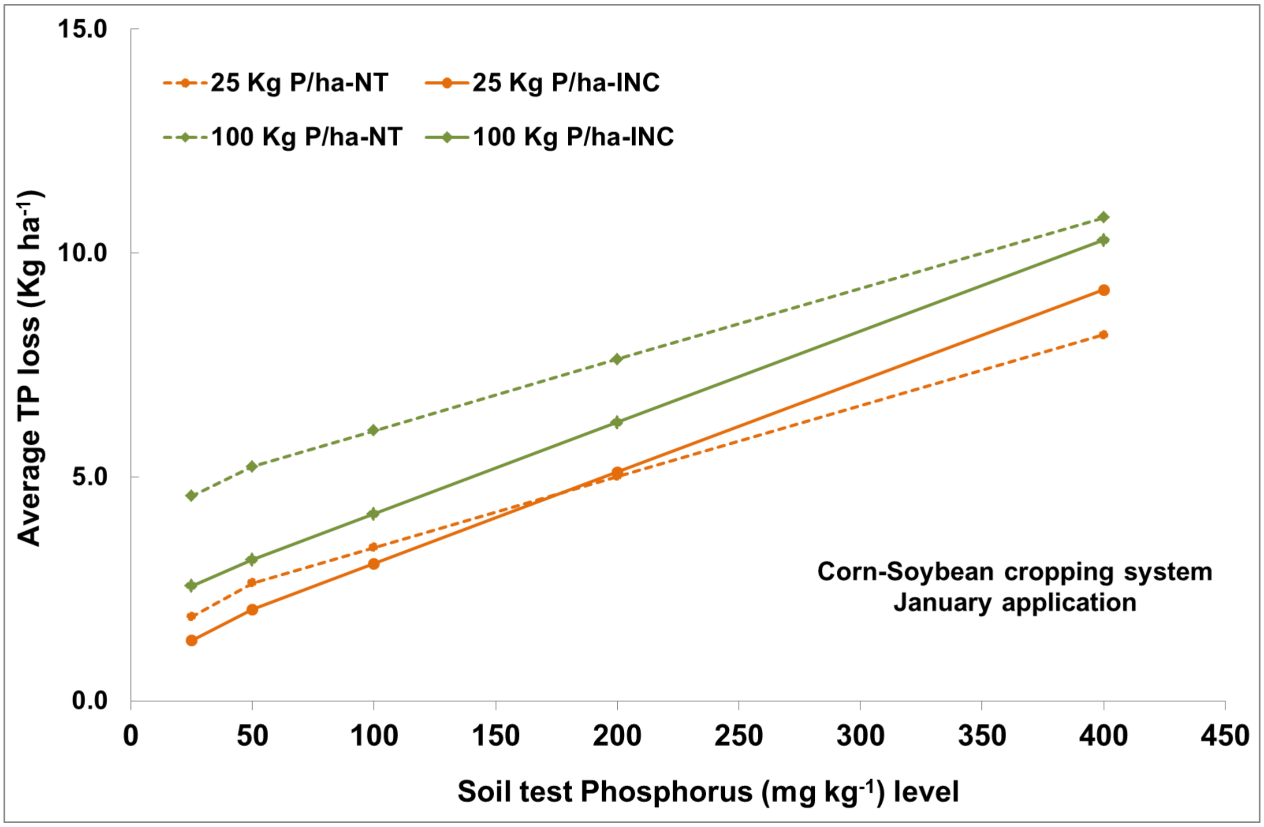


Figure 3.2.The model simulated average annual total phosphorus (TP) loss for different soil test phosphorus level and application rates. NT is poultry litter surface broadcast in a no-till system; INC is poultry litter surface broadcast and incorporated with conventional tillage.

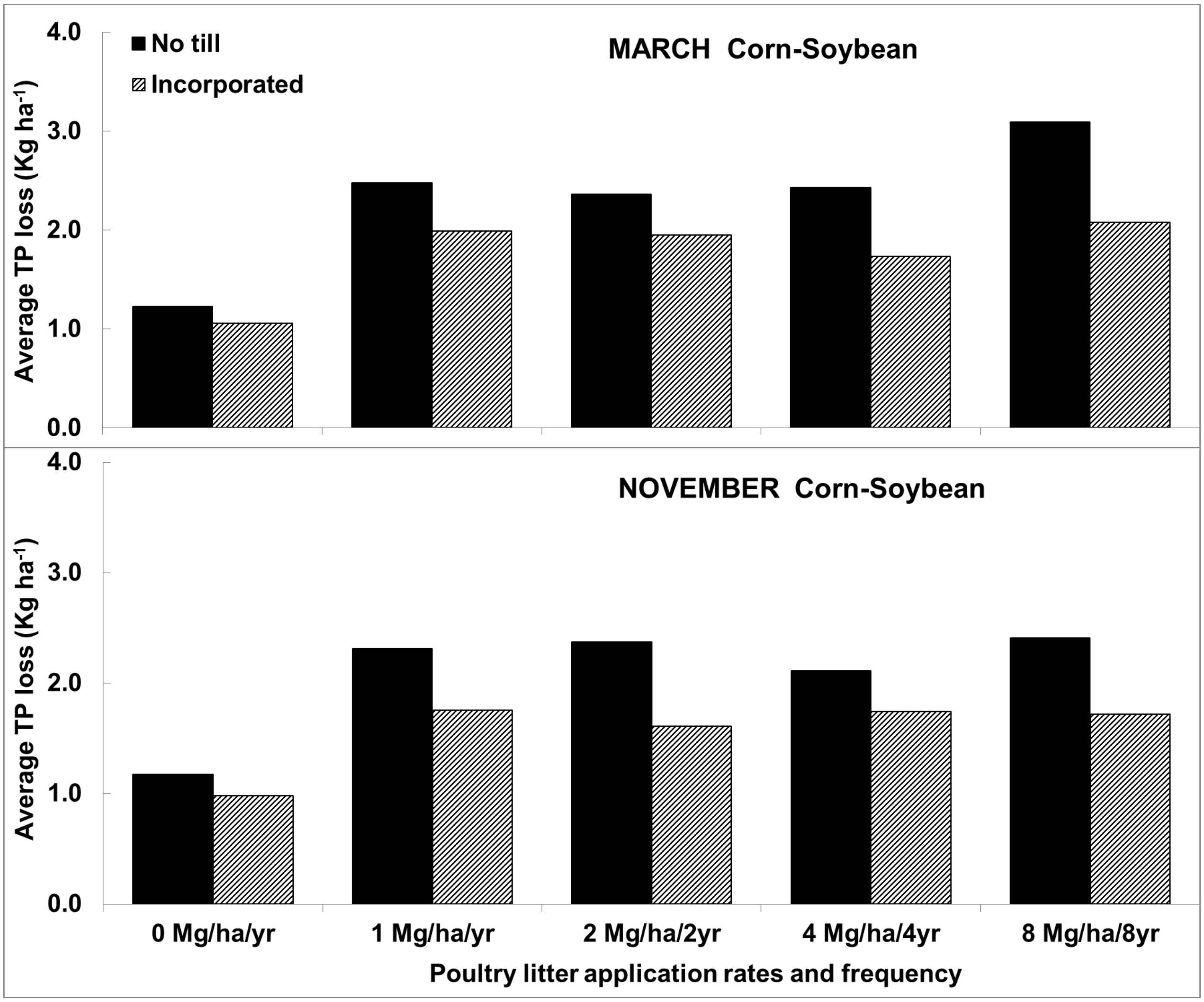


Figure 3.3. Average total phosphorus losses with P-based application rates over eight-year rotation at 25 mg Kg^{-1} soil test phosphorus. MARCH means poultry litter applied on March 15th before planting; NOVEMBER means poultry litter applied on November 15th during late fall. 0/Mg/ha/yr was 0 Mg of poultry per hectare litter applied every year; 1 Mg/ha/yr was 1 Mg of poultry litter per hectare applied every year; 2 Mg/ha/yr was 2 Mg of poultry litter per hectare applied every other year; 4 Mg/ha/yr was 4 Mg of poultry litter per hectare applied every 4 year; 8 Mg/ha/yr was 8 Mg of poultry litter per hectare applied every 8 year.

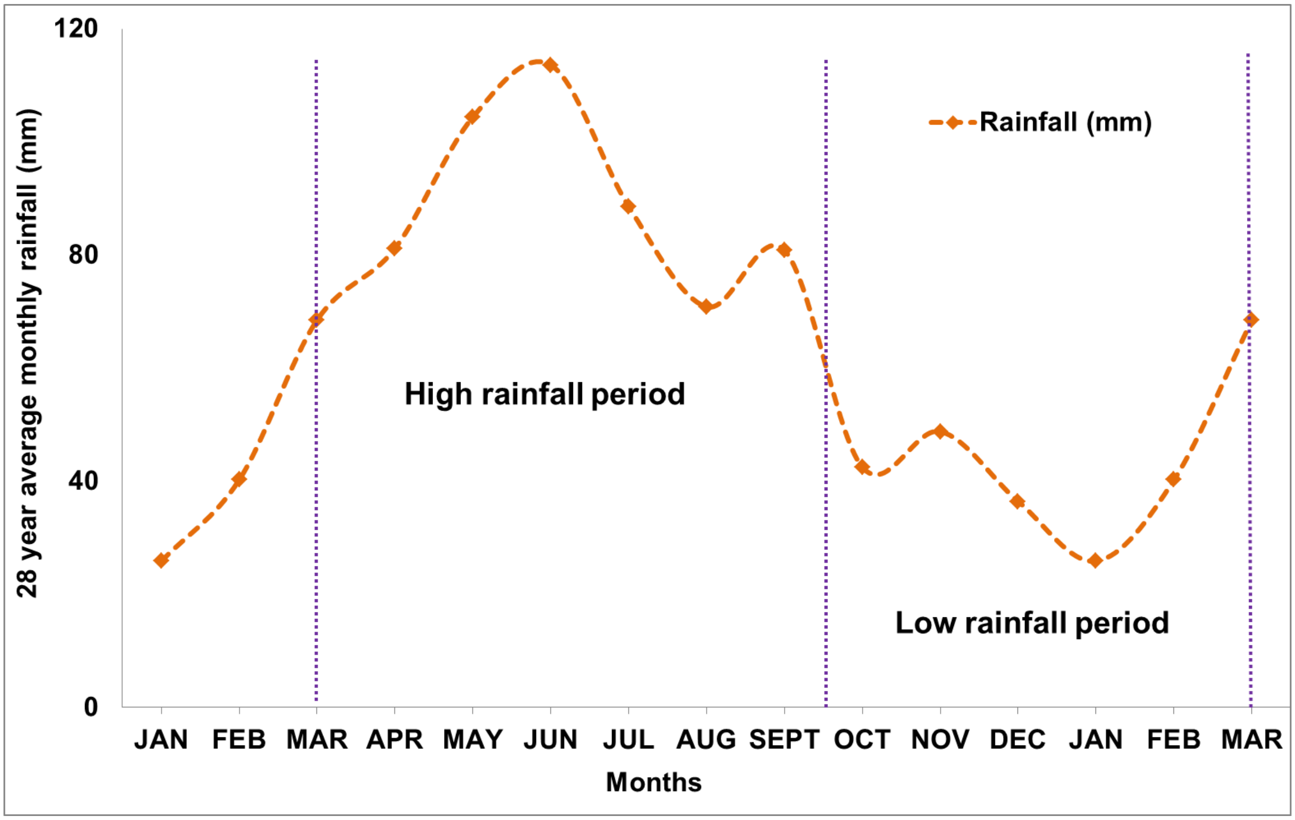


Figure 3.4. Long-term (28 years) average annual monthly rainfall in the study site. The data were obtained from Parsons Weather Station.

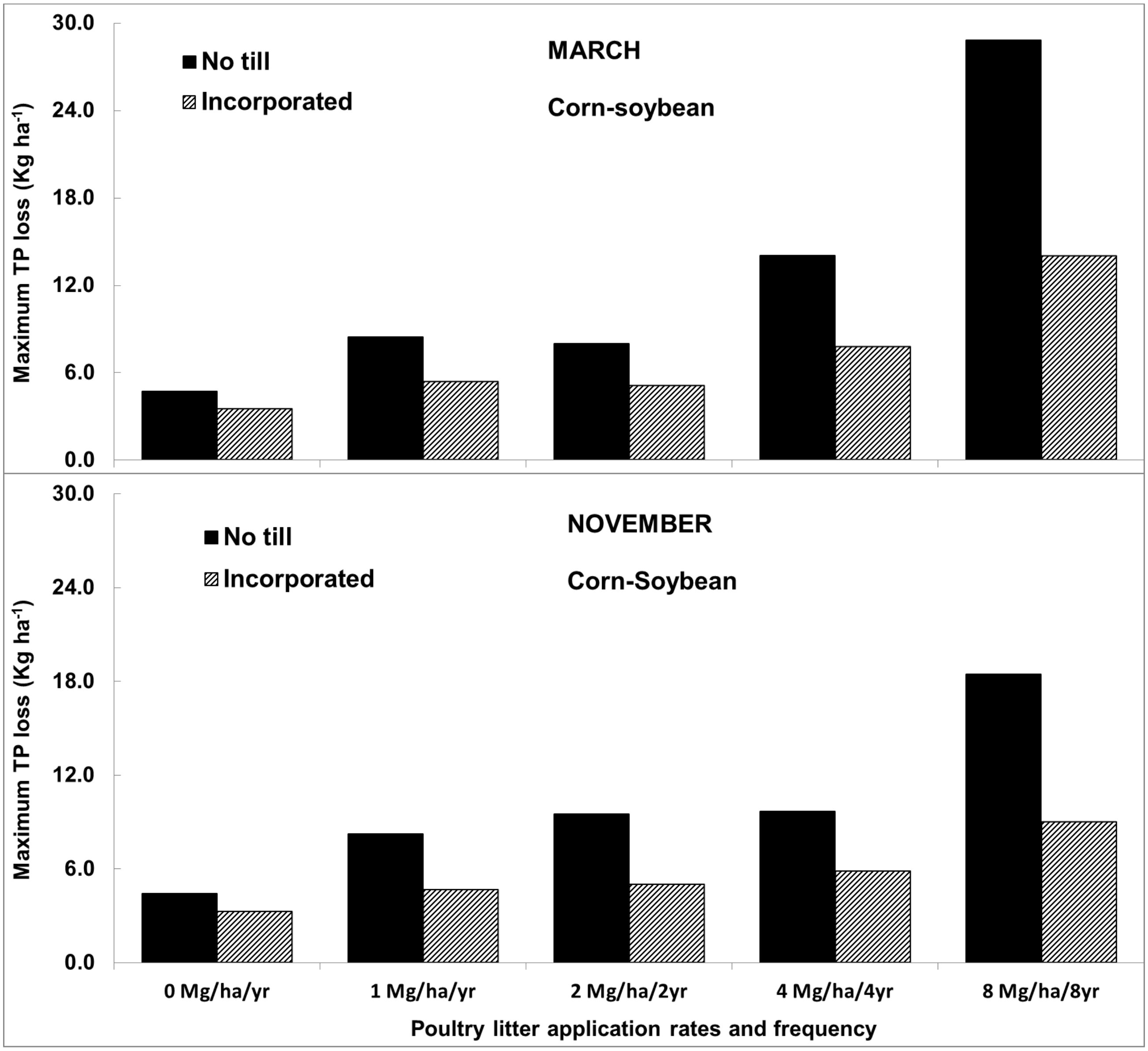


Figure 3.5. Maximum total phosphorus losses with a single poultry litter application over eight-year rotation at 25 mg kg^{-1} soil test phosphorus. . MARCH means poultry litter applied on March 15th before planting; NOVEMBER means poultry litter applied on November 15th during late fall. 0/Mg/ha/yr was 0 Mg of poultry per hectare litter applied every year; 1 Mg/ha/yr was 1 Mg of poultry litter per hectare applied every year; 2 Mg/ha/yr was 2 Mg of poultry litter per hectare applied every other year; 4 Mg/ha/yr was 4 Mg of poultry litter per hectare applied every 4 year; 8 Mg/ha/yr was 8 Mg of poultry litter per hectare applied every 8 year.

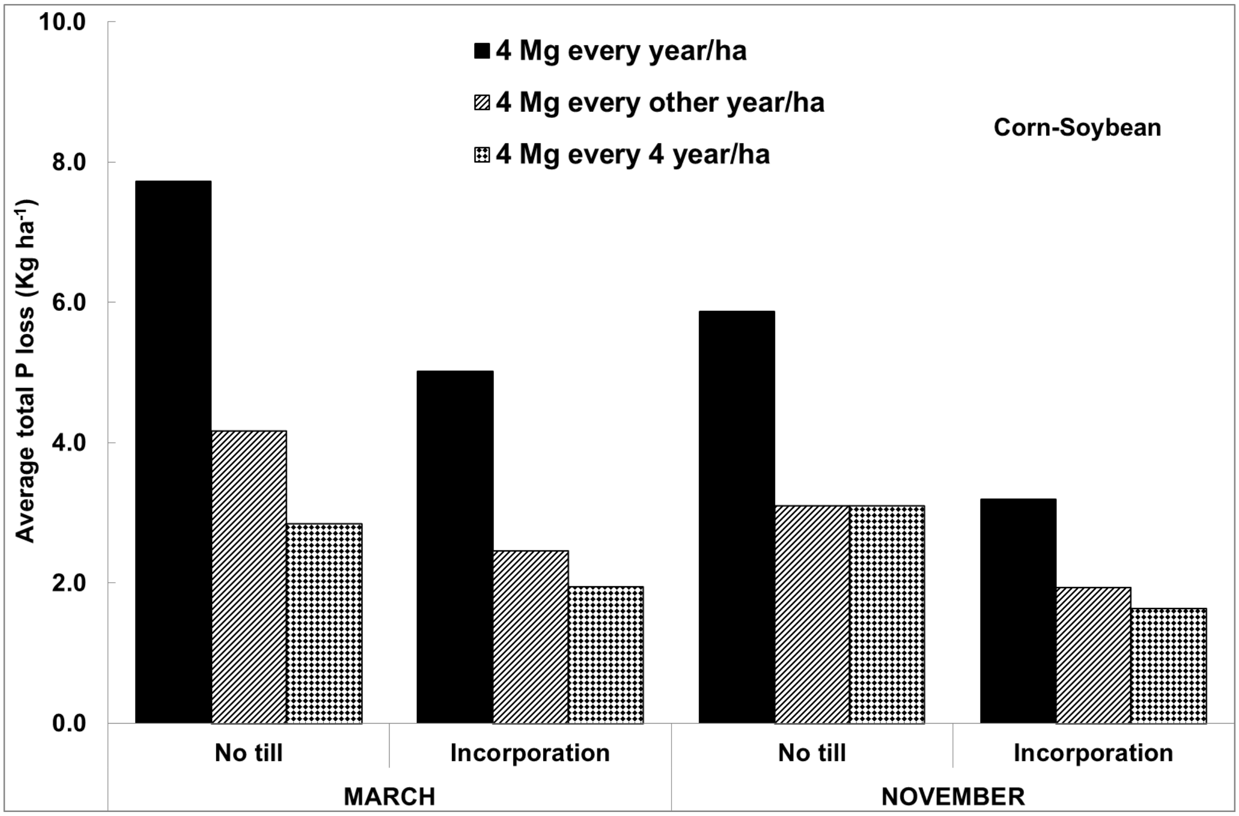


Figure 3.6. Average annual total phosphorus (TP) losses with commonly used poultry litter application rates in the region for 25 mg kg^{-1} soil test phosphorus.

Chapter 4. Evaluation of Management Practices Impacts on Phosphorus Loss with Inorganic Fertilizer Applications Using the APEX Model

ABSTRACT

Mitigating phosphorus (P) loss from agricultural fields is a major challenge that scientists are facing to protect water resources. Selecting optimal rate, timings, cropping systems and methods of P application help to minimize P loss from agricultural fields. However, comprehensive field studies data on the environmental effect of such management implications are limited. Therefore, simulation models offer an alternative way to evaluating management practices performance on P loss in runoff. The objective of the study was to determine the optimal rates, methods, cropping systems and timings of inorganic fertilizer applications in East-central Kansas using the Agricultural Policy/Environmental Extender (APEX) model. A fully calibrated and validated location specific APEX model was used to evaluate the effect of fertilizer rates (25, 50, and 75 kg ha^{-1} P), timing (January, April, November, and October), methods of application (no till-surface broadcast, incorporated with tillage and sub-surface application) and cropping systems (continuous corn, corn-soybean, grain sorghum-soybean and corn-winter wheat-soybean) on total P (TP) loss. The results showed that TP loss increased linearly with the increase in fertilizer rates and soil test phosphorus (STP). Fertilizer applied during late fall (mid of October or November) had lower average annual TP loss compared to spring (January, April) application before planting. No-till surface broadcast application resulted in greater TP loss followed by incorporation and sub-surface application. The effect of P application rates and STP was minimal when the fertilizer was subsurface applied.

Incorporation of fertilizers every year with greater slope resulted in higher TP loss. This is because incorporation increased erosion, thereby increasing sediment-bound P loss. Therefore, incorporation of fertilizer would be a best management practice for soils with lower slopes, low STP, and low erosion, but would not be for soils with greater slopes, high STP or high erosion. Therefore, P application and incorporation with tillage should be discouraged if STP was greater than 50 mg kg^{-1}.Corn-winter wheat-soybean double cropping is the best cropping system to minimize TP loss in runoff

4.1 INTRODUCTION

Phosphorus (P) losses from agricultural fields are a major source of surface water quality impairments, and often considered as limiting nutrient for algal growth and eutrophication in freshwater systems (Graham et al. 2010; Smith et al. 2015; Sharpley and Rekolainen, 1997). In recent years, increasing concern on water quality issues has pressured producers to minimize P loss from agricultural fields (Kimmell et al. 2001). Therefore, different best management practices (BMPs) have been promoted to minimize P loss from agricultural fields to meet water quality goals (Sharpley et al. 2011). For instance, the United States Department of Agriculture (USDA) for decades has promoted BMPs such as conservation reserve program (CRP), conservation tillage with crop rotations, and cover crops to protect water resources (Richardson et al. 2008).

Phosphorus losses from agricultural fields depend mostly on transport factors like runoff and erosion and source factors such as soil test P, timing, method, and type of P applied (Sonmez et al. 2009). The differences in rainfall, slope, and antecedent moisture content and their interactions also play a vital role on P loss in runoff (Kimmell et al. 2001). Assessment of P losses in runoff from agricultural fields is always difficult due to multiple factors that affect P fertilizers reaction in soils (Yuan et al. 2013). However, optimizing management practices such as methods of P application, fertilizer application timings, tillage practices such as no-till or reduced tillage, and cropping systems may help to minimize loss from agricultural fields.

Several studies have found that P application methods such as tillage practices, knife injection, sub-surface banding etc. affected P loss in runoff (Ruark et al. 2006; Zeimen et al. 2006). Nevertheless, studies have also reported conflicting results on the role of tillage, and methods of fertilizer application on P loss in runoff. For instance, Withers et al. (2005) reported fertilizers that are surface broadcast in no-till systems and not incorporated increase potential P loss in runoff compared to conventional tillage, where fertilizer is incorporated. In contrast, others have indicated P loss from conventional tillage often exceeded TP losses in no-till possibly due to P carried to surface water via soil erosion (Cox and Hendricks, 2000 and Sharpley and Rekolainen, 1997). Studies have also indicated that minimum tillage helps to reduce P loss in runoff. For instance, P injected at 5 cm deep and subsurface band application of P fertilizers reduced P loss in runoff compared to no-till surface broadcast systems (Baker and Laflen, 1982; Kimmell et. al. 2001; Rehm et al. 2002; Fernandez et al. 2012).

Fertilizer application timings may play a significant role in optimizing the P availability to crops and minimizing the loss in runoff. Several studies have quantified the effect of initial rainfall timing and the P application in runoff using rainfall simulation methods (Hart et al. 2004; Shuman 2002; Franklin et al. 2006). These results indicated that if fertilizer applications are avoided during the high rainfall period, the P loss in runoff could be minimized substantially. However, to our best knowledge, hardly few studies have evaluated the long-term effect of different timings and inorganic P fertilizer application in runoff at the field or watershed scales.

Likewise, the effects of one cropping systems with fertilizer application on P loss in runoff such as wheat-fallow rotations, corn-soybean rotation, and sorghum-soybean on P loss in runoff have been reported by different studies (Laflen and Tabatabai, 1984; Sharpley et al. 1995; Kimmel et al. 2001). However, the effects of multiple cropping systems on P loss in runoff at the field or watershed scale are not common, and have not been extensively reported in literature.

The interactions between effects of inorganic P fertilizer placement and incorporation on soil test P, rate and application methods, and application methods and different timings have not been studied and are very difficult to quantify in field scale runoff experiments or in rainfall simulation studies. Nevertheless, there is a need to quantify the risk of P loss with inorganic P fertilizers, different application methods, application timings, application rates, and cropping systems based on soils and site characteristics. In addition, due to increasing eutrophication concerns in east central Kansas, implementation of BMPs are significant to reduce non-point P sources from agricultural fields but are costly and time-consuming to test at field or watershed scales (Kimmell et al. 2001). Therefore, calibrated and validated computer models such as APEX could be used as an alternative to analyzing the effect of different management practices on P loss in runoff; extend the field study data and quantify the interactions between application methods, rate, and timings to minimize P loss from agricultural fields in the region.

The objective of the study was to assess the impact of P fertilizer application methods, application timings, and application rates on TP loss and develop BMPs for common cropping systems in the region. This was accomplished by using a calibrated and validated APEX model developed at south-central Kansas using a runoff study data.

4.2 MATERIALS AND METHODS

The fully calibrated and validated location specific model (developed in chapter 2) was used to simulate average annual TP loss in runoff. The watershed 8 (W-8; slope 3.5%), and watershed 4 (W-4; slope 6.5%) were used to simulate TP loss with different management practices to evaluate and update KS-PI. The management practice scenarios analyzed with the APEX model were focused on STP, application timings, P application rate, and method of P application. Those management practices were selected based on the minimum criteria set by NRCS for state PI assessment of P loss risk from fields (USDA-NRCS, 2012). Therefore, the data generated in this study would be helpful to evaluate and update the Kansas Phosphorus index (KS-PI) and provide information on commercial fertilizer application and potential environmental risk.

The fertilizer application, tillage, planting, and harvesting dates were approximated based on the commonly used timings in the region (Keith Jansen, personal communication, 2013). The combinations of management practices analyzed for the study were listed in Tables

1. . Additional details on site characteristics and data collection are available in Zeimen et al. (2006).

The STP selected was 25, 50, 100, 200, and 400 mg kg^{-1}. The five application timings selected were January 15, April 1, June 5 (only for grain sorghum-soybean rotation), October 15 and November 15. The source of nutrient was commercial fertilizer and P application rate was 0, 25, 50, and 75 Kg P ha^{-1}. The application methods were no-till surface broadcast, surface broadcast and incorporated immediately with chisel, disk and field cultivate, and deep band sub-surface application at 7.6-12.7cm depth in a no-till system. The cropping systems used were continuous corn, corn-soybean, grain sorghum-soybean and corn-winter wheat- soybean double cropping. Inorganic fertilizer was applied every year in the continuous corn cropping system. However, in other 2-year rotations that had soybeans, the fertilizer was applied only in the first year of rotation cycle to either corn or grain sorghum.

The model was run for 4 years of warm up (results from initial 4 years were not used). The warmup period had the same management practices as that used in the rotation in each cropping system. During the warmup, inorganic fertilizer was applied on the P-based rate to avoid the P build up in soils. The additional nitrogen (N) fertilizer was applied to minimize the effect of N deficiency on crop yield.

The APEX model was run for 100 different weather scenarios with the APEX weather generator. An automated ‘autoapex tool’ that was written in FORTRAN was used to automatically updates STP, and management practices file. The autoapex tool averages 100 different weather scenarios to output annual maximum, minimum, mean, standard deviation, and median values for runoff, sediment, and TP loss for each management combination. The full data of these model runs for runoff, sediment, and TP loss w listed in the APPENDIX D.

4.3 RESULTS AND DISCUSSION

4.3.1 Average annual TP loss as affected by cropping systems

The average annual TP loss was greater with continuous corn (C-C) followed by corn-soybean (C-S), grain sorghum-soybean (GS-S) and corn-winter wheat-soybean (C-WW-S) cropping systems in watershed 8 (Figure 4.1). Overall, the effectiveness of the cropping system in reducing TP loss decrease with higher STP and P application rates indicating that both high STP and P rates are detrimental from water quality perspective. The average annual TP loss trended similarly with greater loss in continuous corn followed by grain sorghum-soybean, corn-soybean, and corn-winter wheat-soybean cropping systems in watershed 4. However, the extent of loss was even higher possibly due to the greater slope (Appendix D).

Interestingly, the runoff and sediment loss was higher in continuous corn and grain sorghum-soybean compared to other corn cropping systems (Appendix D). The higher sediment loss and sediment-bound phosphorus in continuous corn and grain sorghum-soybean cropping system might have contributed an increased TP loss in runoff as P loss in the form of sediment-bound P in highly eroded areas (Seimens and Oschwald 1976). The plausible reason for higher sediment loss in continuous corn might be due to regular soil disturbance to incorporate fertilizers every year. Similarly, in grain sorghum-soybean cropping system higher sediment loss might be due to less ground cover during spring rains as sorghum was planted one and half month later in early June compared to corn planting ibn April.

The average annual runoff loss decreased by approximately 75 % and 85% with corn-winter wheat double cropping in no-till and incorporated respectively compared to other cropping systems (Appendix D). The average annual sediment loss also reduced substantially in both no-till and incorporated with winter wheat-soybean double cropping compared with other cropping systems (Appendix D). Zeimen et al. (2006) recommended that identifying methods to reduce runoff volume would also help to minimize nutrients loss. Our modeling results indicated that runoff loss was decreased substantially with the use of winter wheat in between corn and soybean cropping system. The C-WW-S double cropping not only reduced runoff but also minimized sediment and TP losses possibly acting as a cover crop. Therefore, including winter wheat in between corn and soybean can potentially be a best management practices (BMPs) to reduce the runoff, sediment, and TP losses in the region.

The average annual runoff and sediment loss trended similarly with greater loss in continuous corn followed by grain sorghum-soybean, corn-soybean, and corn-winter wheat-soybean cropping systems in watershed 4 which had greater slope (6.5%) (Appendix D).

4.3.2 Average annual TP loss as affected by timing of P application

The winter applications (October and November) reduced average annual TP loss compared to spring (January and April) applications regardless of cropping systems in watershed 8 (Figure 4.1). Yuan et al. (2013), reported similar results in three sub-watersheds study in a cotton production system in Mississippi delta. They found higher DP loss from two watersheds with fall fertilizer applications possibly due to high rainfall in the fall and winter in the region. However, the TP was greater with spring applications potentially due to higher levels of sediment loss prior to planting in the spring.

The reduced TP loss during winter might be due to availability of more time to interact and be adsorbed to soil particles. This mechanism could also be described in relation to model P subroutines used in the APEX model. For instance, the inorganic P pool in the APEX model is divided into stable mineral P, active mineral P and labile P pools. Labile P represents easily desorb-able P immediately available for plants or for runoff and leaching loss while active P represents less available not easily desorb-able P that is in equilibrium with labile P (Sharpley et al. 1984). The labile P pool can also became stable and move into a non-labile pool depending on time and soil characteristics (Barrow and Shaw 1979). Therefore, fertilizer applied during October and November had more time to interact with soil particles and potentially some P might have moved to the active or stable P pool reducing the TP loss in runoff as the crop uptake, loss in runoff and leaching are minimal during winter. The trend of TP loss was similar in watershed 4 with regard to application timings (Appendix D).

In addition, the biological mixing efficiency (parameter 29) in the APEX model determines the redistribution of soil constituents because of the activity of the biota in soil (e.g. earthworms). Biological mixing is performed at the end of every calendar year and specifies the fraction of materials (residue, nutrients, pesticides etc.) within the tillage depth that are mixed uniformly throughout that tillage depth (Williams et al. 2012; Steglich and Williams, 2013). Therefore, due to biological mixing (set higher in no-till than incorporation in the model) if fertilizer is surface-apply in October or November it gets incorporated on Dec. 31. However, in spring applications (January and March) remain on the surface for the whole 12 months. This is significant in no-till systems and might be another potential reason, why the model is consistently resulted in higher TP loss with spring (January, April, and June application compared to winter (October and November) applications (Figure 4.1). Thus, the biological mixing efficiency (parameter 29) needs to be fixed in the APEX model to more appropriately simulate the effect of timing on P loss in runoff. Overall, the timing effect on average annual TP loss was found similar in watershed 4 (Appendix D).

4.3.3 Average annual TP loss as affected by the method of P application

The average annual TP loss was the lowest with sub-surface application followed by incorporation and was the highest with no-till surface broadcast application. The sub-surface application (SSA) minimized average annual TP loss approximately by 20 to 56% compared to incorporation and by 20- 85% compared to no-till surface broadcast at lower STP in all cropping systems (Appendix D). This might be due to reduced concentration of labile P on the surface soils with SSA methods, which also determines the P loss in sediment and runoff. For instance, the final labile P concentration in the surface 0-1 cm depth at the end of the simulation with SSA, incorporated with tillage, and no-till surface broadcast application were 362, 374, and 375 mg kg^{-1} respectively. The results also indicated that any management practices that reduced the labile P on top soil layer helps to minimize the TP loss in runoff. Similar to those results Fernandez and White (2012) in a field study reported reduced P values in the soil surface with deep band and sub-surface application due to continuous crop removal of P from the soil surface.

In general, no-till surface broadcast fertilizer resulted in greater annual runoff TP compared to fertilizer incorporation. However, the effect of P incorporation method was different for continuous corn in watershed 4 due to greater slope (Figure 4.2). The frequent soil disturbance every year from tillage to incorporate fertilizer and the greater slope (6.5%) resulted in higher sediment loss (Appendix D). Therefore, the greater TP loss with continuous corn in watershed 4 with incorporation may be due to contribution of sediment bound P loss. Nevertheless, the incorporation decreases average annual TP loss (< 100 mg kg^{-1} STP) compared to no-till in other cropping systems that were without tillage in the second year of the rotation (Appendix D). The results indicated that if proper management practices are implemented such as no-till or including winter wheat in a cropping system to minimize soil disturbance, the TP loss could be controlled as shown in corn-winter wheat-soybean cropping system in both watersheds (Figure 4.3). Thus, in fields that have greater slopes, soil disturbance with continuous tillage and incorporation should be avoided to minimize TP loss in runoff.

The effectiveness of incorporation decreases with increase in STP and P rates and in some instances especially above 100 mg Kg^{-1} resulted in similar or, even more, TP loss than in the no-till surface broadcast (Appendix D). effectiveness of fertilizer incorporation was greater during spring (January and April) application compared to winter (October and November) applications. The spring incorporation reduced average annual TP loss by 17-49 % in low STP levels (25 and 50 mg kg^{-1}) compared to the no-till surface broadcast application. The SSA further reduced average annual TP loss by approximately 20-65% compared to incorporation and 25-80% compared to no-till when fertilizer was applied.

4.3.4 Effect of P application rate and soil test phosphorus (STP) on average annual TP loss

The model-simulated results indicated that in both watersheds, the average annual TP loss in runoff increased with higher P fertilizer application rates (Figures 4.2 and 4.3). Yuan et al. (2013), reported similar results and indicated continuous application of P above crop requirements increases labile P and then soluble P loss in runoff. The effect of P application rate was greater in no-till as indicated by higher TP loss in runoff compared to incorporate and SSA. The effect of P application rate on P loss was minimal when fertilizer was subsurface applied (Figures 2 and 3; Appendix D). The lower loss with SSA method might due to increased adsorption of applied fertilizer P to soil exchange sites and minimum exposure at the top soil surface layer during rainfall events.

In both watersheds, the increase in STP linearly increased the average annual TP loss in runoff (Figure 4.4). The linear TP loss in the runoff with increased STP agrees with the results reported by Pote et al. (1999). Incorporation minimized the average annual TP loss greatly in lower STP levels. For instance, at STP below 50 mg kg^{-1}, incorporation reduced the TP loss substantially compared to no-till. However, above 100 mg kg^{-1} STP, the TP loss in runoff was similar or even greater with incorporation compared to no-till systems (Appendix D).

The effectiveness of fertilizer application method decreased with increases in STP (Figure 4.4) which might be due to saturation of P adsorption sites in higher STP levels. An increase in STP had a greater effect on P loss (steeper slope in Figure 4.4) when the fertilizer was incorporated. This is because incorporation increased erosion, thereby increasing sediment-bound P loss. It follows that although incorporation of fertilizer would be a best management practice for soils with lower slopes, low STP and low erosion, it would not be a BMP for soils with greater slopes, high STP or high erosion. Therefore, P application and incorporation with tillage should be discouraged if STP was greater than 50 mg Kg^{-1}.

The annual average TP loss as an effect of fertilizer application rates and STP trended similarly i.e. highest in the no-till surface broadcast and lowest in the SSA method in other cropping systems and watershed 4(Appendix D: Tables D1; D2; D3; D4; D13; D14; D15; D16).

4.4 CONCLUSIONS

Judicious fertilizer application and management is critical to minimize TP loss in runoff, and increase crop productivity. Overall, the model-simulated results showed P applied during winter (October and November) had lower TP loss compared to fertilizer applied during spring (April, January, June). The increase in STP and application rates increases the TP loss in runoff linearly. No till-surface broadcast resulted in higher TP loss in runoff followed by fertilizer incorporated with tillage and sub-surface application. In general, fertilizer incorporation reduced TP loss in low STP soils. However, fertilizer incorporation by continuous tillage in high STP (>50 mg kg^{-1}) soils and high P fertilizer rates should be discouraged especially in fields with greater slopes. The effect of P application rate was minimal when the fertilizer was sub-surface applied. These model-simulated results were consistent with reported field studies in the literature. However, model simulated results may vary with soils characteristics, watersheds, and climates; thus, any computer simulation models should be calibrated and validated using the site-specific information before using for BMPs evaluation and recommendations. The results also illustrate how a properly calibrated and validated process-based computer models such as APEX can be used to extend field data by simulating BMPs for fertilizer applications. The results would be helpful for producers, planners, and policy makers in developing and guiding BMPs to minimize TP loss to water resources.

4.5 REFERENCES

Baker, J.L., and J.M. Laflen. 1982. Effects of corn residue and fertilizer management on soluble nutrient runoff losses. Trans. ASAE 25:344-348.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Franklin, D., M. Cabrera and V. Calvert. 2006. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci. Soc. Am. J. 70:84-89.

Graham, J.L., M.T. Loftin, A.C. Meyer and Ziegler. 2010. Cyanotoxin mixtures and taste-and-odor compounds in cyanobacterial blooms from the Midwestern united states. Environ. Sci. Technol. 44:7361-7368.

Hart, M.R., B.F. Quin and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. J. Environ. Qual. 33:1954-1972.

Kimmell, R.J., G.M. Pierzynski, K.A. Janssen and P.L. Barnes. 2001. Effects of tillage and phosphorus placement on phosphorus runoff losses in a grain sorghum-soybean rotation. J. Environ. Qual. 30:1324-1330.

Laflen, J.M., and M.A. Tabatabai. 1984. Nitrogen and phosphorus losses from corn-soybean rotations as affected by tillage practices. Trans. ASAE 27:58-63.

Pote, D.H., T.C. Daniel, D.J. Nichols, A.N. Sharpley, P.A. Moore, D.M. Miller and D.R. Edwards. 1999. Relationship between phosphorus levels in three ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170-175.

Ruark, M.D., J.A. Lamb and G.W. Rehm. 2006. Phosphorus runoff from sugarbeet production systems as affected by tillage and phosphorus fertilizer placement. Journal of Sugar Beet Research 43:65-84.

Richardson, C.W., D.A. Bucks and E.J. Sadler. 2008. The conservation effects assessment project benchmark watersheds: Synthesis of preliminary findings. J. Soil Water Conserv. 63:590-604.

Rehm, G., J. Lamb, M. Schmitt. G. Randall, and L. Busman. 2002. Agronomic and environmental management of phosphorus. University of Minnesota. Extension Publication Bo. FO-06797-GO. Available at http://www.extension.umn.edu/distribution/cropsystems/DC6797.html (Accessed February, 2016).

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications.

Sharpley, A.N., D. Beegle, C. Bloster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond, and P. Vadas. 2011. Revision of the 590 nutrient management standard: SERA-17 supporting documentation. Rep. Southern Cooperative Series Bull. 413. Virginai Tech univ. Blacksburg. VA.

Shuman, L. 2002. Phosphorus and nitrate nitrogen in runoff following fertilizer application to turfgrass. J. Environ. Qual. 31:1710-1715.

Smith, D.R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker and A.N. Sharpley. 2015. Surface runoff and tile drainage transport of phosphorus in the Midwestern united states. J. Environ. Qual. 44:495-502.

Sonmez, O., G.M. Pierzynski, L. Frees, B. Davis, D. Leikam, D.W. Sweeney and K.A. Janssen. 2009. A field-based assessment tool for phosphorus losses in runoff in kansas. J. Soil Water Conserv. 64:212-22

Steglich, E. M., and J.R. Williams. 2013. Agricultural Policy/Environmental eXtender Model: User's manual. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX..

Williams, J.R., R.C. Izaurralde, and E.M. Steglich. 2012. Agricultural Policy/Environmental eXtender Model: Theoretical documentation. Texas A&M AgriLife Blackland Research and Extension Center, Temple, TX.

Yuan, Y., M.A. Locke, R.L. Bingner and R.A. Rebich. 2013. Phosphorus losses from agricultural watersheds in the mississippi delta. J. Environ. Manage. 115:14-20.

Zeimen, M.B., K.A. Janssen, D.W. Sweeney, G.M. Pierzynski, K.R. Mankin, D.L. Devlin, D.L. Regehr, M.R. Langemeier and K.A. McVay. 2006. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. J. Soil Water Conserv. 61:258-267

Table 4.1. Management scenarios tested for inorganic fertilizer applications at Franklin runoff study site

Cropping systems	Fertilizer Application timings	Soil test P levels (ppm)	Phosphorus application rates (Kg P)/ha	Application methods	Total model runs
Continuous corn (C-C)	April 1st October 15th November 15th January 15th	5 (25, 50, 100, 200 and 400)	4 (0, 25, 50, and 75)	2 i) No-till-Surface broadcast ii) Surface broadcast incorporated	160
Corn-soybean (C-S)	April 1st October 15th November 15th January 15th	5	4	2	160
Grain sorghum -soybean (GS-S)	April 1st June 5th October 15th November 15th January 15th	5	4	2	200
Corn-winter wheat-soybean (C-WW-S)	April 1st October 15th November 15th January 15th	5	4	2	160

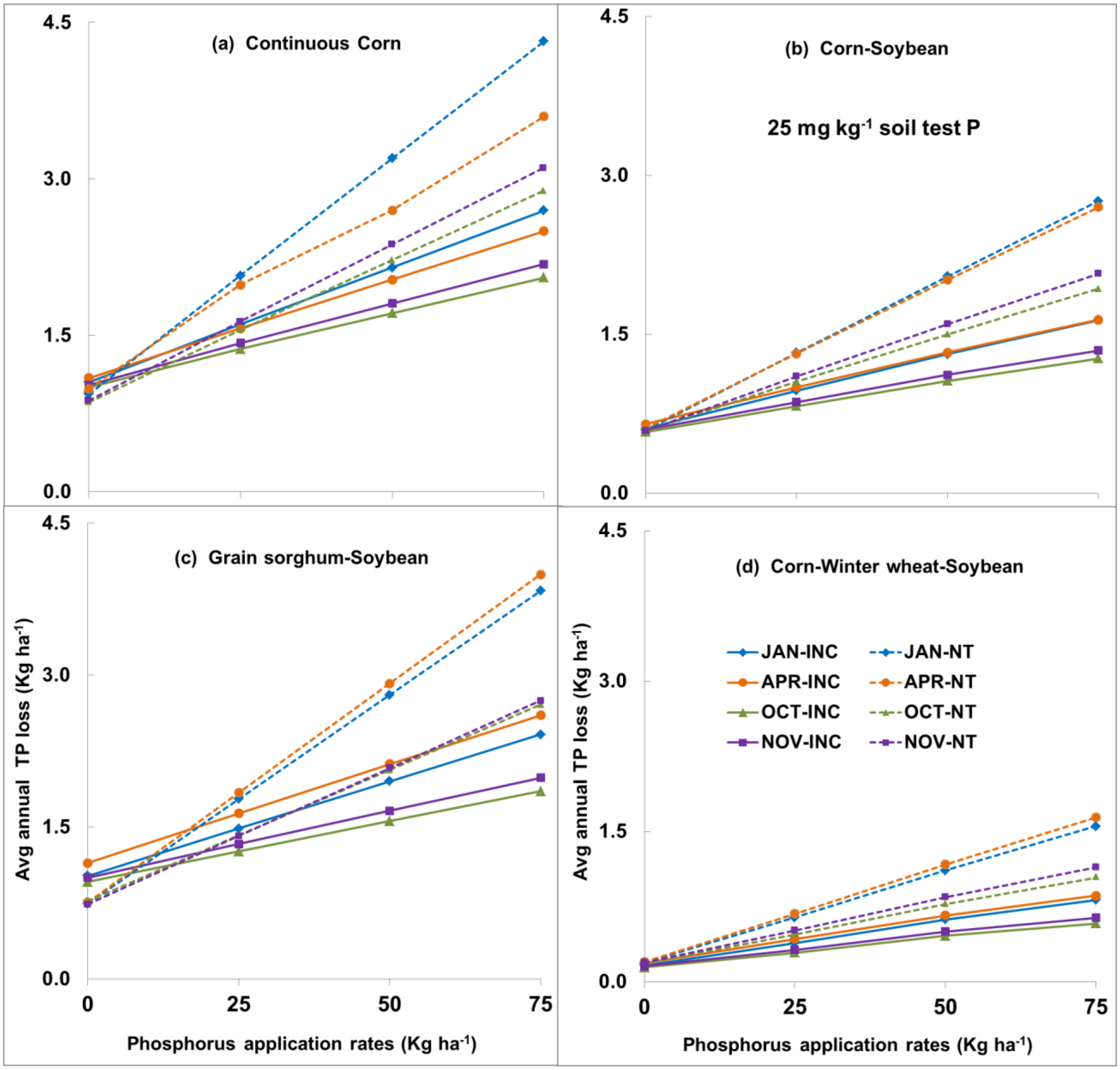


Figure 4.1. Average annual TP loss (kg ha-1) with different cropping systems (25 mg kg^{-1} STP), watershed 8. NT = no-till surface broadcast; INC = fertilizer incorporated with tillage; JAN = January, APR = April application, OCT = October application and NOV = November application.

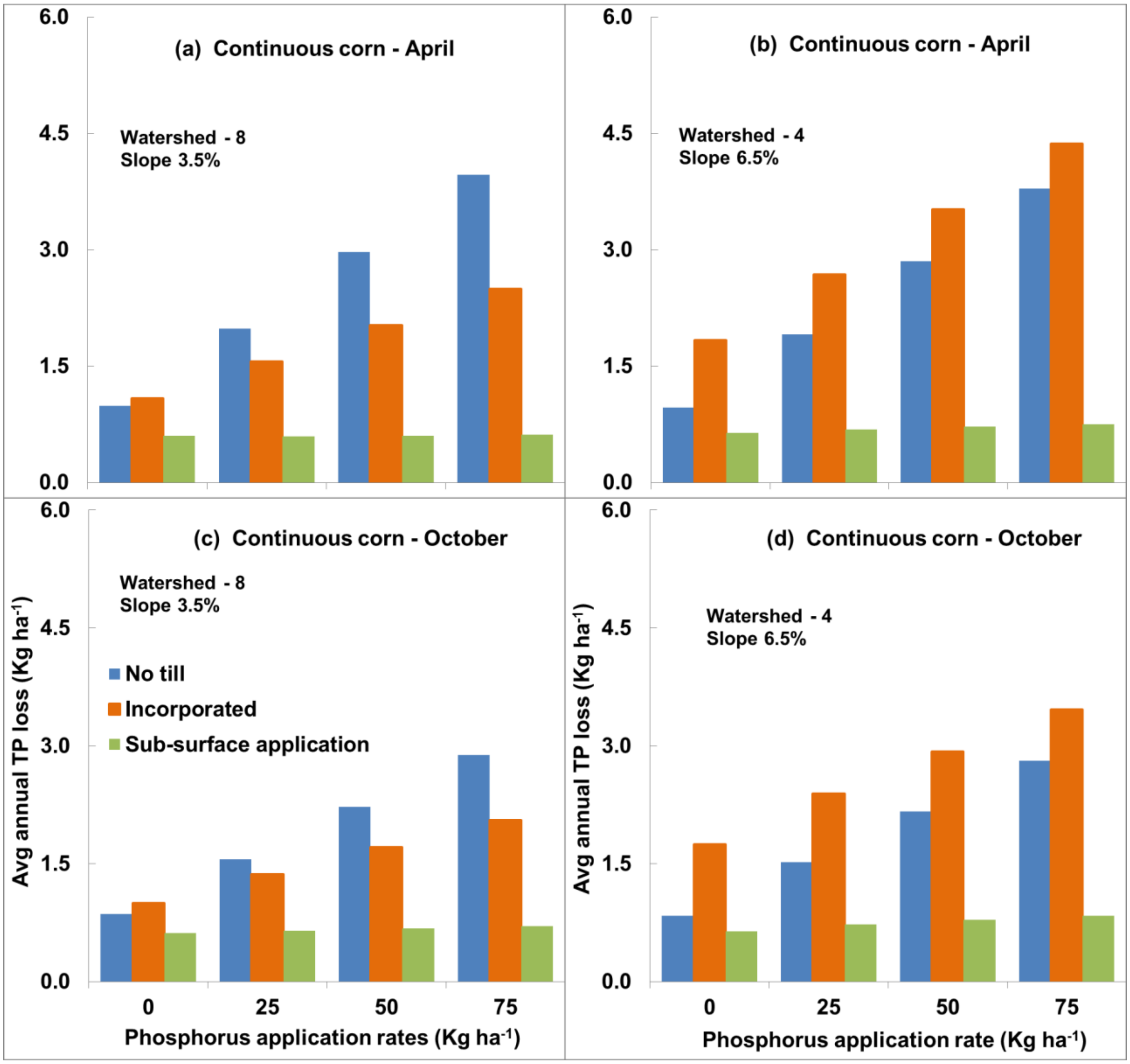


Figure 4.2. Average annual TP loss with different fertilizer application rates and application methods in a continuous corn cropping system a) Watershed 8- Continuous corn-fertilizer applied on April; b) Watershed 4- Continuous corn-fertilizer applied on April; c) Watershed 8- Continuous corn-fertilizer applied on October; d) Watershed 4- continuous corn -fertilizer applied on October

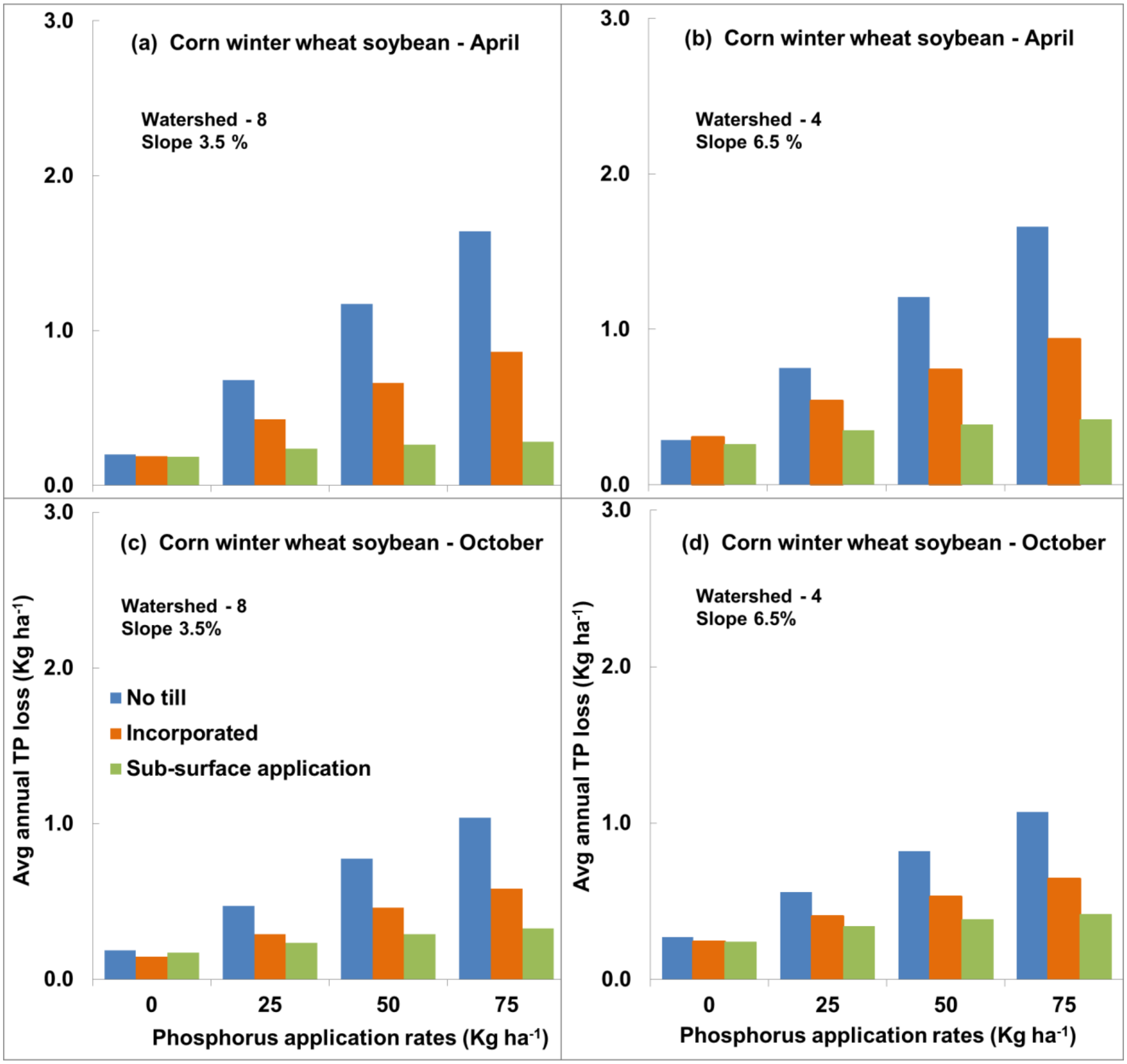


Figure 4.3. Average annual TP loss with different fertilizer application rates and application methods in a corn-witner wheat-soybean cropping system. a) Watershed 8- Corn-winter wheat-soybean-fertilizer applied on April; b) Watershed 4- Corn-winter wheat-soybean-fertilizer applied on April; c) Watershed 8- Corn-winter wheat-soybean-fertilizer applied on October; d) Watershed 4- Corn-winter wheat-soybean-fertilizer applied on October

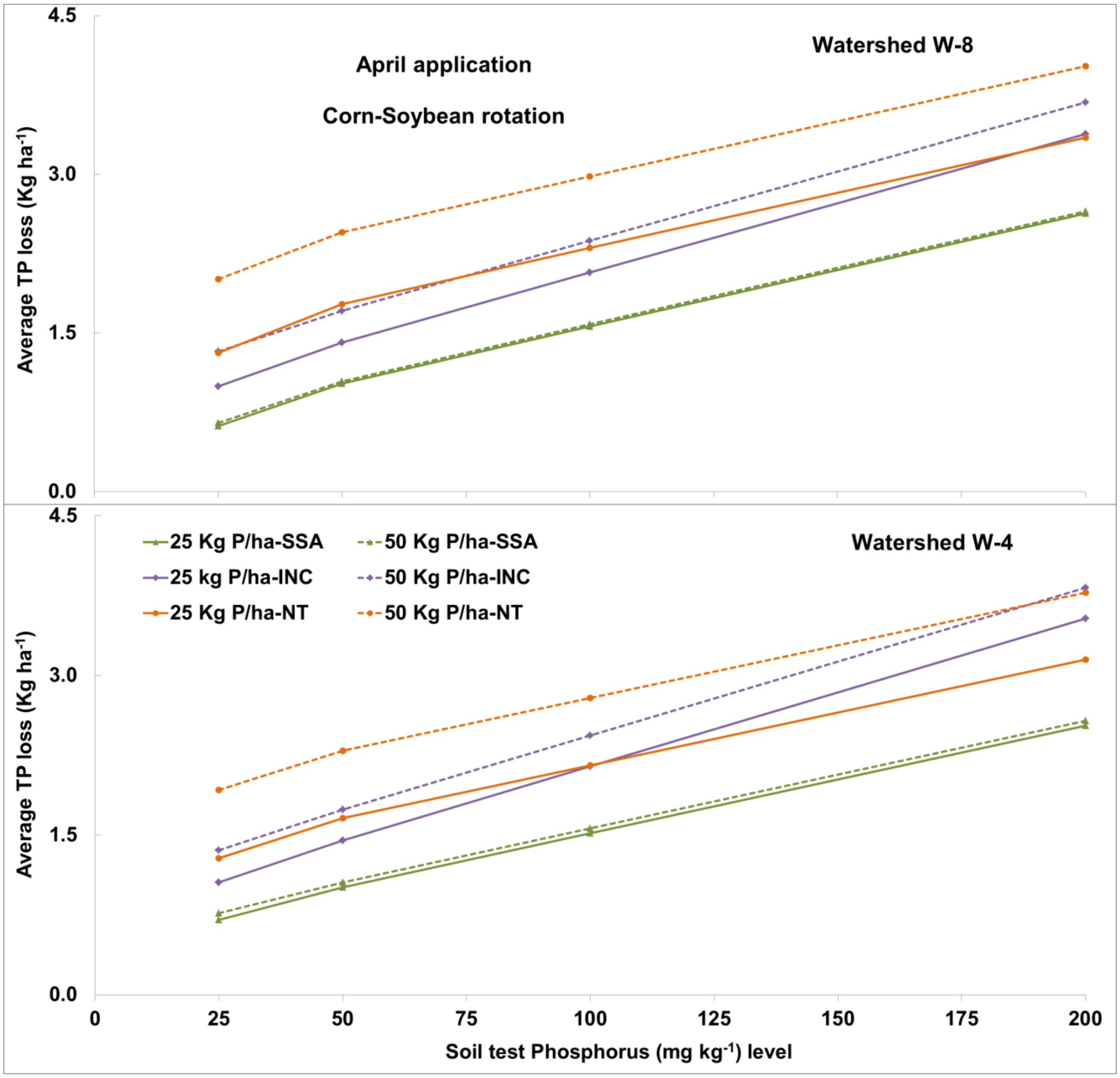


Figure 4.4. Average annual TP loss with different STP and fertilizer application rates. NT = Fertilizer surface broadcast with no-till; INC = Fertilizer surface broadcast and then incorporated immediately with tillage; SSA = Fertilizer sub-surface application.

Chapter 5. Evaluation and Update of the Kansas Phosphorus Index Using Phosphorus Loss Estimates from the APEX Model

ABSTRACT

The phosphorus index (PI) is a commonly used tool to assess the risk of phosphorus (P) loss from agricultural fields. However, concerns have been raised about the effectiveness of P indices in limiting the P loss from agricultural fields and improving water quality. Due to limited or lack of measured P loss data, P indices have not been updated or evaluated rigorously. A process-based computer model such as the Agricultural Policy/Environmental Extender (APEX) can be used as an alternative to generating actual P loss datasets to evaluate and update the P indices. The objectives of the study were to evaluate and update the Kansas PI. Average annual runoff, sediment, and P losses were estimated for 2890 management scenarios, including watershed and management variables of soil series, slope, cropping system, tillage practice, soil test P concentration, P source, P application rate, P application timing, and P application method. Nonlinear regression was used to adjust the weighting factors in the Kansas PI and improve the correlation between the P loss risk ratings and estimated P loss. A new PI was developed based on the component PI structure proposed by Bolster et al. (2012) and selecting weighting factors for each component with multiple regression techniques. The KS-PI rating explained 40% of the variability in estimated average annual P loss (r^2=0.40, p<0.001). The correlation was improved (r^2=0.46) by adjusting weighting factors for P rate, soil test P, and erosion. Using the component index format substantially improved the correlation between average annual P loss and PI ratings (r^2=0.69). The component PI could be further improved by refining methods for estimating cropping system impacts on runoff. Future PI evaluations

should use calculated weighting factors and focus on a component PI model that reflects the better P loss processes in fields.

5.1 INTRODUCTION

Agriculture is a major source of phosphorus (P) loss inciting algae blooms and eutrophication in freshwater systems of the United States (Dale et al. 2011; Hudnell et al. 2010). Management practices influence the amount of P loss from agricultural fields. The reduction of P loss from agricultural fields requires accurate estimates of how management practices influence the P loss. The phosphorus index (PI) is an applied assessment tool that can be used to assess the risk of management practices on P loss, the vulnerability of agricultural fields for P loss and make recommendations to producers (Sharpley et al. 2012; Bolster et al. 2012). Ideally, the PI should accurately predict P loss risk due to changes in management practices. However, there are concerns raised about the use of P indices due to development disparity among P-indices (PIs) across the country, poorly justified and arbitrary selection of weighting factors, and ineffectiveness in improving water quality goals (Bennings and Wortmann, 2005; Osmond et al. 2006; Sharpley et al. 2012; Drewry et. al. 2011; Nelson and Shober et al. 2012).

The ultimate goal of the PI is to improve P management in agricultural fields (Nelson and Shober et al. 2012). Improved PIs will assist researchers and conservationists to better estimates the risk of P loss, identify critical source areas of P export, and target conservation practices more effectively and efficiently. Although, the continuous research, refinement, and improvement has expanded the PI as a tool for manure management, for best management practice selection, and even as a policy and regulatory tool by federal and state agencies (DeLaune et al. 2007; Sharpley et al. 2009, 2012). Additional information is still required on use, impacts and evaluation of P indices to reduce P buildup in soils and P loss from agricultural fields (Nelson and Shober, 2012; Sharpley et al. 2012). In addition, the Natural Resources Conservation Service (NRCS) mandated that the P-index tool must be calibrated to standardize the P loss risk categories across regional, state and watershed boundaries (USDA-NRCS, 2012). Therefore, there is a need to evaluate and update the P indices to improve the PI accuracy in estimating agricultural management practice effects on P loss and to protect the water resources.

5.1.1 Kansas phosphorus index (KS-PI)

The KS-PI is a multiplicative assessment tool and is outlined in Appendix E, Figures E1.1. and E1.2. Each parameter that influences P loss is assigned a P loss rating. The three source and five transport parameters that are individually assigned a P loss rating are ultimately multiplied to determine the KS-PI rating, which can be written as follows (Somez et al. 2009).

KS-PI rating (risk) = P source factor x transport factor

$$\text{KS-PI} = (\beta_1 \text{STP} + \beta_2 \text{Prate} + \beta_3 \text{AM}) \times (\beta_4 \text{Ero} + \beta_5 \text{RO} + \beta_6 \text{DWB} + \beta_7 \text{IrrEro} + \beta_8 \text{IrrRO}) \qquad [1]$$

where, STP = soil test phosphorus, Prate = P additions in the form of organic or inorganic fertilizer (kg ha^{-1}), AM = application method and timing, Ero = soil erosion losses (ton ha^{-1}), RO = soil runoff class, DWB = distance to a water body, IrrEro = irrigation Erosion, IrrRO = Irrigation Runoff (IrrRO) and β_1 to β_8 are weighting factors.

The STP is a categorical variable in KS-PI and is determined by Bray P1, Melich III, or Olson STP values. For instance, if the Bray/ Mehlich III STP is less than <25 mg kg^{-1} then the value of 1 is assigned in the KS-PI rating. For STP of 26-50, 51-75, 76-200 and>200 mg kg^{-1} the values of 2, 4, 8 and 10 are assigned respectively. Similarly, for Olson STP <16, 17-31, 3-47, 48-62 and >62 mg kg^{-1} the values of 1, 2, 4, 8 and 10 are assigned respectively.

The inorganic or organic P application rates are a continuous variable and are multiplied by 0.1 to obtain the KS-PI loss rating. The KS-PI is very sensitive to P rate. Similar to STP, AM is a categorical variable, with values of 0, 1, 2, 4 or 8 assigned based on either P is surface broadcast or incorporation in relation to month of application. For instance, if P is surface broadcast (not incorporated) and applied during the months of September through October or March through June, AM is assigned 8 and represents a greater risk of P loss due to the combined factors of timing and application methods. The soil erosion factor is calculated using the Revised Universal Soil Loss Equation (RUSLE2) and is multiplied by 2 to obtain the KS-PI loss rating. The RO factor is a categorical variable and ranges from 0 (very low) to 16 (very high). The DWB factor is a categorical variable and ranges from 0 (field not in proximity to intermittent stream) to 16 (field immediately adjacent to perennial streams without buffer).The IrrEro and IrrRO were also categorical variables and ranged from 0 (none) to 16 (very high) (Appendix E).

Each source and transport parameter contributing to P loss in KS-PI is assigned a weight that determines its relative contribution to TP loss. The weighting factors in KS-PI (equation I) are 0.1 and 2.0 for β_2 and β_4 respectively and all other weighting factors are 1.0. In most P indices, the weighting factors have been assigned based on professional best judgement of the developers instead of obtaining from measured P loss data (Bolster et al. 2012). For instance, the P rate is a continuous variable and higher rates yield higher P-index source factor value. However, the selection of weighting factor for P rate ($\beta_2 = 0.1$) in KS-PI is not justifiable. In addition, PI formulation itself should accurately reflect the processes governing the P loss. Nevertheless, separating the source and transport factors in multiplicative PI as that in KS-PI does not accurately represent the process-based P loss models (Bolster et al. 2012).

5.1.2 Development of a component phosphorus index (CPI)

The CPI calculates the P loss from each pathway as a product of source and transport parameter. Multiplying each component of the KS-PI source by each transport parameter of the equation 1 results in an expanded computation of the KS-PI (equation 2) (Bolster et al. 2012). The source parameters, STP, P application rates (fertilizer/poultry litter P), application method and timings, and runoff risk and erosion loss of transport factors were considered the dominant in our study sites. The parameters that govern the PI rating based on specific site conditions such as DWB, IrrEro and IrrRO were generally not reported as part of field level datasets and models have limited ability to simulate these factors (Nelson and Shober et al. 2012). Therefore, multiplying the source and transport parameters that interact and affect P loss in runoff, assigning single weighting factor as λ for interaction terms and simplifying the equation 1, the CPI can be written as follows.

$$CPI = \lambda_1 STP*Ero + \lambda_2 STP*RQ + \lambda_3 P\ rate*RQ + \lambda_4 AM*RQ \qquad [2]$$

For the P-index accuracy, the weights for each weighting factor are critical (Bolster et al. 2012). Studies have reported improvement in correlations between P-index rating and P loss by adjusting the weighting factors. For instance, Sonmez et al. (2009) reported improvement in the correlation between KS-PI rating and measured P loss data by modifying weights for erosion (Ero) and STP. Nelson and Shober et al. (2012) indicated that revising weighting factors is one of the potential improvements that can be made in the evaluation of P indices. Bolster et al. (2012) also proposed to use the output from process-based P loss model to evaluate and update the PI weighting factors. However, there is still a lack of standard procedure to determine PI weighting factors and further research is needed (Nelson and Shober, 2012). Thus, this study will help to set a procedure to determine improved PI weighting factors to evaluate P indices.

In addition, the PI uses erosion estimated with RUSLE2 and RUSLE2 estimated erosion using runoff from long-term average annual values. However, most of the measured runoff P loss data collected that can be used to evaluate PI were for short duration, highly dependent on weather and the PIs are not structurally designed to account future weather conditions. Therefore, using the short duration measured data may not reflect the natural weather variability and similar transport processes of P as that of PIs. This induces discrepancy and invalid comparison between measured data and PI values as P indices are not designed to predict annual losses (Nelson and Shober et al. 2012). So, the process based simulation models can be used as an alternative to generate long-term average annual TP loss datasets and evaluate the P-indices (Sharpley et al. 2012). However, very few studies have used model simulated TP loss to evaluate and update the P-indices. Moreover, models must be calibrated and validated adequately to generate P loss datasets required to evaluate the P indices (Nelson and Shober, 2012). Therefore, the overall goal of the study was to evaluate and update the

Kansas P-index with model simulated TP loss, taking advantage of the fully calibrated and validated Agricultural Policy/Environmental Extender APEX model.

Furthermore, the improved PI would help to accurately estimate the potential risk and effectiveness of P management guidelines to reduce P loss from agricultural fields (Sharpley et al. 2012). Therefore, there is a need to evaluate and update the Kansas PI not only to improve estimation and minimize P loss from agricultural fields but also to meet the NRCS nutrient management policy instruction (title 190 national part 302), PI assessment criteria. The objectives of the study were i) to evaluate the KS-PI and ii) to update the KS-PI using the average annual TP loss estimated with the calibrated and validated APEX model.

5.2 MATERIALS AND METHODS

The fully calibrated and validated location specific models (developed in chapter 2) were used to simulate average annual TP loss in runoff. The watershed 8 (W-8; slope 3.5%), and watershed 4 (W-4; slope 6.5%) at Franklin site and watershed 104 (approx. 1% slope) at Crawford site were used to simulate TP loss with different management practices to evaluate and update KS-PI. The management practice scenarios analyzed with the APEX model were focused on STP, application timings, P application rate, and method of P application. Those management practices were selected based on the minimum criteria set by NRCS for state PI assessment of P loss risk from fields (USDA-NRCS, 2012).

At the Crawford site, the STP selected was 25, 50, 100, 200, and 400 mg kg^{-1}. The 5 application timings selected were January 15th, April 1st June 5th and November 15th, October 15th. The source of P used at the Crawford site was poultry litter and the P application rate selected were 0 (control), 25, 50, 100, and 200 kg P ha^{-1}. The method of application was either no-till surface broadcast or incorporated immediately with chisel, disk and field cultivate. In this site, nitrogen (N) rate poultry litter application supply approximately 200 kg P ha^{-1}. The remaining N in other P rate applications was applied with a commercial fertilizer. The cropping systems used were continuous corn, corn-soybean, grain sorghum-soybean and corn-winter wheat- soybean double cropping.

At Franklin site, the same five different level of STP, and 5 different application timings were used as in Crawford site. The source of P used was commercial fertilizer and P application rate was 0, 25, 50, and 75 Kg P ha^{-1}. The application methods were no-till surface broadcast, surface broadcast and incorporated immediately with chisel, disk and field cultivate, and deep band sub-surface application at 7.6-12.7cm depth. The same 4 different cropping systems were used as in Crawford site.

Poultry litter or inorganic fertilizer was applied every year in the continuous corn cropping system. However, in other 2-year rotations that had soybeans, the poultry litter or the fertilizer was applied only in the first year of rotation cycle. The model was run for 4 years of warm up. The warmup period had the same management practices as that used in the rotation in each cropping system. During the warmup, the poultry litter or inorganic fertilizer was applied on the P-based rate to avoid the P build up in soils. The additional nitrogen (N) fertilizer was applied to minimize the effect of N deficiency on crop yield.

The APEX model was run for 100 different weather scenarios with the APEX weather generator. An automated ‘autoapex tool’ that was written in FORTRAN was used which automatically updates STP, and management practices file. The autoapex tool averages 100 different weather scenarios to output annual maximum, minimum, mean, standard deviation, and median values for runoff, sediment, and TP loss for each management combination.

5.2.1 Acquisition of other inputs for PI evaluation

The sediment loss inputs required for the KS-PI for each cropping system were determined using RUSLE2 (NRCS, 2012). The rotation builder in the RUSLE2 was customized to reflect the management practices as in the APEX model. Therefore, each management practices in the RUSLE2 consist of 6 years of crop rotation similar to the management practices in the APEX model. The estimated sediment loss for each management practices were listed in Table 5.1. The brief description of RUSLE2 model was in Appendix E.

The RO values of 16 were used for all soils in this study, which was determined from United States Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS) official soil survey descriptions (USDA-NRCS, 2015). The model estimated TP loss were edge of the field data so, DWB were considered as immediately adjacent to perennial stream or surface water without effective buffer and a rating of 16 was assigned for all the watersheds. The watersheds used in the study had no irrigation, hence irrigation runoff and erosion were considered as negligible and zero values were used.

5.2.2 Procedure to evaluate Kansas multiplicative model (KS-PI)

The APEX model simulated average annual TP loss data (n = 2890) from both locations and three watersheds were used to determine the improved weighting factors for multiplicative Kansas P index (KS-PI). The original weighting factors for the soil test P (STP), P application rate (Prate), application method and timings (AM) and erosion (Ero) i.e. $\beta_{1,}$ $\beta_{2,}$ β_3 and β_4 of the

KS-PI (equation 4) are 1, 0.1, 1 and 2.0 respectively. New weighting factors were adjusted by fitting the KS-PI (equations 9, 10 and 11) with SAS Proc nlin procedure (SAS Institute, 2015). The weighting factors were re-calculated because the current values of $\beta_{1,}$ $\beta_{2,}$ β_3 and β_4 were neither justifiable nor backed with scientific research. The input data used to calculate weighting factors were STP, Prate, AM and the RUSLE2 calculated erosion (Ero).

i. Method 1: The weighting factors $\beta_{2,}$ and β_4 were adjusted using the SAS proc nlin procedure. The $\beta_{2,}$ and β_4 are the only weighting factors different than 1 that has been used current in the KS-PI. Therefore, this step intended to directly compare the KS-PI rating relationship with model simulated TP loss using the current and newly adjusted weighting factors. The model used to determine $\beta_{1,}$ and $\beta_{2,}$ was

$$\text{KS-PI} = (\text{STP} + \beta_2\text{P rate} + \text{AM}) \times (\beta_4\text{Ero} + 16 + 16 + 0 + 0) \quad [3]$$

ii. Method 2: The weighting factors $\beta_{1,}$ $\beta_{2,}$ β_3 and β_4 were adjusted for all the variables using the SAS Proc nlin procedure. The model used to determine $\beta_{1,}$ $\beta_{2,}$ $\beta_{3,}$ and β_4 was

$$\text{KS-PI} = ((\beta_1\text{STP} + \beta_2\text{P rate} + \beta_3\text{AM}) \times (\beta_4\text{Ero} + 16 + 16 + 0 + 0))/100 \quad [4]$$

The model were divided by 100 to scale up the weighting factors value to match the KS-PI rating.

Using the new adjusted weighting factors the KS-PI rating for each P loss combination was recalculated and the results were compared. The P values were also estimated using SAS Proc corr procedure to determine the relationship of each KS-PI parameters.

5.2.3 Procedure to evaluate component model (CPI)

The component model (CPI) outlined in equation 2 was evaluated using the estimated weighting factors λ_1, λ_2, λ_3, and λ_4 (Table 2). The weighting factors were estimated using either the independent RUSLE2 or the model simulated APEX runoff using multiple regression Proc mixed procedure (SAS Institute, 2015)

Ideally, the P index should be evaluated with independently derived runoff and sediment loss. Therefore, in this method RUSLE2 generated runoff and sediment loss were used to calculate weighting factors β_1, β_2, β_3, and β_4 (Table 2) and evaluate the CPI. The CPI (equation 2) rating for 2890 management scenarios were estimated with the new weighting factors and compared with the APEX model simulated average annual TP loss. The model used to generate weighting factors was

$$\text{Average TP loss} = STP*Rsed + STP*RQ + Prate*RQ + AM*RQ \qquad [5]$$

where RQ is the RUSLE2 estimated runoff, the Rsed is RUSLE2 estimated erosion loss, STP is soil test P, Prate= P application rate, and AM is P application timing and method.

In the second method, the APEX model simulated average annual runoff and RUSLE2 estimated erosion loss data were used to calculate the weighting factors β_1, β_2, β_3, and β_4 (Table 2). The CPI rating for all 2890 management scenarios were calculated using new weighting factors and compared with the APEX model simulated average annual TP loss. The runoff estimated with the RUSLE2 was insensitive to changes in cropping systems. Therefore, the APEX model simulated runoff was used instead of RUSLE2 because the APEX model was simulating runoff well, was the only variable that passed every time and was sensitive to change in cropping systems. The model used to generate weighting factors was

$$\text{Average P loss} = STP*Rsed + STP*AQ + Prate*AQ + AM*AQ \qquad [6]$$

where, AQ is the APEX model simulated average annual runoff and Rsed is the RUSLE2 simulated average annual erosion loss.

5.3 RESULTS AND DISCUSSION

5.3.1 Evaluation of KS-PI with model simulated TP loss (all watersheds; both locations)

The model simulated TP loss (all watersheds with both locations) and KS-PI ratings were significantly linearly correlated with an r^2 value of 0.40 ($p<0.001$; Figure 5.1). The relationship indicated that if the KS-PI value is very low (0-75), low (76-150) and medium (151-300) then average annual TP loss could range from 0.5-2.0 kg ha^{-1} yr^{-1}. Likewise, if the KS-PI rating is 300-400, the TP loss might be approximately 2.0-3.0 kg ha^{-1} yr^{-1} (Figure 5.1). But based on the linear relationship, the KS-PI rating above 400 was too sporadic and would be unrealistic to legitimately estimate the amount of TP loss (Figure 5.1). The cluster of data points falling below the fitted curve reflected that the model simulated TP loss was over-predicted by the KS-PI (Figure 5.1). Overall, at the Crawford site, the higher TP loss and KS-PI rating resulted from N rate poultry litter rate application treatments. Likewise, at the Franklin site, the higher TP loss was from watershed 4, a continuous corn cropping system that had relatively higher slope (6.5%), greater runoff,and sediment loss (Appendix E).

Evaluation of KS-PI with model simulated TP loss by method of P application-all watersheds

The data from all three watersheds (W-4, W-8 and Crawford site) were grouped together and evaluated by the method of application. The model simulated TP loss and KS-PI rating for the no-till surface broadcast application and fertilizer/poultry litter incorporated with conventional tillage were significantly correlated with r^2 of 0.57 and 0.31 respectively ($p<0.001$; Figure 5.2a, 5.2b). Although both P application methods were significant, the greater r^2 and correlation coefficient with no-till surface broadcast application method indicated that the KS-PI tended to quantify the TP loss better with no-till application compared to incorporation with conventional tillage method. It might be due to an inability of the KS-PI to accurately account for the sediment-bound P loss with the incorporated method as the sediment loss is substantially greater with incorporation method compared to no-till (Appendix E).

The method of application data were split, and also evaluated by watersheds. For the no-till surface broadcast, at Franklin, W- 8 and W-4 model simulated TP loss and PI ratings were significantly correlated with r^2 of 0.56 and 0.50 respectively ($p<0.001$; Figure 5.2a). Similarly, at the Crawford site the model-simulated TP loss and PI ratings were significantly correlated with an r^2 of 0.53 ($p<0.001$; Figure 2b). Likewise, for the incorporated fertilizer at Franklin W-8 and W-4, the model simulated TP loss and the PI rating was significantly correlated with r^2 of 0.33 and 0.39 respectively ($p<0.001$; Figure 5.2b). At Crawford, the model simulated TP loss and PI ratings for incorporated method were significantly correlated but with slightly lower r^2 of 0.31 ($p<0.001$; Figure 5.2b).

Overall, the results indicated that the KS-PI rating corelated better when the TP loss was higher. For instance, the greater sediment and sediment-bound P loss due to the higher slope

(6.5 %) and incorporation method in Franklin W-4 resulted in higher TP loss and geater corealtion with an r^2 of 0.39 compared with other watersheds (Figure 5.2b). Simialrly, the relatively greater TP loss with no-till surface braodcast application at the Franklin W-8 and the Crawford sites had resulted in better co-relation of KS-PI rating and model simualted TP loss comapred to Franklin W-4 (Figure 5.2a).

5.3.2 Effect of cropping systems on model simulated TP loss and KS-PI ratings

The continuous corn systems resulted in greater average annual TP loss followed by grain sorghum-soybean, corn-soybean and corn-winter wheat-soybean cropping systems regardless of STP levels. The greater TP loss with continuous corn might be due to the application of fertilizer or poultry litter every year. Interesingly, the different amount of TP loss with cropping systems had approximately same KS-PI rating which reflected the insenitiveness of KS-PI with cropping systems (Figure 5.3.). For instance, the model simulated TP loss with GS-S, C-S, and C-WW-S cropping systems at 25 mg Kg^{-1} STP were approximately 4.0, 3.0, and 1.5 Kg ha^{-1} yr^{-1}, respectively. But the KS-PI ratings were approximatley same for all the cropping systems regardless of the total amount of TP loss (Figure 5.3.). The trends of TP loss and KS-PI rating with respect to cropping systems and STP were similar at watershed 4.

Similar results were found in the Crawford site with the greatest loss from continuous corn and the lowest with corn-winter wheat-soybean. The extent of TP loss and relative KS-PI rating were also relatively higher in Crawford site compared to Franklin site watersheds (Figure 5.3.). Overall, the greater TP loss in this site was because of higher P application rates with poultry litter. The lack of KS-PI sensitivity to changes in the cropping system was discernible in this site as indicated by the large effect on the P loss with changing cropping system but a minor (or no effect) on the PI rating.

For instance, the model simulated TP loss with GS-S, C-S, and C-WW-S cropping systems at 25 mg Kg^{-1} STP were approximately 11.6, 8.3, and 5.4 Kg ha^{-1} yr^{-1}, respectively. The higher runoff and sediment loss in GS-S and C-S compared to C-WW-S cropping system resulted in greater TP loss with the earlier ones. Nevertheless, the KS-PI rating was assigned approximately same for all the cropping systems (Figure 5.3). The TP loss and respective KS-PI ratings follow the similar trend with 100 mg kg^{-1} STP (Figure 5.3). Therefore, the comparisons illustrate that the KS-PI failed to account the impact of cropping systems on TP loss and adjust the PI ratings accordingly.

Perhaps, the reduced runoff and sediment loss when switching from one cropping system to another had helped to lower the P-index ratings. In short-term, changing the cropping system from one to another may help to mitigate the TP loss and potentially lower the P-index values but it may not be the viable option for long-term. The results also indicated that intense cropping systems such as corn-winter wheat-soybean double cropping might reduce the runoff, sediment, and TP loss substantially. The impact of changing cropping system on the KS-PI should be accounted for the different RUSLE2 erosion rate. However, the APEX model simulation results indicated that the different cropping systems also influenced the runoff from the soils. The effect of cropping system on runoff is not reflected in the KS-PI because the runoff portion of the PI is strictly a function of soil properties (runoff class).

5.3.3 Effect of application timings on model simulated TP loss and KS-PI values

The average annual TP loss was affected by the application timings. The results indicated that the average annual TP loss was different for January, April, October, and November application timings for each cropping systems (Figure 4). However, the November and January application, and April and October application resulted in approximately same KS-PI rating for both corn-soybean and grain sorghum-soybean cropping systems (Figure 5.4). This is significant because the model simulated TP loss clearly indicated that the fall (October and November) application had relatively lower TP losses compared to the spring (January, April, June) application. The trend of TP loss and KS-PI rating were similar in Franklin W-4.

Similar results were obtained at Crawford site with very high average annual TP loss in April application compared to October grain sorghum or corn-soybean but the KS-PI ratings were approximately similar (Figure 5.4.). Therefore, the results indicated that there is a difference in annual TP loss with different application timings and methods but the differences were not reflected in the KS-PI ratings. One way to correct this might be separating the application timing and methods in KS-PI formulation with different index rating.

5.3.4 Effect of method of application on P loss and KS-PI ratings

Although the method of application is not a separate parameter of the KS-PI, the results indicated that the average annual TP loss decreased substantially with fertilizer or poultry litter incorporated compared to the surface broadcast application (Figure 5.5). The average annual TP loss and P-index rating were greater in April and October application compared to January and November application regardless of method of application (Figure 5.5). The impact of sub-surface fertilizer application in reducing TP loss in runoff was more substantial (Appendix D).

Interestingly, the TP loss was approximately same for both October and November application with no-till surface broadcast (Figure 5.5.). Nevertheless, the KS-PI assigned the different P-index rating, if fertilizer or poultry litter was applied in October instead of November and had different application methods. Similarly, the April application resulted in greater TP loss but the P-index rating was similar as that of October possibly due to the use of inappropriate weighting factor or incorrectly combining application methods and timings. Therefore, the weighting factor for application timing and method of the application need to be re-evaluated or should be separated as a different component to increase the KS-PI accuracy. This also strengthens the earlier conclusion to separate the P-index application timing and methods in the KS-PI formulation.

In addition, the APEX model applies the biological mixing at the end of every year. Therefore, if poultry litter or inorganic fertilizer is surface-apply in November (or December 30) the inorganic fertilizer or poultry litter gets incorporated with biological mixing on December 31. Hence, the no-till applications made on October and November in this study were incorporated at the end of the December based on how the model is structured. However, applications in January, April and July remain on the surface for the whole 12, 8 and 6 months, respectively. Therefore, this needs to be fixed in the APEX model to make decisions on the effect of timing more accurately.

5.3.5 Effect of P application rates on model simulated average annual TP loss and P index ratings

Phosphorus application rates and STP are important factors that control the risk of P loss in runoff (DeLaune et al. 2004; Sistani et al. 2010)**.** The increase in the STP and P application rates increased the average annual TP loss in runoff and respective KS-PI ratings at Franklin W-8 (Figure 5.6). Similar trends were found at the Crawford (Figure 5.6) and Franklin W-4 runoff study sites (Appendix E).

The STP is a categorical variable in KS-PI. The difference in TP loss was substantial above 100 mg kg^{-1} STP, but the P-index ratings were approximately the same for STP of 100 and 200 mg kg^{-1} STP (Figure 6). The TP loss increased considerably when STP was 400 mg kg^{-1}, however, the P-index ratings did not increase very much. For instance, the average annual TP loss with STP of 200 mg kg^{-1} and P applied at 200 kg P ha^{-1} applied during January at the Crawford site was 11.5 kg ha^{-1}. With the increase in STP from 200 to 400 mg kg^{-1} the TP loss increased approximately by 23% (14.7 kg ha^{-1}) but the P index only increased by 6% (Figure 5.6). Similar trends were found in Franklin site with an approximately 30% increase in TP loss when increasing STP from 200 (4.8 kg ha^{-1}) to 400 (4.8 kg ha^{-1}) mg kg^{-1}. But, the PI rating increased only by 10%. Therefore, the KS-PI does not appear to be sensitive to differences in STP, if above 200 mg $kg^{-1}$and categorized all the fields with a same PI rating of 10.

The consequences of failing to represent the STP appropriately in KS-PI would be that it would not stop building STP in soils and reflect the impact of STP on P loss in runoff accurately, especially for soils associated with concentration feeding operations (CAFOs) where the PI is heavily used for nutrient management plans. Our APEX model-simulated average annual TP loss results showed a linear increase in TP loss in runoff with increasing STP. Several studies reported similar effects of STP on P loss in runoff (Cox and Hendricks 2000; Torbert et al. 2000; Davis et al. 2005). Therefore, the over-simplification of the effect of STP on runoff in the KS-PI should be corrected and can be simply done by changing the STP from categorical variable to continuous variable.

5.3.6 Evaluating Kansas multiplicative P Index (KS-PI) with new weighting factors

The adjusted new weighting factors β_1, β_2, β_3 and β_4 for soil test P (STP), P application rate (Prate), application method and timings (AM), and erosion (Ero), respectively were adjusted by fitting equations 3 and 4 with SAS proc nlin procedure to evaluate the KS-PI. The SAS output indicated that the effect of AM was negligible with very low β_3 value. Thus, was not included in the computation of KS-PI rating.

The results indicated that with the new weighting factors for STP (β_1), P rate (β_2), and Err (β_4) the modified multiplicative Kanas P index rating slightly better correlated with the APEX simualted TP loss data with $r^2 = 0.46$ (Figures 5.7 and 5.8) than the KS-PI of 0.40 (Figure5.1). Somnez et al. (2009) reported similar results using the field measured and rainfall simulated data to manually adjust the source and transport factors values of the KS-PI. They reported multiplying STP by 10, and decreasing erosion by half was the best combination to modify the KS-PI that resulted in the best r-value. The modification improved the correlation between the measured TP loss data and KS-PI slightly increasing r from 0.79 to 0.89. However, the procedure they used to modify the KS-PI is very difficult to follow as they did a rigorous manual adjustment of the weighting factors.

Interestingly, eliminating the weighting factor of STP (β_1) (equation 4) and using only the $\beta_{2,}$ and β_4 values in the modified Kansas multiplicative P index model resulted in a similar r^2 (0.46) (Figure 5.8). Therefore, either equation 3 or 4 can be used as the best-modified Kansas multiplicative P index (KS-PI) model.

5.3.7 Evaluating phosphorus index weighting factors of the component PI (CPI)

The KS-PI was also further evaluated as a component model to determine the potentiality of further improvement and to better represent the P loss process as indicated by Bolster et al. (2012). For this, the component model (CPI) outlined in equation eight (2) was evaluated by generating weighting factors (β_1, β_2, β_3, and β_4) using multiple regression (Table 5.2; Figure 5.9). The weighting factors were generated in two different ways (Table 5.2).

5.3.8 Independently generated RUSLE2 runoff and erosion loss

The results indicated that the component P index (CPI) model simulated average annual TP loss correlation was improved greatly with an r^2 of 0.69 compared to the multiplicative KS-PI (r^2 = 0.40) when weighting factors were generated with independently calculated RUSLE2 runoff and erosion loss (Figure 5.9a and Figure 5.1). Sonmez et al. (2009) reported similar results with improved PI accuracy with revised weighting factors using the Kansas multiplicative P index. In addition, Bolster et al. (2012) reported similar improvements with the calculated weighting factors using the APLE generated P loss with modified Pennsylvania PI. However, they selected the APLE input values randomly from uniform distribution within a certain range and assumed the parameters were uncorrelated. Then the APLE-generated data were used to determine the weighting factors. Thus, their procedure to determine the weighting factors was different from ours. In our case, we used both the APEX-simulated and the independently calculated input (runoff and erosion) or the combination of both to determine the weighting factors.

Bolster et al.(2012, 2014) using an APLE model (Vadas et al. 2009) estimated P loss values also reported similar improved PI accuracy results with component PI models of Pennsylvania and Kentucky. Estimating P loss for each pathway as the product of source and transport that better reflected the P loss processes in fields (Bolster et al. 2012) might have improved the CPI accuracy.

5.3.9 The APEX model simulated runoff and RUSLE2 estimated sediment loss

In this step, the weighting factors β_1, β_2, β_3, and β_4 were calculated using the APEX model simulated average annual runoff and RUSLE2 estimated erosion to estimate the CPI total P loss. The purpose of using the APEX-simulated runoff was to compare the impact of runoff on TP loss with CPI TP loss. The co-relation between the APEX model simulated TP loss and CPI rating improved with r^2 of 0.86 compared to an r^2 of 0.69 as determined by using RUSLE2 runoff and sediment loss. The improvement indicated that the runoff loss is important and should be accurately estimated (Figures 5.8 and 5.9b).

The results reflected the importance of using accurate runoff and sediment loss in the evaluation of P indices. Ideally, independently estimated runoff and sediment loss should be used to calculate the weighting factors. The correlation results with CPI and using the APEX simulated runoff to calculate weighting factors indicated that if the independently estimated runoff correlated well with the model-simulated runoff, the TP loss estimation could be further improved. Therefore, APEX model simulated runoff could be potentially used to cross check the independently determined runoff during the PI evaluation processes.

5.3.10 Practical implication of PI

The CPI would better correlate TP loss with P index ranking i.e., the risk of P loss as compared to KS-PI because it describes 69 % variability compared to 40 % with KS-PI. The imminent practical use of CPI could be in concentrated animal feeding operations (CAFOs) to assess the risk of P loss. For instance, CAFOs have to submit a nutrient management plan during the establishment year and in every 5 years to renew the operations. The PI is a part of the nutrient management plan that would guide the CAFOs to manage the P produced with manure. In addition, the PI can be adapted to a producer's field to assess the risk of P loss and identify critical source areas where there is P loss concern. It also provides the assessment for best management practices on TP loss from agricultural fields so that producers can use the right management practices to minimize the P loss to water resources.

The improvement in TP loss and PI rating with CPI compared to KS-PI was notable. For instance, let us take one management practices from Franklin runoff study, watershed 4 that had everything same except the STP. The management practice was continuous corn, and P was applied at 25 kg P ha^{-1} on October. The STP level for the first case was 100 mg kg^{-1} and second case was 200 mg kg^{-1}. The APEX model simulated TP loss was 5.24 and 9.0 kg ha^{-1}, respectively for those two STP levels and the P index ratings for both cases were 715 with the multiplicative KS-PI. It indicated that the KS-PI failed to assess a difference in STP and rank the PI rating accordingly because the STP is used as a categorical variable in KS-PI and both the 100 and 200 mg kg^{-1} had the same categorical value of 8. In contrast, the CPI rating for the same management practices and STP resulted in 2.84 and 4.70 P index rating, which was more reasonable based on the relative increase in TP loss and PI rating.

Therefore, the CPI would better correlate the PI rating with TP loss compared to the KS-PI and that would have a substantial impact in both CAOFs and agricultural fields. For instance, with the KS-PI a producer's field that does not have a high TP loss compared with another producer may get the same PI rating as illustrated above and unfairly penalized. However, with the CPI the relative increase in TP loss and PI rating are in good agreement therefore, a producer whose CAFOs or agricultural fields have less TP loss would end up with lower PI rating and will not be restricted or penalized. Thus, there would be substantial practical implications of using the CPI compared to KS-PI in ranking the P loss and managing P loss in both CAFOs and agricultural fields.

5.4 CONCLUSIONS

Overall, the Kansas multiplicative P index (KS-PI) rating co-related with the APEX simulated average annual TP loss with r^2 of 0.40. The calculated weighting factors for STP, Prate and erosion improved the correlation between KS-PI and TP loss to an r^2 of 0.46 ($p<0.001$). Each factor of KS-PI was multiplied to formulate the component P index (CPI) and the weighting factors for the interaction terms of the new CPI were calculated. The linear relationship and correlation between the APEX simulated and CPI-estimated TP loss was greatly improved with r^2 of 0.69. The better co-relation of CPI with the APEX-simulated TP loss supports the hypothesis that the CPI formulation better represents the interactions between processes controlling P loss and improves the P loss risk assessment compared to multiplicative Kansas P index (KS-PI).

The improvement in the CPI with different sets of the estimated weighting factors also indicated that proper estimation of these factors is significant in accurately determining the risk of P loss with PI. Therefore, using calibrated and validated model to generate the long-term TP loss dataset, estimating the weighting factors with multiple regression, and evaluating the PI using the estimated weighting factors could be a viable option where there is a lack of measured runoff and P loss dataset and this procedure could potentially be utilized to evaluate the P indices. Thus, this study would be helpful to provide roadmap in development and testing the state and regional level PIs.

5.5 RECOMMENDATIONS AND FUTURE RESEARCH NEED

- The weighting factors are significant to determine the PI risk assessment. Therefore, in any future PIs evaluation the weighting factors should be calculated or analyzed as a first step using standard procedure as used in our study, which can be replicated.
- The component P index (CPI) model resulted in greater improvement correlating the APEX simulated TP loss with CPI indicating that the component model reflects the P loss processes better in the fields, Therefore, component model should be used in any future PIs evaluation processes.
- The independent runoff and erosion loss should be used to calculate the weighting factors to increase the PI risk assessment accuracy. Our results indicated that if the independently estimated runoff was correlated with the model-simulated runoff to estimate weighting factors it greatly improved the correlation of PI with the model simulated TP loss. Therefore, runoff loss used to calculate the weighting factors should be accurate to the site of PI assessment. A different process based computer model

such as SWAT can be used to simulate the independent set of runoff data and can be used in the weighting factors calculation. Developing a standard and an easy way to simulate independent data for runoff and erosion is needed.

- Separating application timings and application methods to two different components of the KS-PI might improve the P estimation. Therefore, should be included as a separate term in the future PI risk assessment through a justifiable procedure.
- More research is needed to include watersheds from central and western Kansas to widen the applicability of the KS-PI and CPI.
- More research is also needed to investigate and incorporate the other components of the KS-PI which were negligible in our studies such as irrigation erosion, irrigation runoff etc.

5.6 REFERENCES

Benning, J., and C. Wortmann. 2005. Phosphorus indexes in four Midwestern states: An evaluation of the differences and similarities. J. Soil Water Conserv. 60:221-227.

Bolster, C.H., T. Horvath, B.D. Lee, S. Mehilhope, S. Higgins and J.A. Delgado. 2014. Development and testing of a new phosphorus index for Kentucky. J. Soil Water Conserv. 69:183-196.

Bolster, C.H., P.A. Vadas, A.N. Sharpley and J.A. Lory. 2012. Using a phosphorus loss model to evaluate and improve phosphorus indices. J. Environ. Qual. 41:1758-1766.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Dale, A.W., S. Sommer, L. Bohlen, T. Treude, V.J. Bertics, H.W. Bange, O. Pfannkuche, and T. Schorp. 2011. Rates and regulation of nitrogen cycling in seasonally hypoxic sediments during winter (Boknis Eck, SW Baltic Sea): Sensitivity to environmental variables. Estuarine, Coastal and Shelf Science. 2011;95:14–28. doi: 10.1016/j.ecss.2011.05.016.

Davis, R., H. Zhang, J. Schroder, J. Wang, M. Payton and A. Zazulak. 2005. Soil characteristics and phosphorus level effect on phosphorus loss in runoff. J. Environ. Qual. 34:1640-1650.

DeLaune, P., P. Moore, D. Carman, A. Sharpley, B. Haggard and T. Daniel. 2004. Development of a phosphorus index for pastures fertilized with poultry litter - factors affecting phosphorus runoff. J. Environ. Qual. 33:2183-2191.

Drewry, J.J., L.T.H. Newham and R.S.B. Greene. 2011. Index models to evaluate the risk of phosphorus and nitrogen loss at catchment scales. J. Environ. Manage. 92:639-649.

Gburek, W. A., Sharpley, L. Heathwaite and G. Folmar. 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index. J. Environ. Qual. 29:130-144.

Hudnell, H.K. 2010. The state of U.S. freshwater harmful algal blooms assessments, policy and legislation. Toxicon 55:1024-1034.

Kovzelove, C., T. Simpson, and T. Korcak. 2010. Quantification and implications of surplus phosphorus and manure in major animal production eegions of Maryland, Pennsylvania, and Virginiaa. Water Stewardship, Annapolis, MD. http://waterstewardshipinc.org/downloads/P_PAPER_FINAL_2-9-10.pdf (accessed Feb 28. 2016)

Lemunyon, J., and R. Gilbert. 1993. The concept and need for a phosphorus assessment-tool. J. Prod. Agric. 6:483-486.

Nelson, N.O., and A.L. Shober. 2012. Evaluation of phosphorus indices after twenty years of science and development. J. Environ. Qual. 41:1703-1710.

Osmond, D.L., M.L. Cabrera, S.E. Feagley, G.E. Hardee, C.C. Mitchell, P.A. Moore Jr. R.S. Mylavarapu, J.L. Oldham, J.C. Stevens, W.C. Thom, F. Walker and H. Zhang. 2006. Comparing ratings of the southern phosphorus indices. J. Soil Water Conserv. 61:325-337.

Osmond, D. A., Sharpley, C. Bolster, M. Cabrera, S. Feagley, B. Lee, C. Mitchell, R. Mylavarapu, L. Oldham, F. Walker and H. Zhang. 2012. Comparing phosphorus indices from twelve southern U.S. states against monitored phosphorus loads from six prior southern studies. J. Environ. Qual. 41:1741-1749.

Sharpley, A.N., P. Kleinman, R. McDowell, M. Gitau and R. Bryant. 2003. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities (vol 57, pg 425, 2003). J. Soil Water Conserv. 58:127-127.

Sharpley, A.N., D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond and P. Vadas. 2012. Phosphorus indices: Why we need to take stock of how we are doing. J. Environ. Qual. 41:1711-1719.

Sharpley, A.N., L. Bergstrom, H. Aronsson, M. Bechmann, C.H. Bolster, K. Borling, F. Djodjic, H.P. Jarvie, O.F. Schoumans, C. Stamm, K.S. Tonderski, B. Ulen, R. Uusitalo and P.J.A. Withers. 2015. Future agriculture with minimized phosphorus losses to waters: Research needs and direction. Ambio 44:S163-S179.

Sistani, K.R., C.H. Bolster, T.R. Way, H.A. Tobert, D.H. Pote and D.B. Watts. 2010. Influence of poultry litter application methods on the longevity of nutrient and E. coli in runoff from tall fescue pasture. Water Air and Soil Pollution 206:3-12.

Sonmez, O., G.M. Pierzynski, L. Frees, B. Davis, D. Leikam, D.W. Sweeney and K.A. Janssen. 2009. A field-based assessment tool for phosphorus losses in runoff in Kansas. J. Soil Water Conserv. 64:212-222

Torbert, H., T. Daniel, J. Lemunyon and R. Jones. 2002. Relationship of soil test phosphorus and sampling depth to runoff phosphorus in calcareous and noncalcareous soils. J. Environ. Qual. 31:1380-1387.

U.S. Department of Agriculture-Natural Resource Conservation Service. 2012. Revised Universal Soil Loss Equation, Version 2 (RUSLE2) official NRCS database. NRCS, Washington, DC. http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm (accessed 31 Jan 2016.

U.S. Department of Agriculture-Natural Resource Conservation Service, 2012. Title 190-National Instruction (Title 190-NI, Amend . January 2012) Part 302-X.3- Nutrient management policy implementation. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046435.pdf (Accessed 20 Jan. 2016).

U.S. Department of Agriculture-Natural Resource Conservation Service 2015. Soil Survey Division. Official Soil Series Descriptions. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/data/?cid=nrcs142p2_053587 (Accessed 9 Dec 2015)

Table 5.1. RUSLE2 estimated sediment loss by cropping systems and method of P applications

Location/ Watershed†	C-C- NT	C-C- INC	C-C- SSA	CS-NT	CS- INC	CS- SAA	GS-S- NT	GS-S- INC	GS-S- SSA	C-WW-S- NT	C-WW-S- INC	C-WW-S- SSA
Franklin W-4	0.98	4.2	1.9	1.7	5.4	2.4	2.0	5.9	1.7	0.93	1.2	1.2
Franklin W-8	0.64	3.5	1.6	1.2	4.9	2.0	1.4	5.4	2.2	0.66	2.0	0.89
CRAWFORD	0.43	2.0	-	0.62	2.7	-	0.83	3.0	-	0.47	2.5	-

† C-C-NT = Continuous corn no-till; C-C-INC = Continuous corn fertilizer incorporated; CS-NT = Corn-soybean no-till; CS-INC = Corn-soybean fertilizer incorporated; GSS-NT = Grain sorghum-soybean no-till; GSS-INC = Grain sorghum-soybean fertilizer incorporated; CWS-NT = Corn-winter wheat-soybean no-till; CWS-INC = Corn-winter wheat soybean fertilizer incorporated; C-C-SSA = Continuous corn-subsurface application; C-S-SAA = Corn-soybean-subsurface application; GS-S-SSA = Grain sorghum-soybean-subsurface application; C-WW-S-SSA = Corn-winter wheat-soybean-subsurface application.

Table 5.2. Weighting factors calculated using the independently estimated RUSLE2 runoff and sediment loss and with APEX model simulated runoff and RUSLE2 estimated erosion loss

Index weights†	CPI (RQ & Rsed)‡	CPI (AQ & Rsed)§
Intercept	-0.015000	-0.6021
β_1	0.002307	0.000697
β_2	0.000048	0.000131
β_3	0.000074	0.000124
β_4	0.000593	0.002379

†β_1 = weighting factor for STP*Rsed; β_2 = weighting factor for STP*RQ ; β_3 = weighting factor for Prate*RQ; and β_4 = weighting factor for AM*RQ for RUSLE2 estimated runoff and sediment loss
or
†β_1 = weighting factor for STP*Rsed; β_2 = weighting factor for STP*AQ ; β_3 = weighting factor for Prate*AQ; and β_4 = weighting factor for AM*AQ for APEX simulated runoff and sediment loss
(STP = soil test P; RQ = RUSLE2 estimated runoff loss, Rsed = RUSLE2 estimated sediment loss; AQ =AAPEX model simulated runoff)
‡CPI (RQ & Rsed) = Component phosphorus index weighting factors calcaulated using RUSLE2 runoff and sediment loss
§CPI (AQ & Rsed) = Component phosphorus index weighting factors calcaulated using Apex simulated runoff and RUSLE sediment loss

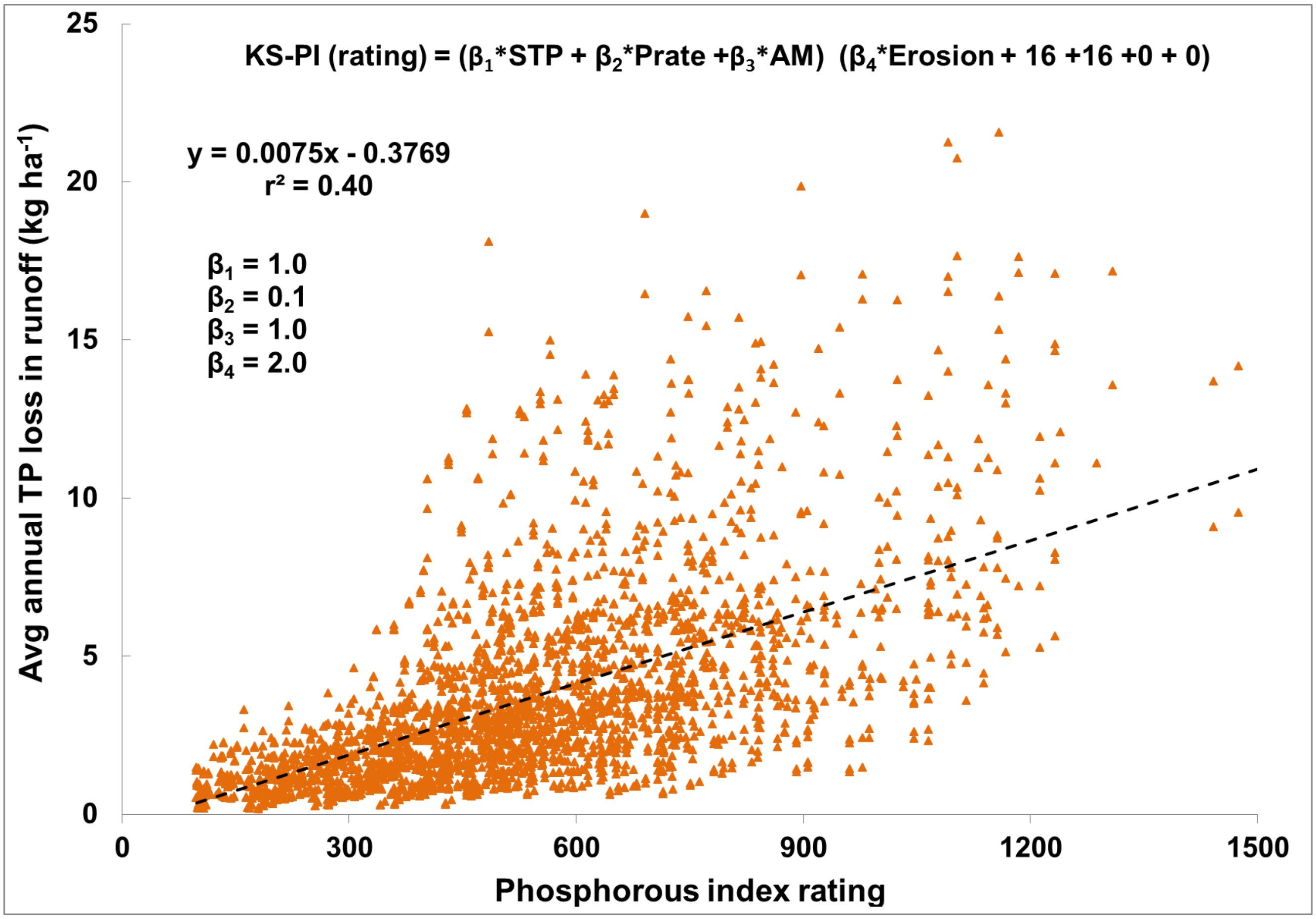


Figure 5.1. The relationship between KS-PI and average annual TP loss (Franklin W-4 and W-8 and Crawford sites; n=2890) generated by location specific calibrated and validated APEX model. The β_1 - β_4 were weighting coefficients.

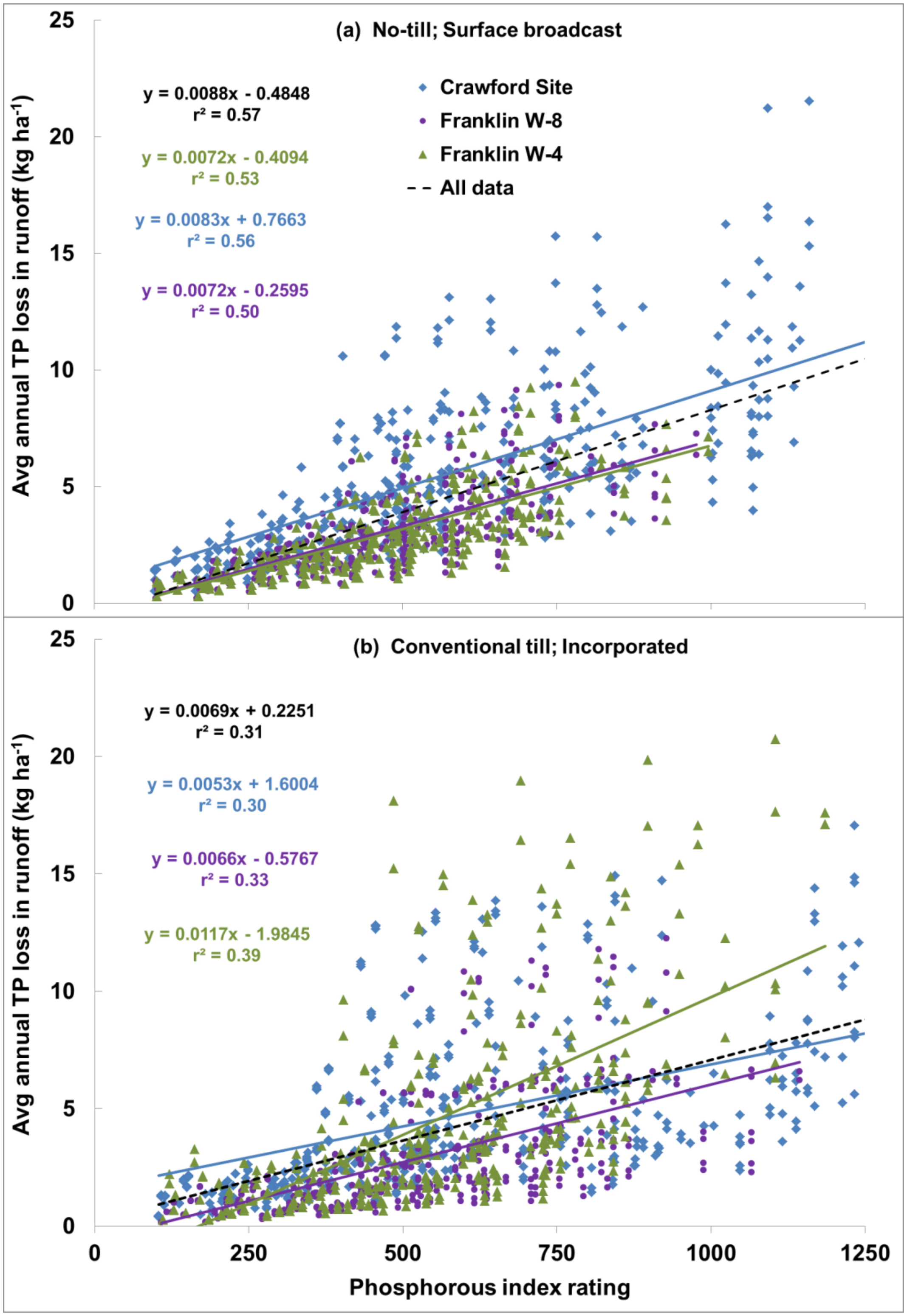


Figure 5.2. The relationship between KS-PI and average annual TP loss (simulated by APEX) for no-till surface broadcast fertilizer and conventional tillage-incorporated fertilizer, all data in each site and by watersheds at both Franklin and Crawford locations.

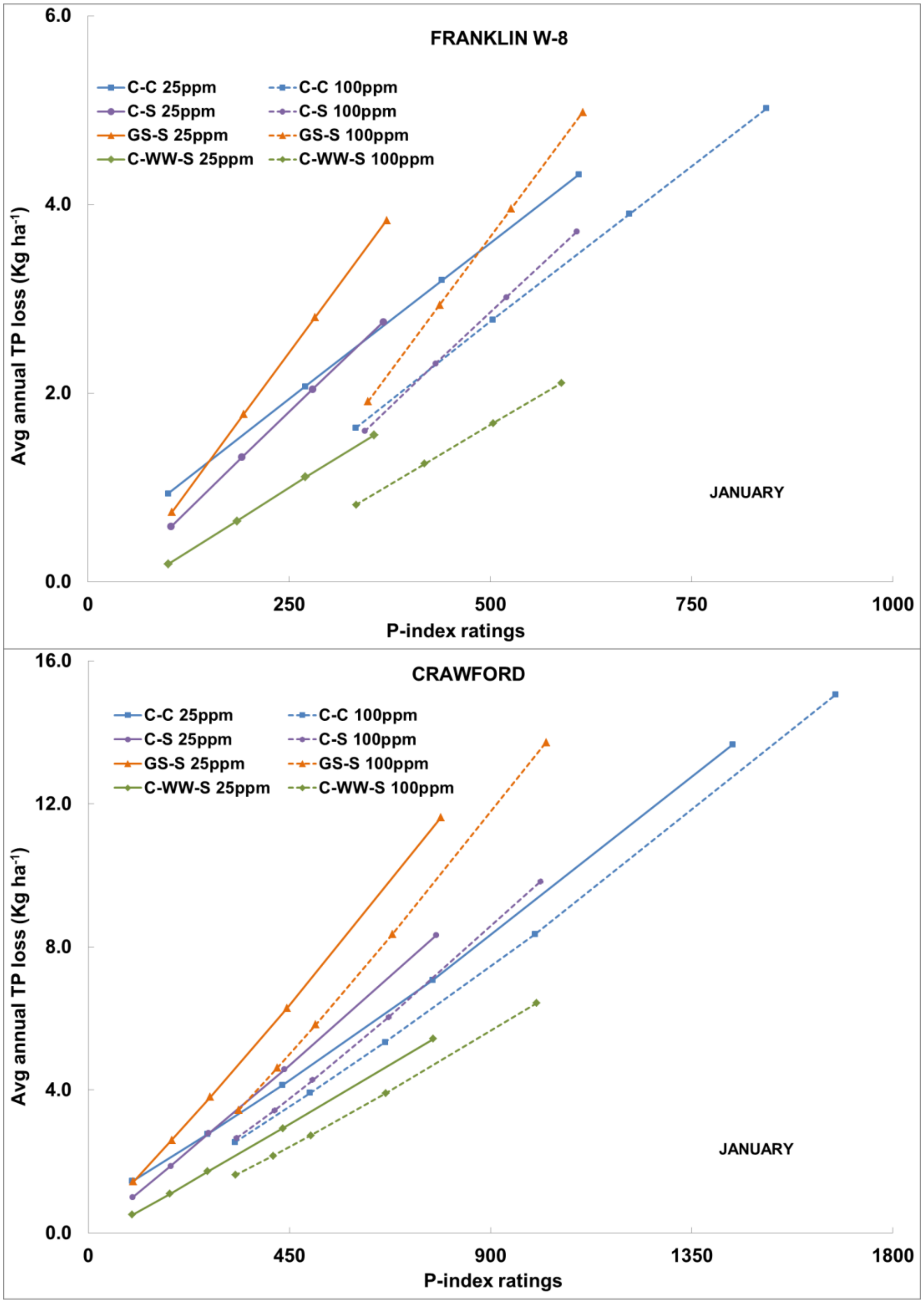


Figure 5.3. Comparison of KS-PI values and average annual TP loss from watersheds with 25 or 100 mg kg^{-1} STP and P applied prior to corn or grain sorghum at 0 to 200 kg ha-1 in January (Jan) with P surface-broadcast with no-tillage (NT) in continuous corn (C-C), corn-soybean (C-S), grain sorghum-soybean (GS-S) or Corn-winter wheat-soybean (C-WW-S) cropping systems.

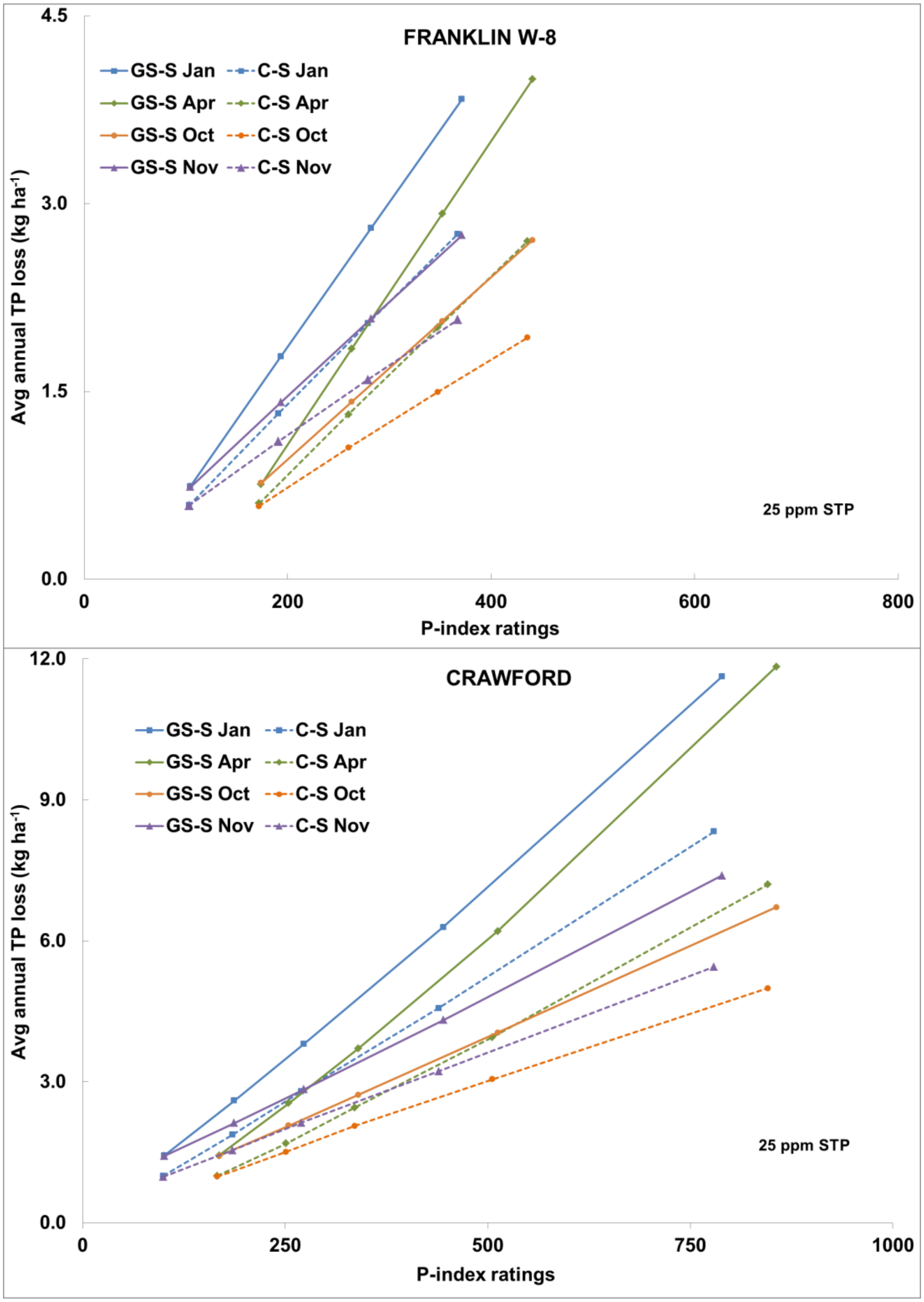


Figure 5.4. Comparison of KS-PI values and average annual TP loss from watersheds with 25 mg kg^{-1} STP and P applied prior to corn or grain sorghum at 0 to 200 kg ha-1 in October (Oct), November (Nov), January (Jan), or April (Apr), with P surface-broadcast with no-tillage (NT) in corn-soybean (C-S) or grain sorghum-soybean (GS-S) cropping systems.

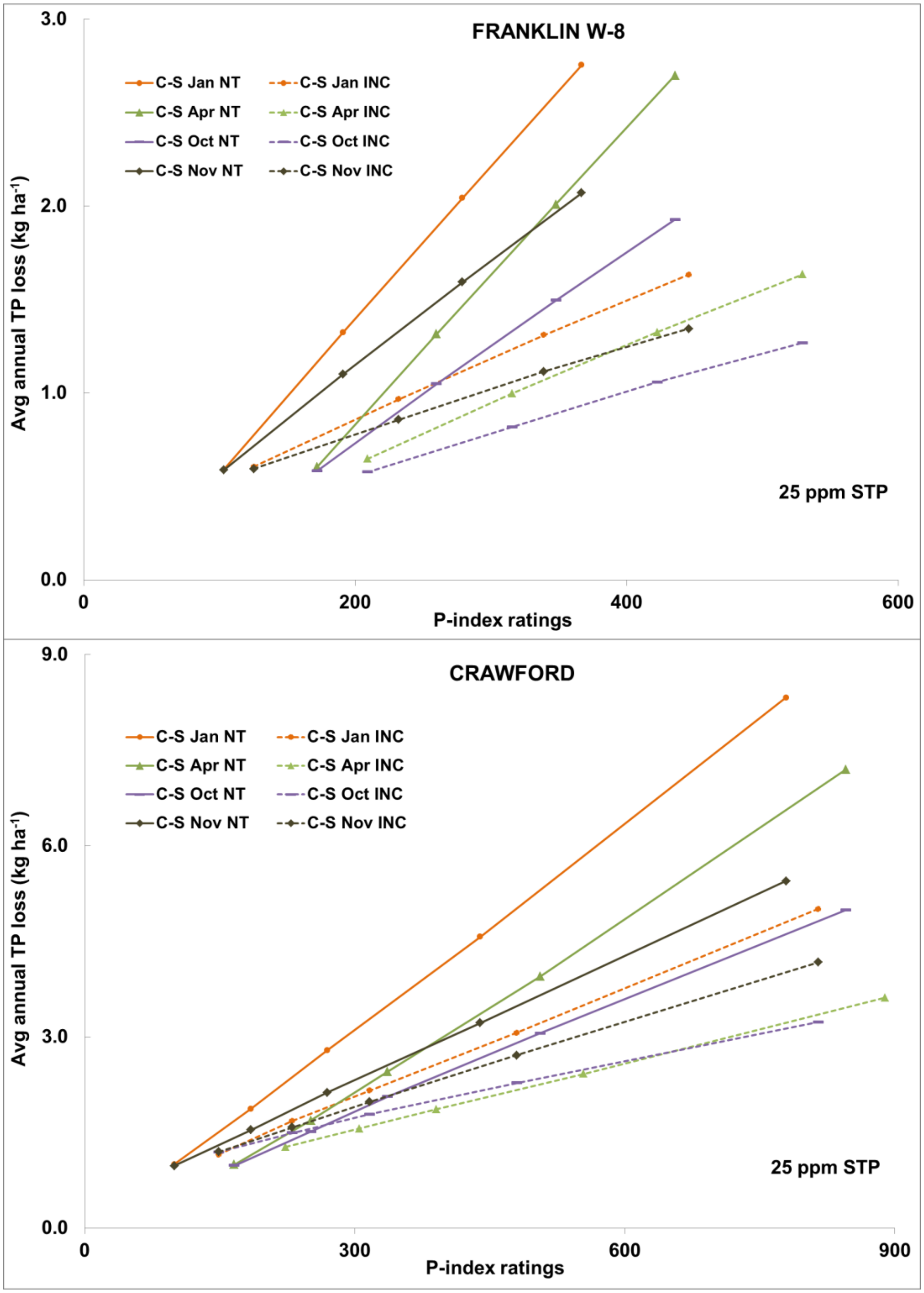


Figure 5.5. Comparison of KS-PI values and average annual TP loss from fields with 25 mg kg^{-1} STP and P applied prior to corn at 0 to 200 kg ha-1 in October (Oct), November (Nov), January (Jan), or April (Apr), with P either surface-broadcast with no-tillage (NT) or incorporated with conventional tillage (INC) in corn-soybean cropping systems.

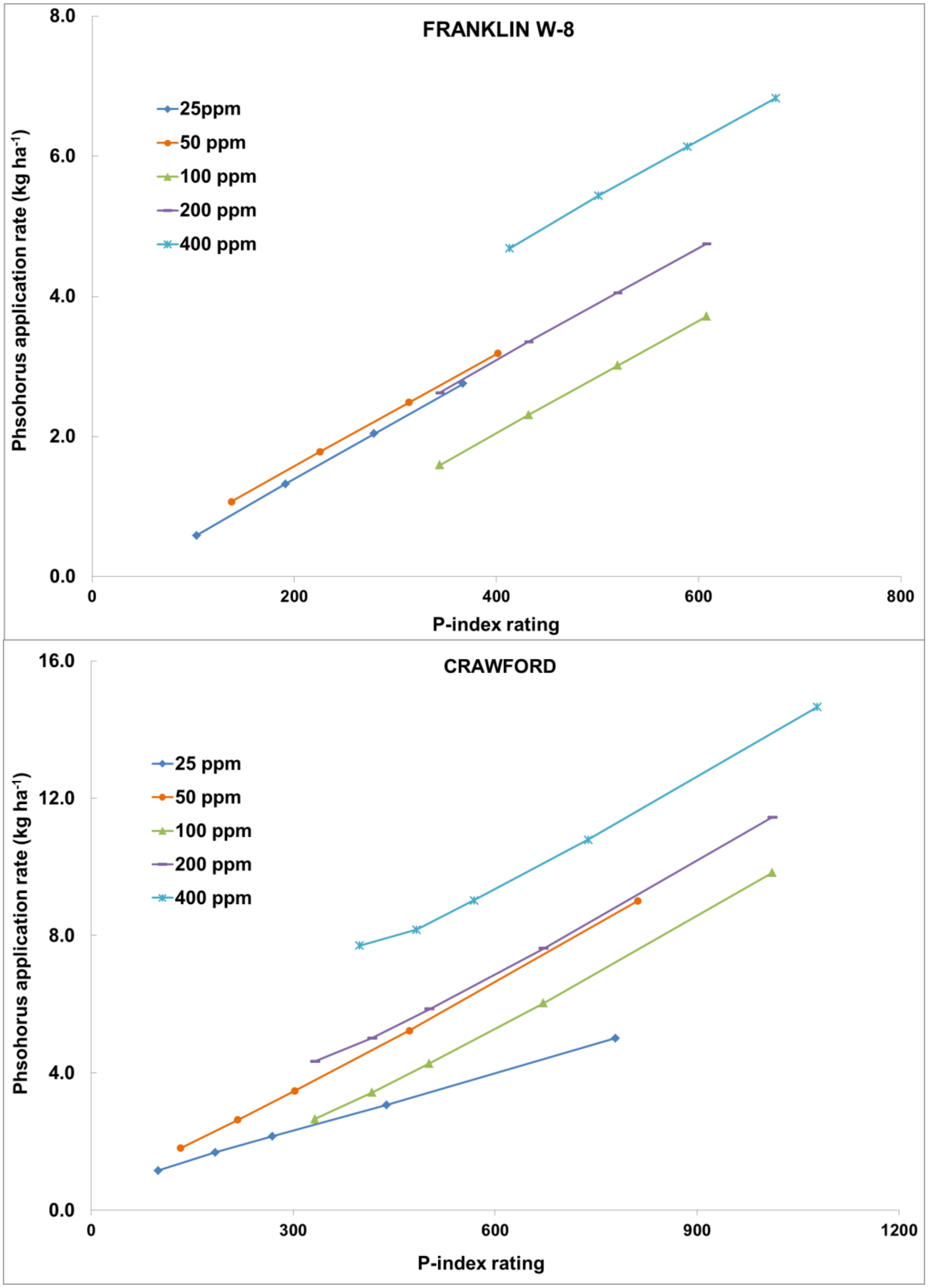


Figure 5.6. Comparison of KS-PI values and average annual TP loss with different STP, same application rates and timing in a no-till surface broadcast fertilizer/poultry litter application in a corn-soybean cropping system

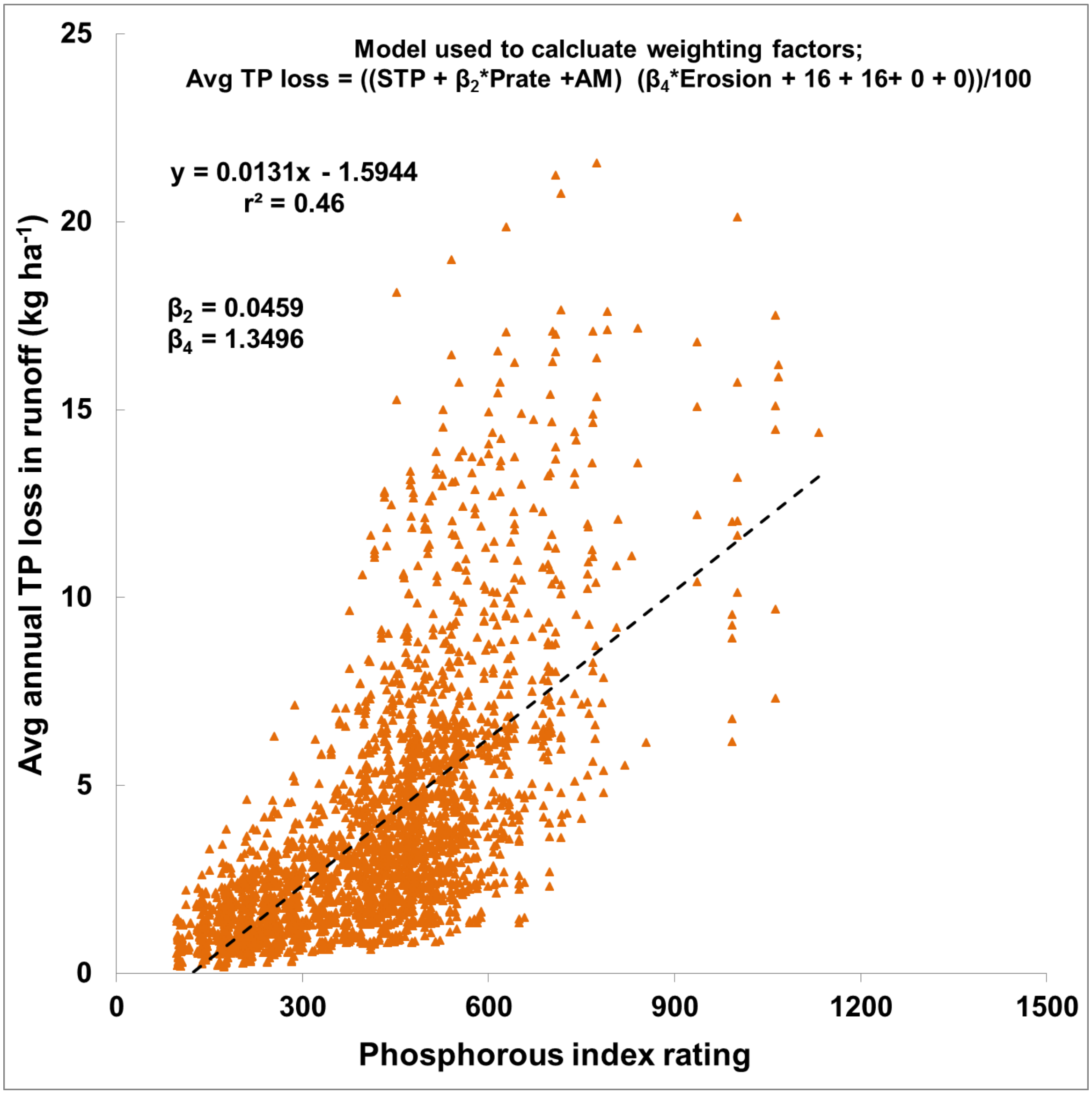


Figure 5.7. The relationship between KS-PI and average annual TP loss (all the watersheds -Franklin 4, 8 and Crawford site; n=2890) generated by location specific calibrated and validated APEX model. The KS-PI index ratings were determined using new weighting factors for STP, and erosion. The β_1-β_3 were weighting coefficients.

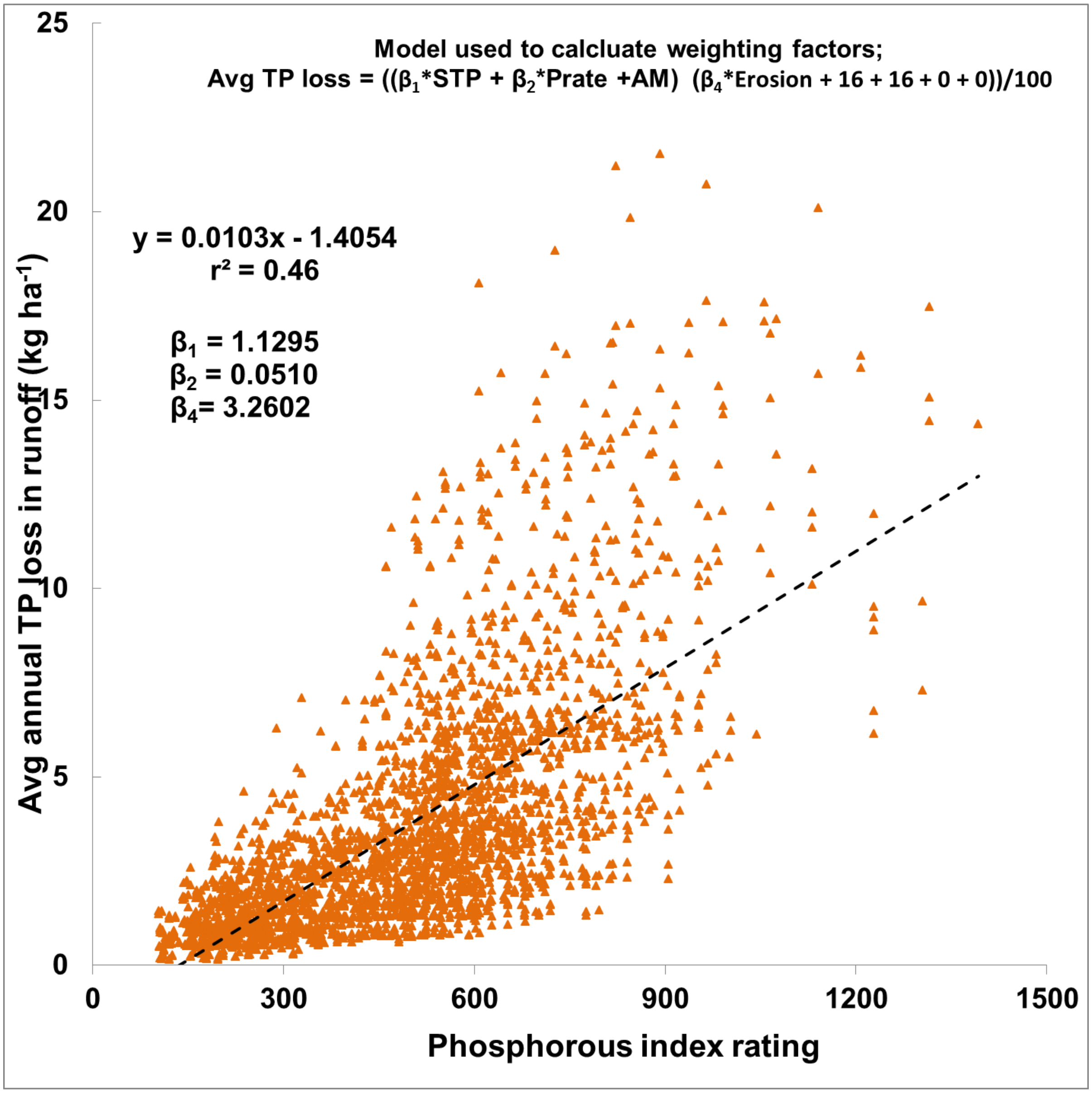


Figure 5.8. The relationship between KS-PI and average annual TP loss (all the watersheds -Franklin 4, 8 and Crawford site; n=2890) generated by location specific calibrated and validated APEX model. The KS-PI index ratings were determined using new weighting factors for STP, P application rates, and erosion loss. The β_1-β_4 were weighting coefficients. However, β_3 was excluded because it was very low.

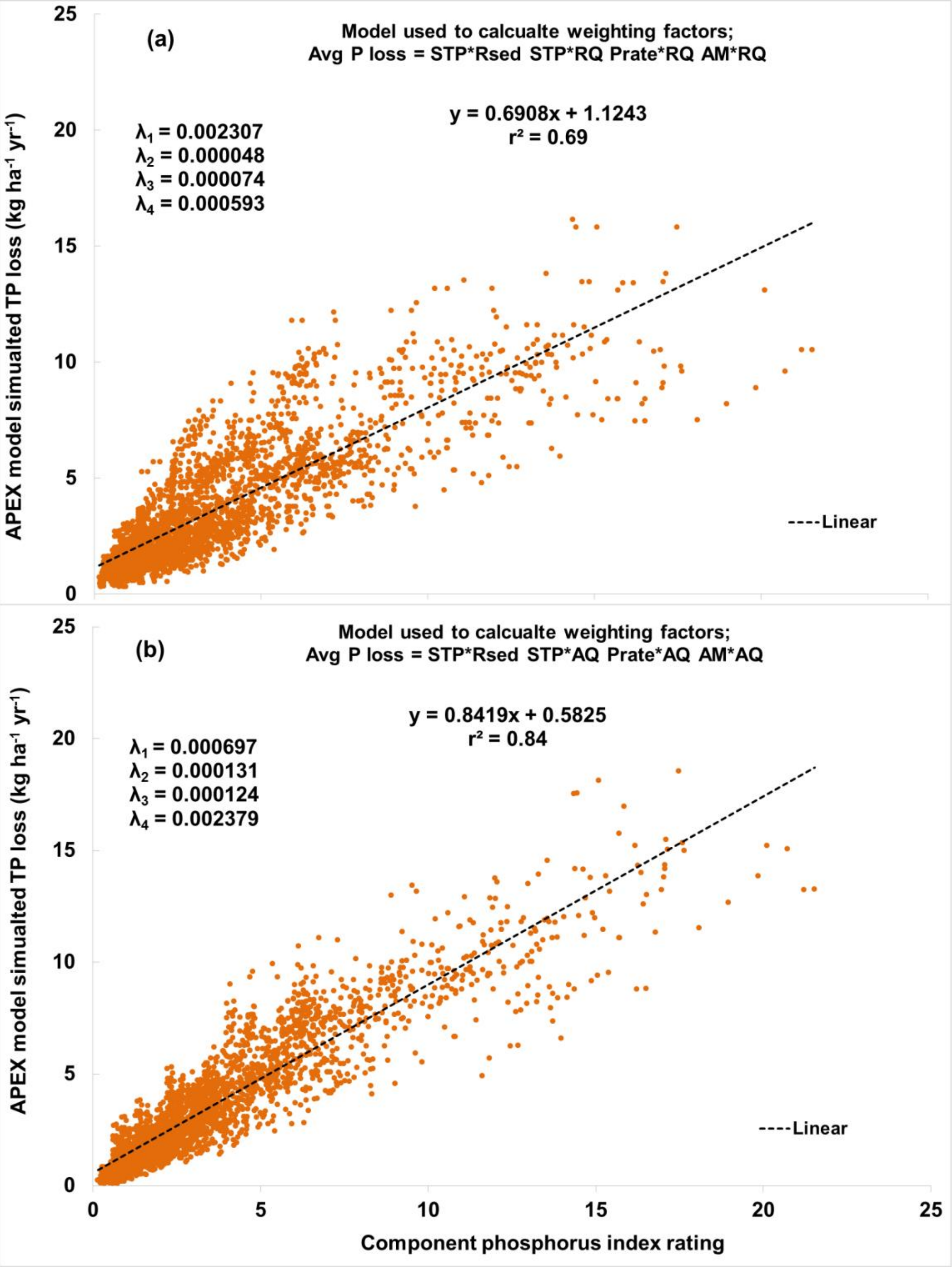


Figure 5.9. The APEX model simulated average annual (n = 2890) and component phosphorus index model (CPI) predicted TP loss. a) with independently estimated RUSLE2 runoff and erosion loss b) with APEX model simulated runoff and RUSLE2 erosion loss. The λ_1-λ_4 were weighting coefficients.

Chapter 6. Phosphorus Transport in Soil: A soil Column Leaching Experiment

ABSTRACT

Phosphorus sub-routines used in the computer model should reflect the processes present in the fields. The mineral P model (3 pools -labile, active, and stable) with linear adsorption isotherm has been used in the APEX model to simulate P loss. However, using linear adsorption isotherm model in the APEX's P sub-routine does not accurately simulate the P leaching from the top soil layer to the next especially when the soil P concentration is very high. The consequences of this would be over prediction of P on the top soil surface layer and in runoff giving incorrect model simulation. Therefore, there is a need to test the three P pool model in the APEX sub-routines with appropriate non-linear adsorption isotherm to better reflect the leaching and P processes in the fields. The goal of this study was to determine the appropriate adsorption isotherm and fit the 3-pool model with advection-dispersion equation using MATLAB. Specific objectives were to i) determine appropriate adsorption isotherm (Linear, Langmuir, Freundlich) with advection-dispersion equation in predicting P movement in soil using MATLAB. ii) test and compare non-linear (Langmuir and Freundlich) adsorption isotherms with a different rate of P applications. Soil sample was collected from a P runoff study in south-east Kansas at 0-7.62 cm in no-till control (no fertilizer/poultry litter) management. The soil was air dried, ground, and wetted to an approximately 15% moisture using a 0.01M $CaCl_2$ solution. The accurate moisture content of the wetted soil was determined by drying it in an oven at 105^{o}C temperature for 24 hours. Then after, the wetted soil was packed in a 10 cm long acrylic clear plastic column. The column was saturated for 16 hours using 0.01M $CaCl_2$ solution with a

very slow flow rate of 0.85 mL hr^{-1}. After 16 hours, the solution was switched to either 30 or 90 mg kg^{-1} P solution and the flow rate of 4.32 or 6.25 mL hr^{-1}. Leachate (1 mL for fast flow and 2 mL for slow flow rate) was collected from the column with an auto-sampler. The collected samples was diluted as required and analyzed for ortho-phosphate. The breakthrough curves were fitted manually and with a numerical model in MATLAB to determine the appropriate P adsorption isotherm. Adsorption isotherm parameters was also determined with batch experiments. The experimental data did not fit well with both the linear and nonlinear (Langmuir and Freundlich) adsorption isotherms. It might be due to complexity of the P loss and transformation processes, P precipitation, iron reduction etc. that might have happened inside the column but was not reflected in the advection-dispersion numerical model. The adsorption isotherm parameters differ with the change in P application and flow rates. Selecting appropriate adsorption isotherm to use in the P sub-routines in the computer models would help to better estimate the P loss and management from agricultural fields.

6.1 INTRODUCTION

In recent years, computer models are used as an alternative to generating P loss datasets and evaluation of the P-indices (Sharpley et al. 2012; Nelson and Shober, 2012). The computer models used in the process of modifying and improving P-indices must accurately predict P loss across a wide range of soil P, runoff, erosion, and field management conditions (Bolster et al. 2012). For this, the P sub-routines used in the computer models should accurately reflect the field condition and basic mechanisms of P reactions in soils. However, most of the computer models only simulate P loss via erosion and surface runoff excluding vertical movement within the soil profile and P leaching loss (Sharpley, 2002; Nelson and Parson, 2005).

The sub-surface P losses can be high enough to cause environmental risk (Sims et al. 1998, Heathwaite and Dils, 2000). Studies have indicated phosphorus (P) accumulation and potential P loss through leaching especially when manure and fertilizer P is applied above crop requirements (Stone et al. 2001; Gachter et al. 2004). Phosphorus accumulation in surface layer also increases the risk of P loss with eroded soil particles, increase the risk of P loss to the sub-surface pathways and decrease the P sorption capacity of soils (Sharpley et al. 1984, Sims et al. 1998; Sharpley et al. 2004; Glaesner et al. 2011). Thus, understanding the basic P chemistry in soils would be helpful to understand and incorporate the basic concept of P soil chemistry in computer models to simulate long-term P loss. This will also help to avoid an unrealistic predictions of excessive P transport in sediment and surface runoff and inaccurate prediction of P loss in the long term (Stone et al. 2001; Nelson and Parsons, 2006).

In addition, the current P-subroutine used in different hydrological models (SWAT, EPIC, and APEX) was developed back in 1980's and thereafter, its parameters were neither refined nor improved to include the advancements made in the area of P research (Vadas and White, 2006; Nelson and Shober, 2012). Therefore, there is a need to oversee the chemical processes of P leaching used in mechanistic models and update the P sub-routines appropriately to strengthen the P loss predictability of computer models before using them to simulate long-term P losses for BMPs evaluation.

6.1.1 Phosphorus adsorption and desorption in soils

The reversible fast adsorption and irreversible slow desorption process occur simultaneously in soils (McGechan and Lewis, 2002). The fast reversible adsorption reaction of inorganic P at surface sites and slow release or desorption of P through the solid phase describe the overall reaction of inorganic P in soils (Barrow, 1981; Van Riemsdijk et al. 1984). Once, the P from soil solution is removed by plants, desorption reactions will occur and P adsorbed to surface sites move to the soil solution P pool (Van der Zee et al. 1987). Therefore, the P adsorption and desorption (interactions between P in solution and soil solid phases) parameters in soils affect the concentration of P in solution and solid phase and are key to determine the P loss in surface runoff, sediment and leaching loss (Sims and Pierzynski, 2005).

The depletion of P in surface sites may be replenished by desorption of slow released P adsorbed to the solid phase but in a slow rate and in the long term (Barrow, 1981). Thus, such slow but long term desorption processes of P from soil solid phase is important and both adsorption and desorption should be considered in P sub-routines used in computer models to better predict P loss in runoff and leaching. Although, these relationships are difficult to define experimentally (due to slow desorption kinetics) but using an appropriate adsorption isotherm that defines the relationship between soil solution P and sorbed P helps to determine the total amount of P available for plant use, P loss in runoff or leaching loss (Koopmans et al. 2002). Therefore, understanding P adsorption and desorption mechanism in soils is important and there is a need to include a realistic adsorption-desorption isotherm in the P sub-routines of computer models to accurately simulate the P loss in runoff and leaching.

The process of adsorption and desorption in soils can be described with non-linear equations relating the solid-phase (sorbed) P to dissolved P (solution) in soils (McGechan and Lewis, 2002) in which soil samples are equilibrated with different concentration of P for different time steps. Freundlich and Langmuir are the two most commonly used nonlinear equations used in field-scale models that describe P leaching.

The general form of Freundlich equation is

$$S = (K_f) \times (C^{\beta}) \qquad [1]$$

The general form of Langmuir equation is

$$S = S_{max} \times [\, K_l C/(1+ K_l C)] \qquad [2]$$

Where S is the quantity of P sorbed (mg Kg^{-1}), K_f is the Freundlich adsorption coefficient, C is the concentration of P in solution (mg L^{-1}), β is fitting coefficients, S_{max} is the maximum amount of P adsorbed to the soil (mg Kg^{-1}), and K_l is the Langmuir adsorption constant which describes the affinity of the soil for P, or adsorption strength.

There are advantages and disadvantages of using these adsorption isotherm equations. The Freundlich equation fits the experimental data very well but the fitting parameters lack to correspond with the theoretical model of surface adsorption. Likewise, the advantage of Langmuir adsorption model is that it describes the theoretical maximum adsorption but may not fit the experimental data. Besides, determining the parameters for these equations in the lab are time, labor intensive and model parameters are soil specific since the soil chemical, and physical properties affect the P adsorption (Nelson and Parsons, 2006). Hence, selecting an appropriate adsorption isotherm is critical to accurately represent the P adsorption-desorption mechanism and in areas where it requires accurate predictions to develop strict guidelines and restrict further P applications (Vadas et al. 2006).

6.1.2 Phosphorus dynamics in the APEX model and P loss

Though, phosphorus is an immobile plant nutrient; downward movement of P through soil profile is slow, some recent studies have pointed the potential risk of P leaching in both clay loam, sandy and with high STP soils (Van Es et al. 2004; Nelson and Parsons, 2005). Excluding P leaching loss component in a process based model like APEX would inaccurately simulate the P loss especially for long terms model simulations. Phosphorus sub-routines used in the computer models should reflect all the soil P processes as that in field conditions and provide an accurate simulation of P distribution in both surface and sub-surface (Sims et al. 1998; Sharpley et al. 2004; Glaesner et al. 2011). However, there are some concerns on the P subroutines used in the APEX model adopted from the EPIC P sub-routines and need further model modifications (Vadas et al. 2006). Therefore, an accurate representation of P leaching in a process-based model like the APEX is significant to simulate the P distribution in the surface soil and consequent loss in runoff.

For instance, the results of our current work with the uncalibrated APEX model showed that the APEX model greatly over predicts P loss for poultry litter treatments. Perhaps, a primary factor contributing to the over-prediction is the approach APEX uses to compute soil solution P concentration. Currently, the APEX model is using a simple linear approach to estimate P leaching from the top soil layer to the next layer based on P concentration in soil and solution. But, P sorption in soils is non-linear and when P concentration in soil increases the relationship becomes non-linear (Koopmans et. al. 2002). Thus, using a linear adsorption model to determine the solution P concentration in the soil will underestimate the solution P concentration. Consequently, the model will underestimate P flux to lower soil horizons and overestimate P concentration in surface soil horizon. This will result in overestimation of P loss with erosion and provide incorrect information to decision makers. This error is particularly important when simulating management practices with high P application, such as when nitrogen (N) rate poultry litter is applied.

In addition, due to use of inappropriate adsorption isotherm and not accounting the P leaching loss, other parameters in the APEX model might have been unnecessarily over parametrized. For instance, parameter 29 is the biological mixing efficiency (due to biota such as earthworms) that redistributes the plant residue, soil, nutrients, pesticides etc. throughout the tillage depth 0.3m (user defined) at the end of the calendar year (December 31st). The biological mixing efficiency was very sensitive for runoff, sediment, and P losses and was set to 0.5 for the no-till system in our study. The biological mixing efficiency of 0.5 means 50 % of the nutrients applied and crop residue was redistributed and mixed to the depth of 0.3. Such a high biological mixing efficiency due to soil biota is not realistic in most of the agricultural fields. Moreover, setting up such high (50%) biological mixing efficiency during the calibration process of the APEX model was perhaps compensating the error that was caused because of not accounting the P loss via leaching to the sub-surface layer and using the inappropriate adsorption isotherm in the model. Therefore, improving the P sub-routines by accounting vertical P movement and using a nonlinear adsorption model is essential to accurately predicting P loss.

In addition, some computer models such as Root Zone Water Quality Model (RZWQM) and DRAINMOD have no soil P sub-routines and simulate hydrology differently. Thus, the findings of this work will also lay out a foundation for future research to include P sub-routine with the advection-dispersion equation with a possibility to be adapted to RZWQM and DRAINMOD models as their P subroutines. The long-term goal of the project was to determine and understand the P-transport with advection-dispersion equation. The objective of the study was to determine appropriate P adsorption isotherm with advection-dispersion equation using experimental data from column leaching experiment.

6.2 MATERIALS and METHODS

6.2.1 Governing equation used in the MATLAB

The proposed governing equation (advection-dispersion), discretization scheme, derivation of m-linear equations and the boundary conditions to fit the different adsorption-isotherms are explained below.

In the presence of steady-state, unit-gradient water flow, the advection-dispersion equation for reactive solutes used in this study was

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{\theta}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} \qquad [3]$$

where C is the solute concentration in the liquid phase [M L^{-3}], ρ_b is the bulk density [M L^{-3}], θ is the volumetric water content [L^3 L^{-3}], S is the concentration of adsorbed solute [M M^{-1}], D is the effective dispersion coefficient [L^2 T^{-1}], v is the average pore-water velocity [L T^{-1}], z is the space coordinate [L], and t is time [T]. By making use of the chain rule, this expression can be written in the form

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{\theta}\frac{\partial S}{\partial C}\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} \qquad [4]$$

Or $R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z}$ [5]

where the retardation factor *R* [-] is defined as

$$R = 1 + \frac{\rho_b}{\theta}\frac{\partial S}{\partial C} \qquad [6]$$

6.2.1.1 Adsorption isotherms

Linear adsorption isotherm equation has been widely used but the process of adsorption and desorption in soils can be better described with non-linear equations relating the solid-phase (sorbed) P to dissolved P (solution) in soils (McGechan and Lewis, 2002) in which soil samples are equilibrated with different concentration of P for different time steps. Beside linear adsorption isotherm, Freundlich and Langmuir are the two most commonly used nonlinear equations used in field scale models that describe P leaching.

The general form of Linear equation is

$$S = K_d C \qquad [7]$$

Where K_d is the distribution coefficient (m^3 Kg^{-1}) or slope of the adsorption isotherm. Differentiating this linear equation with respect to time

$$\frac{\partial S}{\partial t} = K_d \frac{\partial C}{\partial t}$$

$$R = 1 + \frac{\rho_b K_d}{\theta} \qquad [8]$$

The retardation factor in this case is not a function of the solute concentration, so equation [5] is a linear partial differential equation.

For solutes that exhibit nonlinear, equilibrium sorption, the Freundlich and Langmuir isotherms are the two most commonly used adsorption isotherms. The Freundlich isotherm is written as

The general form of Freundlich adsorption isotherm equation is

$$S = K_f\, C^{\beta} \qquad [9]$$

Where S is the quantity of P sorbed in mg kg^{-1}, C is the concentration of P in solution in mg L^{-1}, K_f is the Freundlich adsorption coefficient and β is fitting coefficients.

Differentiating equation [7] with respect to time we get

$$\frac{\partial S}{\partial t} = K^{f} \frac{\partial C^{\beta}}{\partial t}$$

Or $\dfrac{\partial S}{\partial t} = K^{f} \beta C^{\beta-1} \dfrac{\partial c}{\partial t}$

Therefore, for the Freundlich adsorption isotherm the retardation factor in the governing (advection-dispersion) equation was

$$R = 1 + \frac{\rho_b K_f \beta C^{\beta-1}}{\theta} \qquad [10]$$

The general form of Langmuir adsorption isotherm equation is

$$S = S_{max}\, [\, K_l\, C/(1+ K_l C)] \qquad [11]$$

Where S_{max} is the maximum amount of P adsorbed to the soil (mg kg^{-1}), C is the concentration of P in solution in mg L^{-1}, and K_l is the Langmuir adsorption constant which describes the affinity of the soil for P, or adsorption strength.

Differentiating equation [9] with respect to time and concentration we get

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial c}\left[S_{\max} \frac{K_l C}{(1+K_l C)} \right] \frac{\partial c}{\partial t} \quad \text{or,}$$

$$\frac{\partial S}{\partial t} = \left[S_{\max} \frac{(1+K_l C)K_l - K_l C K_l)}{(1+K_l C)^2} \right] \frac{\partial c}{\partial t} \quad \text{or,}$$

$$\frac{\partial S}{\partial t}=\left[\frac{K_l S_{\max})}{(1+K_l C)^2}\right]\frac{\partial c}{\partial t} \qquad [12]$$

Therefore, for the Langmuir adsorption isotherm the retardation factor in the governing (advection-dispersion) equation was

$$R=1+\frac{\rho_{\mathrm{b}} K_l S_{\max}}{\theta(1+K_l C)^2} \qquad [13]$$

It is evident from equation [10] and [13] that the retardation factor is a function of the solute concentration *C* for both the Freundlich and Langmuir isotherms. Thus, for both of these isotherms, equation [5] is a *non-linear* partial differential equation.

6.2.1.2 Difference approximations

A numerical model with convection-dispersion equation was developed to test the adsorption isotherms in MATLAB. The linear adsorption isotherm with the numerical model was tested with analytical solution as described in the upcoming section. However, the non-linear adsorption isotherms were not tested due to lack of analytical solution. The information in this section was adapted from Dr. Klutenberg's AGRON 915 class notes with permission (Dr. Klutenberg, personal communication, 2016).

The backwards implicit approximation of equation [5] is obtained by using an $O(\Delta t)$ backward difference approximation for the time derivative and $O[(\Delta z)^2)]$ central difference approximations for the first and second space derivatives. When these two approximations are centered at the point (z_i, t_{n+1}),

$$R_i^{n+1}\left(\frac{C_i^{n+1}-C_i^n}{\Delta t}\right)=D\frac{C_{i+1}^{n+1}-2C_i^{n+1}+C_{i-1}^{n+1}}{(\Delta z)^2}-v\frac{C_{i+1}^{n+1}-C_{i-1}^{n+1}}{2\Delta z} \qquad [14]$$

Owing to the fact that this approximation is centered at (z_i, t_{n+1}), the retardation factor is evaluated at time t_{n+1} and is therefore a function of C^{n+1}. This makes the backward implicit approximation nonlinear. Explicit linearization of this approximation is achieved by simply evaluating *R* at the previous time step, i.e. at time t_n. Thus, the backwards implicit approximation with explicit linearization is

$$R_i^n \left(\frac{C_i^{n+1} - C_i^n}{\Delta t} \right) = D \frac{C_{i+1}^{n+1} - 2C_i^{n+1} + C_{i-1}^{n+1}}{(\Delta z)^2} - v \frac{C_{i+1}^{n+1} - C_{i-1}^{n+1}}{2\Delta z} \qquad [15]$$

and it follows that

$$-(a_i + b_i)C_{i-1}^{n+1} + (1 + 2a_i)C_i^{n+1} - (a_i - b_i)C_{i+1}^{n+1} = C_i^n \qquad [16]$$

where a_i and b_i are defined as

$$a_i = \frac{(\Delta t)D}{(\Delta z)^2 R_i^n}\,; \quad b_i = \frac{(\Delta t)v}{2(\Delta z)R_i^n}\,; \quad i = 1, 2, \ldots, m$$

[17]

The truncation error for the backwards implicit approximation also is of $O[\Delta t + (\Delta z)^2]$.

To solve this problem with a steady state unit gradient situation the boundary conditions were set as follows

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z}\,; \quad z > 0, t > 0 \qquad [18]$$

$$C(0,t) = C_{\mathrm{a}}\,; \quad t > 0 \qquad [19]$$

$$\lim_{z\to\infty}\frac{\partial C(z,t)}{\partial z}=0\,; \quad t>0 \qquad [20]$$

$$C(z,0)=0\,; \quad z>0 \qquad [21]$$

where it is understood that $C(z,t)$ represents flux concentrations rather than resident concentrations. The solution of this problem was used to determine $C(L,t)$, the flux concentration at *z* = *L*. The finite difference method cannot be used to obtain a solution for the entire semi-infinite domain $0<z<\infty$. Nevertheless, accurate values of $C(L,t)$ can be obtained if the numerical solution of equation [18] – [21] is obtained for a domain having a length substantially larger than *L*. In other words, if x L_{d} was used to represent the length of this domain, accurate values of $C(L,t)$ can be obtained if L_{d} was chosen so that $L_{\text{d}} >> L$. More specifically, it is necessary to use a value for L_{d} large enough that the effect of the boundary condition at *z* = L_{d} does not propagate back to depth *z* = *L*. In practice, it is easiest to ensure this by choosing L_{d} large enough that the invading solute front does not arrive at depth *z* = L_{d}.

Therefore, for Dirichlet condition at *z* = 0 and a Neumann condition at *z* = L_{d}, the mesh used with *m* + 1 equally spaced nodes in the *z* direction. The indexing for z_i is $i=0,1,2,\ldots,m$, and the mesh is positioned so that the nodes (z_0,t_n) lie on the line *z* = 0 and the nodes (z_m,t_n) lie in the line *z* = L_{d}. Thus, $z_0=0$ and $z_m=L_{\text{d}}$, and the node spacing in the *z* direction is $\Delta z=(z_m-z_0)/m$ or $\Delta z=L_{\text{d}}/m$. In the *t* direction, the mesh consists of *N* + 1 equally spaced nodes and the indexing for t_n is $n=1,2,3,\ldots,N+1$, where *N* is number of time steps. The mesh is positioned so that the nodes (z_i,t_1) lie on the line *t* = 0 (i.e. $t_1=0$) and the nodes

(z_i, t_{N+1}) correspond to the final time at which the solution is to be evaluated based on the node diagram (Figure 6.1).

To formulate the backwards implicit approximation for this problem, with equation [16]

$$
\begin{aligned}
-(a_1+b_1)C_0^{n+1}+(1+2a_1)C_1^{n+1}-(a_1-b_1)C_2^{n+1} &= C_1^n \\
-(a_i+b_i)C_{i-1}^{n+1}+(1+2a_i)C_i^{n+1}-(a_i-b_i)C_{i+1}^{n+1} &= C_i^n\,; \quad i=2,3,\ldots,m-1 \\
-(a_m+b_m)C_{m-1}^{n+1}+(1+2a_m)C_m^{n+1}-(a_m-b_m)C_{m+1}^{n+1} &= C_m^n
\end{aligned}
\qquad [22]
$$

where C_{m+1}^{n+1} corresponds to the fictitious node (z_{m+1}, t_{n+1}) that lies outside the problem domain. For this approximation, satisfying the boundary conditions requires that $C_0^{n+1} = C_\mathrm{a}$ and $C_{m+1}^{n+1} = C_{m-1}^{n+1}$. Upon substituting these results into Eq. [22], C_{m+1}^{n+1} is eliminated and the *m* linear equations to be solved at each time step are

$$
\begin{aligned}
(1+2a_1)C_1^{n+1}-(a_1-b_1)C_2^{n+1} &= C_1^n+(a_1+b_1)C_\mathrm{a} \\
-(a_i+b_i)C_{i-1}^{n+1}+(1+2a_i)C_i^{n+1}-(a_i-b_i)C_{i+1}^{n+1} &= C_i^n\,; \quad i=2,3,\ldots,m-1 \\
-2a_mC_{m-1}^{n+1}+(1+2a_m)C_m^{n+1} &= C_m^n
\end{aligned}
\qquad [23]
$$

with the coefficients a_i and b_i from equation [17].

For the backwards implicit approximations, the retardation factor for linear, equilibrium sorption is

$$
R_i^n = 1+\frac{\rho_\mathrm{b}K_\mathrm{d}}{\theta}\,; \quad i=1,2,\ldots,m \qquad [24]
$$

whereas the retardation factors for the Freundlich and Langmuir isotherms are

$$R_i^n = 1 + \frac{\rho_b K_f \beta (C_i^n)^{\beta-1}}{\theta}; \quad i = 1, 2, \ldots, m \tag{25}$$

and

$$R_i^n = 1 + \frac{\rho_b k S_{\max}}{\theta(1 + kC_i^n)^2}; \quad i = 1, 2, \ldots, m \tag{26}$$

The initial condition requires that

$$C_i^1 = 0; \quad i = 1, 2, \ldots, m \tag{27}$$

and a solution is obtained by evaluating equation [22] or [23] with the coefficients in equation [17] for $n = 1, 2, 3, \ldots, N$.

6.2.1.3 Analytical solution to test the linear adsorption model

The problem defined by equations [16] to [19] was solved using alternative analytical solution replacing the boundary condition at z = L by

$$\lim \frac{\partial J(z,t)}{\partial z} = 0; t > 0$$

This will consider the solute transport in the semi-finite domain 0<z<∞, however it will provide a good approximation of solution to the original problem, considering L is large enough and the solute front will not reach the boundary. The solution of this problem is

$$C(z,t) = \left\{ \frac{1}{2} erfc\left(\frac{Rz - vt}{\sqrt{4DRt}} \right) + \sqrt{\frac{v^2 t}{\pi DR}} \exp\left[\frac{(Rz - vt)^2}{4DRt} \right] \right\} \tag{28}$$

$$- \frac{1}{2}\left(1 + \frac{vz}{D} + \frac{v^2 t}{DR} \right) \exp\left[- \frac{(Rz - vt)^2}{4DRt} \right] erfc\left(\frac{Rz - vt}{\sqrt{4DRt}} \right)$$

The script to solve the above-mentioned conditions was written in MATLAB (Appendix F). The erfcx(x) function is available as a MATLAB's built-in function erfcx.

6.2.2 Batch experiment

Soil samples were shaken for 24 hours with different P concentration, centrifuged and supernatant are analyzed for ortho-phosphate. The difference between the initial solution P concentration and the final represents the quantity of P adsorbed in soil. The procedure follows outline by Gratez and Nair (2009) which was based on Nair et al. (1984). The detail procedure of batch experiment was outlined in Appendix F.

The maximum amount of P adsorbed (S_{max}) to the soil (mg kg^{-1}), langmuir adsorption constant (K_l) which describes the affinity of the soil for P, the Freundlich adsorption coefficient (K_f) and the fitting coefficient (β) were determined using excel spreadsheet developed by Bolster and Hornberger (2007). These parameters were used to initialize the breakthrough curve fitting in MATLAB.

6.2.3 Procedure for column leaching experiment

6.2.3.1 Soil sample preparation

Soil from Crawford runoff study site, watershed 105 (control - without any fertilizer or manure applications) was collected on 03/10/2014 for the column leaching experiment. The bulk soil sample was collected across the watershed at 0-7.62 cm depth using hand-held soil probe. The soil samples were air-dried and ground to 2 mm sieve. The soil (one batch = 0.426 kg and was enough to pack two column) was weighted and approximately 68.0 mL (16 % moisture content target) of 0.01 M $CaCl_2$ deionized water was added with the sprayer to moisten the soil.

The soil was spread on a plastic sheet uniformly, the 0.01 M $CaCl_2$ deionized water was added slowly, and the soil was mixed thoroughly in each addition until all the targeted water was added. The weight of the 0.01M $CaCl_2$ deionized water and the sprayer was measured frequently to make sure, only the desired amount was added. A sub-sample of few grams of the wet soil was then oven dried for 24 hours in 105^0C temperature. The water content of the wet soil was calculated by the difference in dry and wet soil after 24 hours of oven dry. The whole procedure of soil wetting was replicated four times as one batch of 0.426 kg soil was only used for one time due to limitation of the auto samplers. The pore space, volumetric water content, pore water velocity, flux, discharge, and pore volume that was used in the experiment was determined as follows.

Pore space $(f) = 1 - \frac{\rho_b}{\rho_s}$ [29]

Where f= porosity, ρ_b = bulk density g cm^{-3}, ρ_s = particle density g cm^{-3} and assumed to be 2.65. Assuming porosity (f) = volumetric water content (θ).

The volumetric content water (θ) dimension less, is defined as follows

$$\theta = 1 - \frac{\theta_g \rho_b}{\rho_w} \quad [30]$$

Where θ_g = gravimetric water content, and calculated as difference between wet soil and oven dry soil (after 24 hours at 105^oC) divided by the oven dry soil. ρ_w = density of water

The volume of air in the column was calculated as

(a) = (f – θ) [31]

So the volume of water required to fill the air space of the column was calculated as volume of column x volume of air (a)

where volume of column is defined as $v = \pi r^2 h;$ r the radius and h the height of the column

Likewise, the flux (q) ms^{-1} was calculated as

q = v x θ [32]

where v = pore water velocity and θ = volumetric content water

The discharge from the column (Q) was calculated as (Q) = q x A

[33]

Where q = flux and A = Area of the column and calculated as $A = \pi r^2$

Therefore, one pore volume of the column was defined as (PV) = (θ) x (v)

where (θ) = (f) = volumetric water content and (v) = volume of the column

6.2.4 Procedure to pack the column (10 cm long acrylic clear plastic) and sample collection

The targeted bulk density was 1.40 for the soil leaching experiment. The column was packed in 2 cm increment. The mass of wet soil required to pack each 2 cm increment of column was calculated as

[(Desired bulk density) x (volume of the 2 cm length)] x

[1 + (gravimetric water content θ_g)] [34]

The amount of soil determined with equation 8 (approximately 15.60 g) for 2 cm increment was added into the column. The soil was then uniformly spread and gently compacted with a small knife. Finally, soil was compacted using the compactor that fits inside the column (Appendix F). The top of the compacted soil layer was disturbed gently with a small metal rod before adding same amount of weighted soil for second increment. The process was repeated for 5 times (10 cm height). The column was then closed with two plates in each ends and tubing were added as necessary.

6.2.5 Bromide breakthrough curve

The column was saturated for 16 hours using 0.01M $CaCl_2$ solution with a very slow flow rate of 0.85 mL hr^{-1} and flushed with 1 mg kg^{-1} of potassium bromide (Kbr) for 3-pore volume (PV) (1 PV =23.06 ml). One (1) ml of effluent (sample) was collected in each collection tube using an auto sampler. After 3-PV the solution was switched to 10 mg kg^{-1} potassium bromide. The experiment was run for another 3-PV and 1 mL sample each was collected using the auto sampler. Three different pore water velocities of 0.21, 0.42, and 1.25 cm hr^{-1} were selected and each flow rate was replicated twice. The bromide concentration in the effluent was analyzed using the Lachat QuickChem 8500 (method, 10-135-21-2-B) and was fitted for breakthrough curve using MATLAB.

6.2.6 Phosphorus breakthrough curve

The column was saturated for 16 hours using 0.01M $CaCl_2$ solution with a very slow flow rate of 0.85 mL hr^{-1}. After 16 hours, the solution was switched to either 30 or 90 mg kg^{-1} P solution. Potassium phosphate monobasic (KH_2PO_4) was dissolved in 0.01M $CaCl_2$ solution and used as a source of P in the experiment. Enough KH_2PO_4 solution was prepared in a single batch for the whole experiment. The P solution was bubbled with oxygen for approximately 3-5 minutes before stored in a 140 ml syringe fitted with a tube and a male luer-lock to ensure airtight.

The flow rate was then adjusted based on a slow flow rate (pore water velocity of 1.87 cm hr^{-1}) or fast flow rate (pore water velocity of 2.70 cm hr^{-1}) (Table 1). The P solution in the column was passed from the bottom of the column upwards and the effluent was collected from the top of the column with an auto-sampler using capped plastic vials (Appendix F).

Approximately 3-meter long tube (Tygon 0.3175 cm (1/8 inch) internal diameter) was fitted to collect 6 mL of effluent to avoid the atmospheric oxygen contact. Three samples (6 mL each) were taken to analyze for iron (Fe^{+2}) reduction test throughout the experiment. The first was taken immediately after switching the solution, 2nd was taken after 3-PV and the third was taken at the end of the experiment. Iron reduction was measured using UV-spectrophotometer and the procedure used in this experiment was based on Greenberg, et al. (1992) with some modifications (APPENDIX F: Section 2).

Several pore (24-30 PV for 30 mg kg^{-1} P and 9-12 PV for 90 mg kg^{-1} P) volume of solution was passed through the column to ensure the P breakthrough. The samples (2 mL in slow flow rate and 1 mL in fast flow rate) were collected in 15 mL plastic vials using an auto-sampler. The auto sampler was timed in a way so that desired amount of sample was collected in each vial. The collected samples were refrigerated, diluted as needed using an auto diluter (Microlab 600 series) and analyzed for ortho-phosphorus using Lachat quickchem 8500 (method, 10-115-01-1-A). Each flow rate and P concentration were replicated twice. So eight columns were used for the entire experiment.

The experimental data were fitted for P breakthrough curves using excel spreadsheet in two different ways. Firstly using the adsorption isotherm parameters determined with the batch experiment and secondly by manually adjusting the adsorption isotherm parameters so that the initial breakthrough of the numerical model fitted well with the experimental breakthrough data.

6.3 RESULTS AND DISCUSSION

6.3.1 Batch experiment

The batch experiment data was fitted in the excel spreadsheet and the adsorption isotherm parameters were estimated (Figure 6.2a, and b). The estimated values Langmuir and Freundlich were S_{max} = 198.5 mg kg^{-1}; K_l = 0.178; K_f = 62.33; and β = 0.271. The linear adsorption distribution coefficient (k_d = 2.4358) was estimated using the linear model in excel spreadsheet (Figure 6.3.). The adsorption isotherm parameters were used to initialize the MATLAB model run and compare the P break-through curves.

6.3.2 Bromide breakthrough curve

The measured bromide break through curve data were fitted using analytical solution A1 of van Genuchten and Alves (1982). The bromide column leaching experimental data were used to determine dispersion coefficients D (Figures 6.4a, b, c, d, e, and f). The dispersion coefficients were then used to determine the dispersivity (λ) using equation [35] and assuming the relationship between pore water velocity and dispersion coefficient was linear (Horton and Jury, 1984). Therefore, the average value of λ (0.10) was used.

$$D = \lambda V^n \qquad [35]$$

where v = pore water velocity.

6.3.3 Iron Reduction Analysis

Iron reduction was a common problem in saturated column study (Dr. Ganga Hettiarachchi, personal communication 2015) and was noticed during the course of this study (Appendix F). To overcome the problem we oxygenated the P solution that was used in this experiment using a pressurized oxygen tank (85% oxygen) and a regulator. The oxygenating of P solution helped to minimized iron reduction (Table 6.2. and Appendix F). Therefore, we recommend oxygenating the solution at least for 3-5 minutes before using it. Literally, once oxygenated the solution can be stored in an airtight syringe for more than 24 hours if it is airtight. The tubing and male luer-lock was used to ensure airtight. However, we found that oxygenating the solution every time when changing the syringe reduced iron reduction compared to the when it was oxygenated and stored. The results indicated that in the slow flow rate even after oxygenating there was presence of some reduced iron (Table 6. 2.).

6.3.4 Phosphorus breakthrough curve and the adsorption isotherms comparison with advection-dispersion model using MATLAB

6.3.4.1 Use of analytical solution to test linear adsorption isotherms model

The numerical model developed was tested with the analytical solution from equation [28] for the non-linear adsorption model. Results from the backward implicit approximation-numerical model (open circles) and analytical solution (red lines) showed a very good agreement for both the flow rates and P concentrations (Figures, 6.5a, b, c, and d). However, the model with non-linear adsorption isotherms were not tested due to lack of analytical solution and were assumed to be working well based on the Peclet number (Pe) and Courant number (C_r) calculated during each model runs. The P_e number should be less than 2 and Cr number should be less than 1 for non-reactive solutes as recommended by Huyakorn and Pinder, (1983). The P_e and C_r were calculated using equation [36] and [37], and met those criteria's throughout the study.

$$P_e = \frac{v\Delta z}{D} < 2 \quad [36]$$

$$C_r = \frac{v\Delta t}{\Delta z} < 1 \quad [37]$$

where, Δz is space increment (cm), Δt is time increment (day), v is pore water velocity (cm day^{-1}) and D is the dispersion coefficient.

6.3.4.2 Breakthrough curve with adsorption isotherm parameters developed using batch experiment

After the numerical model was tested for both the non-linear and linear adsorption isotherms with analytical solution, Pe, and Cr, it was used to develop breakthrough curves using adsorption parameters estimated with batch experiment. The advection-dispersion backward implicit approximation model simulated results for linear adsorption isotherms indicated that the breakthrough occurs earlier than the experimental data (Figures 6.5a, b, c, and d). In contrast to this, the non-linear adsorption isotherms breakthrough lag behind the experimental data i.e. breakthrough occurs at higher number of pore volumes or took longer time. For instance, with both flow rates and the P concentrations (30 mg kg^{-1} or 90 mg kg^{-1} P) breakthrough lags behind or occurred at higher PV (Figures, 6.6a, b, c, and d; 6.7a, b, c, and d) indicating greater P sorption capacity of the soils. The, the measured data indicated that P breakthrough occurred soon after approximately at 10 PV and 5 PV with 30 mg kg^{-1} P and 90 mg kg^{-1} P, respectively (Figures, 6.8a, b; 6.9a, b; 6.10a, b; and 6.11a, b). The plausible reason for this lag in breakthrough (increased adsorption capacity) of P with batch experiment might be due breakdown of soil particles because of continuous shaking and mixing for 24 hours exposing more accessible sorption sites (Barrow and Shaw, 1979; Ho et al. 1995).

In addition, because of greater turbulence in batch experiment and decrease in P concentration in solution over time, the rate of P sorption increases in batch experiment. In contrast, with column leaching experiment, the solution concentration increases overtime, which may increase rate of P sorption but the effect may be still less compared to the turbulence effect of batch experiment resulting higher P sorption capacity of soils (Ho et al. 1995).

6.3.4.3 Sensitivity analysis and manual adjustment of adsorption isotherm parameters to fit the measured data

The manual adjustment of adsorption isotherm parameters improved the breakthrough time between numerical model simulated breakthrough and experimental data. For instance, changing S_{max} from 198.5 to 1100 and K_l from 0.178 to 0.0015 for fast flow rate and 90 mg kg^{-1} P rate improved the fit by pushing forward the breakthrough time between model simulated and experimental data (Table 3; Figure 6.11a, b). Likewise, for Freundlich adsorption isotherm adjusting K_f from 62.33 to 4.30 and β from 0.271 to 0.91 for slow flow rate and 30 mg kg^{-1} P improved the P breakthrough timing (Figures, 6.8a, b). The different values selected for K_l, K_f and β were listed in table 6.3.

Although the initial breakthrough timing was improved by adjusting adsorption isotherms parameters and minimized the time lag that occurred when using the batch experiment estimated adsorption isotherm parameters, still nor the linear neither the non-linear adsorption isotherm (Langmuir or Freundlich) models fit the experimental data. In addition, the maximum concentrations of the ortho-pohsphate measured in the experimental data were slightly lower compared to the model simulated values. For instance, the maximum concentration with 30 mg kg^{-1} P with the experimental data was less than 25 and 80 mg L^{-1}, respectively. However, the maximum concentration with model simulated data were approximately 30 and 90 mg L^{-1}, respectively.

The plausible reason for the lag in breakthrough and difference in maximum concentrations might be due to the inability of the numerical model to capture and process all the P mechanisms that had happened inside the column. For instance, the numerical model did not explain the kinetic adsorption that may happen inside the column. Likewise, , precipitation, rate of P transfers, hysteresis (between adsorption and desorption), diffusion of P in soil minerals etc. were not considered and explained by the numerical model. Moreover, iron reduction might have happened inside the column as indicated by the iron reduction test especially with the slow flow rates (Table 6.2.). The reducing conditions might have changed the sorption capacity of the soils resulting in some sporadic experimental data points.

6.4 CONCLUSION:

The P loss data from column leaching experiment was manually fitted with the results from a numerical advection-dispersion model in MATLAB. Overall, both the linear and nonlinear adsorption isotherms did not fit the experimental breakthrough data. During the initial stage of the P breakthrough, the langmuir adsorption isotherm model fitted the experimental data slightly better compared to the linear and freundlich adsorption isotherm. However, no adsorption isotherm models fit for the experimental data at the later stage. The adsorption isotherm parameters for linear and langmuir differ greatly with the change in P application and flow rates. Nevertheless, the parameters vary slightly for the freudlich adsorption isotherm indicating a possibility to develop a common set of parameter for different P rates and flow rates.

The overall goal of the project was to determine P transport with the advection-dispersion equation and understand the influence of the adsorption isotherm models using the P (breakthrough) leaching data. Once the appropriate adsorption isotherm was incorporated with the P-subroutines, it will help two things; first the over parametrization of other parameters to compensate the P leaching to the sub-surface would be avoided and secondly the models would better estimate the P loss from agricultural fields and help in minimizing the loss to water resources. However, the results indicated that none of the adsorption isotherm model (linear and non-linear) tested fit the column leaching P data. It might be due to complexity of P chemistry in soils. The data collected in this study would be helpful to guide and extend the future research in testing and incorporating appropriate adsorption isotherms with the advection-dispersion equation. Therefore, future work should focus to explain all the complexities associated with P and processes that might have happened inside the column. Perhaps, a multi-reactional advection-dispersion model that better describes all the processes and complexities such as precipitation, diffusion of P in soil minerals, P transfer rates etc. as an additional sink term should be used in the future.

6.5 Recommendation for future works.

- Oxygenating the solution every time when changing the syringe reduced iron reduction compared to the when it was oxygenated once. In the slow flow rate even after oxygenating the effluent sample analysis indicated presence of some reduced iron. Therefore, oxygenating sample every time before changing the solution (syringe) might help to supply fresh oxygenated solution and overcome this problem.
- Using curve-fitting approach in the MATLAB and incorporating multi-reactional advection dispersion equation would possibly help to better fit the experimental data with adsorption isotherms and should be the next step in the experiment.

6.6 REFERENCES

Barrow, N.J., J.W. Bowden, A.M. Posner, and J.P. Quirk. 1981. Describing the adsorption of copper, zinc and lead on a variable charge mineral surfaces Aust J. Soil Res 19 : 309-321.

Barrow, N. J., and T. C. Shaw. 1979. Effects of solution:soil ration and vigour of shaking on the rate of phosphate adsorption by soil. J. Soil. Sci. 30: 67-76.

Bolster, C.H., P.A. Vadas, A.N. Sharpley and J.A. Lory. 2012. Using a phosphorus loss model to evaluate and improve phosphorus indices. J. Environ. Qual. 41:1758-1766.

Bolster, C.H., and G.M. Hornberger. 2007. On the use of linearized langmuir equations. Soil Sci. Soc. Am. J. 71:1796-1806.

Gachter, R., S.M. Steingruber, M. Reinhardt M. and B. Wehrli. 2004. Nutrient transfer from soil to surface waters: differences between nitrate and phosphate. Aquatic Sci 66: 117-122.

Glaesner, N., Kjaergaard, C. Rubek, G.H. and Magid, J. 2011. Interactions between soil texture and placement of dairy slurry application: II. Leaching of phosphorus forms. J. Environ. Qua. 40: 344-351.

Graetz, D.A., and V.D. Nair. 2009. Phosphorus sorption isotherm determination. In: Kovar, J.L. Pierzynski, G.M. (Eds.), Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters, 2nd Southern Cooperative Series Bulletin no. 408. Virginia Tech University, pp. 33–36.

Greenberg, A.E., Clesceri, L.S. Eaton, A.D. 1992. Phenanthroline method. In: Standard Methods for the Examination of Water and Wastewater, 18th ed. APHA, Washington, 3500-Fe D

Heathwaite, A.L., and R. M. Dils. 2000. Characterizing phosphorus loss in the surface and sub-surface hydrological pathways. Sci Total Environ. 251-252:523-538.

Ho, G., and S. Notodarmojo. 1995. Phosphorus movement through soils and groundwater - application of a time-dependent sorption model. Water Science and Technology 31:83-90.

Huyakorn, P.S., and G.F. Pinder. 1983. Computational methods in sub-surface flow. Academic Press, INC. San Diego, CA.

Koopmans, G. F., R.W. McDowell, W.J Chardon, O. Oenema, and J. Dolfing. 2002. Soil phosphorus quantity-intensity relationships to predict increased soil phosphorus loss to overland and sub-surface flow. Chemosphere 48:679-687.

McGechan, M.B., and D.R. Lewis. 2002. Sorption of phosphorus by soil, part 1: principles, equations and models. Biosyst. Eng. 82:1-24

Nair, P., T. Logan, A. Sharpley, L. Sommers, M. Tabatabai and T. Yuan. 1984. Interlaboratory comparison of a standardized phosphorus adsorption procedure. J. Environ. Qual. 13:591-595.

Nelson, N. O., H. E. Parsons and Mikkelsen. 2005. Field scale evaluation of phosphorus leaching in acid sandy soils receiving long-term swine waste applications. J. Environ. Qual. 34: 2024-2035

Nelson, N. O., and H. E. Parsons. 2006. Modification and Validation of GLEAMS for Prediction of Phosphorus Leaching in Waste Amended Soils. Transactions of the ASABE 49 (5): 1395-1407.

Nelson, N.O., and A.L. Shober. 2012. Evaluation of phosphorus indices after twenty years of science and development. J. Environ. Qual. 41:1703-1710.

Sharpley, A.N., C.A.jones, C.Gray, and C.V. Cole. 1984b. A simplified soil and plant phosphorus model:2 Prediction of labile, organic, and sorbed phosphorus. SSSA J. 48(4): 805-809.

Sharpley, A.N., C.A. Jones. and J.R. Williams. 1984. A simplified soil and plant phosphorus model: I SSSA J. 48 (4): 810-813.

Sharpley A. N., R.W. McDowell, and P.J.A. Kleinman. 2004. Phosphorus loss in agricultural drainage: historical perspective and current research. J Environ Qual 27: 277-293.

Sharpley, A. N., P.J.A. Kleinman, R.W. McDowell, M.Gitau, and R.B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. J. soil and water conserv. 57 (6): 425-439.

Sharpley, A.N., S.J.Smith, B.A. Stewart, and A.C. Mathers. 1984. Forms of phosphorus in soil receiving cattle feedlot waste. J. Environ. Qual. 13: 211-215.

Sharpley, A.N., D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond and , P. A. Vadas. 2012. Phosphorus indices: Why we need to take stock of how we are doing. J. Environ. Qual. 41:1711-1719.

Sims, J.T., T.R. Simard, and B.C. Joren, 1998 Phosphorus loss in agricultural drainage: Historical prospective and current research. J. Environ. Qual. 27 (2): 353-360.

Sims J.T., and G.M Pierzynski. 2005. Chemistry of Phosphorus in Soils. Chemical Processes in Soils. SSSA Book Series, no 8.

Stone, K.C., B.K. Gerwig, R.G. Williams. D.W. Watts, and J.M. Novak. 2001. Using GLEAMS and REMM to estimate nutrient movement from a spray field through a riparian forest. Trans ASAE 44: 505-512.

Vadas, P.A., T.Krogstad, and A.N. Sharpley. 2006. Modeling phosphorus transfer between labile and non-labile soil pools. Updating the EPIC model. SSSA J. 70(3): 736-743.

Van Der Zee, S.E.A.,T.M. L.G.J. Fokkink & W.H. Van Riemsdijk, 1987. A new technique for assessment of reversibly adsorbed phosphate. Soil Science Society ofAmerica Journal 51: 599-604.

Van Es, H.M., Schindelbeck, R.R. and Jokela, W.E. 2004. Effect of manure application timing crop and soil type on phosphorus leaching. J. Environ. Qual. 33: 1070-1080.

Van Riemsdijik, W.H., L.J.M. Boumans, and F.A.M. de Haan. 1984. Phosphate sorption by soils: A model for phosphate reaction with metal oxides in soil. Soil. Sci. Soc. Am J. 48:537-541.

Williams, J.W., R.C. Izaurralde, and E.M. Steglich. 2008. Agricultural policy/environmental extender model. Theoretical Documentation. BREC Report # 2008-17.

Table 3.1. Physical parameters used in the column leaching experiment

Flow	Column length	Targeted bulk Density (g cm^{-3})	Water content (θ)	Pore-water velocity (cm hr^{-1})	Cross section area A (cm^{2})	Flux (q) (cm hr^{-1})	Discharge (ml hr^{-1})
Slow	(10 cm)	1.40	0.47	1.875	4.8891	0.8843	4.32321
Fast	(10 cm)	1.40	0.47	2.708	4.8891	1.2773	6.24463

Table 4.2. Iron reduction test; analysis of column leaching effluent collected during the experiment using UV-Spectrophotometer. The first sample was collected immediately after switching to P solution, second sample was after 3-pore volume, and the third was taken at the end of the experiment.

Column number	P conc. mg kg^{-1}	Pore water velocity cm hr^{-1}	Sample collected after saturation at PV	Fe^{2+} (mg L^{-1})
1	30	1.875	0	<DL
1	30	1.875	3	<DL
1	30	1.875	25	1.15
2	30	1.875	0	<DL
2	30	1.875	3	3.17
2	30	1.875	25	0.75
3	30	2.708	0	2.86
3	30	2.708	3	<DL
3	30	2.708	12	0.35
4	30	2.708	0	0.65
4	30	2.708	3	<DL
4	30	2.708	12	0.36
5	90	1.875	0	<DL
5	90	1.875	3	<DL
5	90	1.875	25	1.86
6	90	1.875	0	<DL
6	90	1.875	3	<DL
6	90	1.875	25	1.44
7	90	2.708	0	<DL
7	90	2.708	12	0.12
8	90	2.708	0	<DL
8	90	2.708	12	0.35

Fe^{2+} detection limit = 0.01 mg kg^{-1}

Table 5.3. Manual adjustment and sensitivity analysis of adsorption isotherm parameters

Adsorption isotherm parameters	Slow flow rate-30 mg kg^{-1} P	Fast flow rate- 30 mg kg^{-1} P	Slow flow rate- 90 mg kg^{-1} P	Fast flow rate- 90 mg kg^{-1} P
Maximum adsorption capacity of soil (S_{max})	1100	2800	3225	1100
Langmuir distribution or affinity coefficient (K_l)	0.00385	0.0016	0.0011	0.0015
Freundlich distribution or partitioning coefficient (K_f)	5.10	5.70	4.70	5.40
Empirical parameter (β)	0.91	0.90	0.92	0.88
Kd is the distribution coefficient (K_d)	4.3	4.40	3.30	1.6

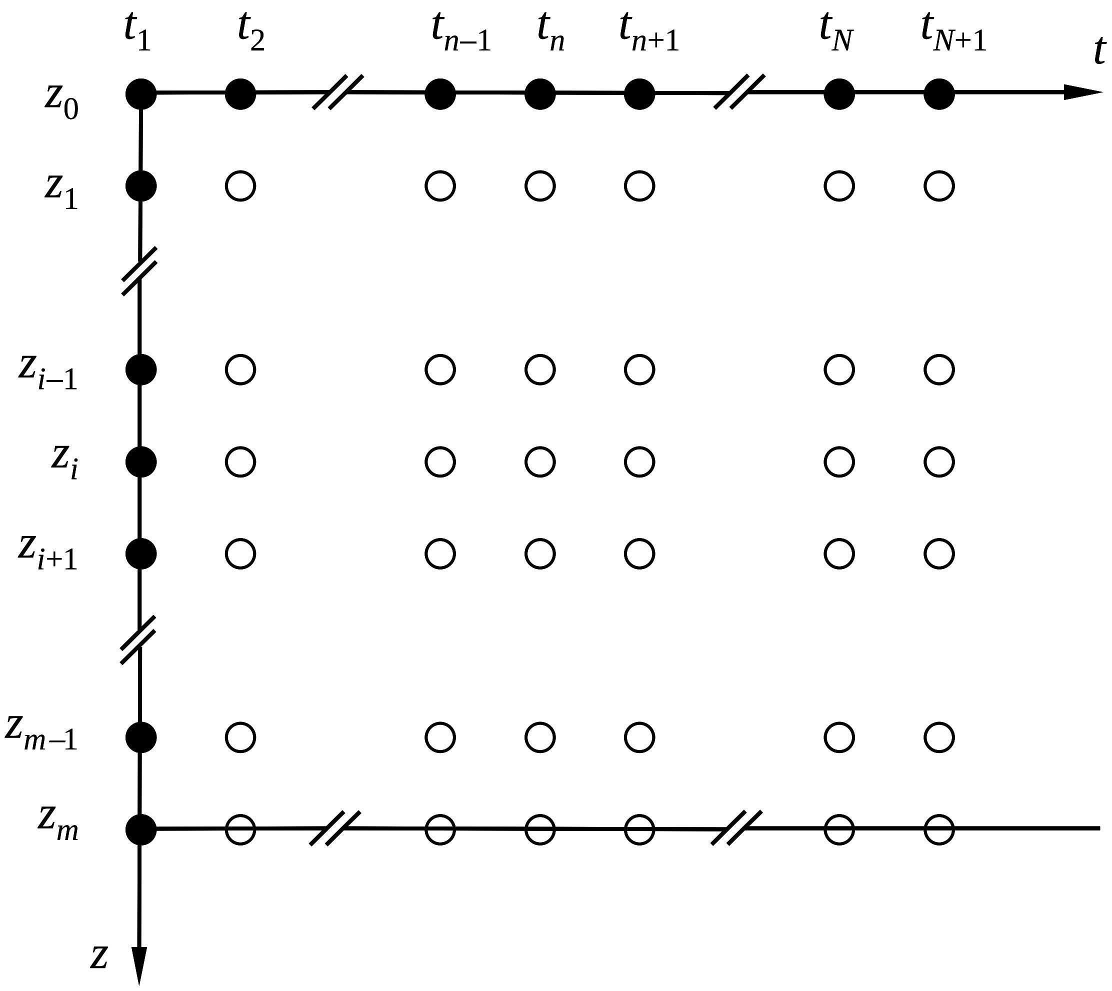


Figure 6.1. Node diagram for the advection dispersion equation for solute transport with Dirichlet boundary condition on the top and Neumann boundary conditions at both boundaries. (Source, Dr. Kluitenberg, AGRON 916, Lecture notes, 2013).

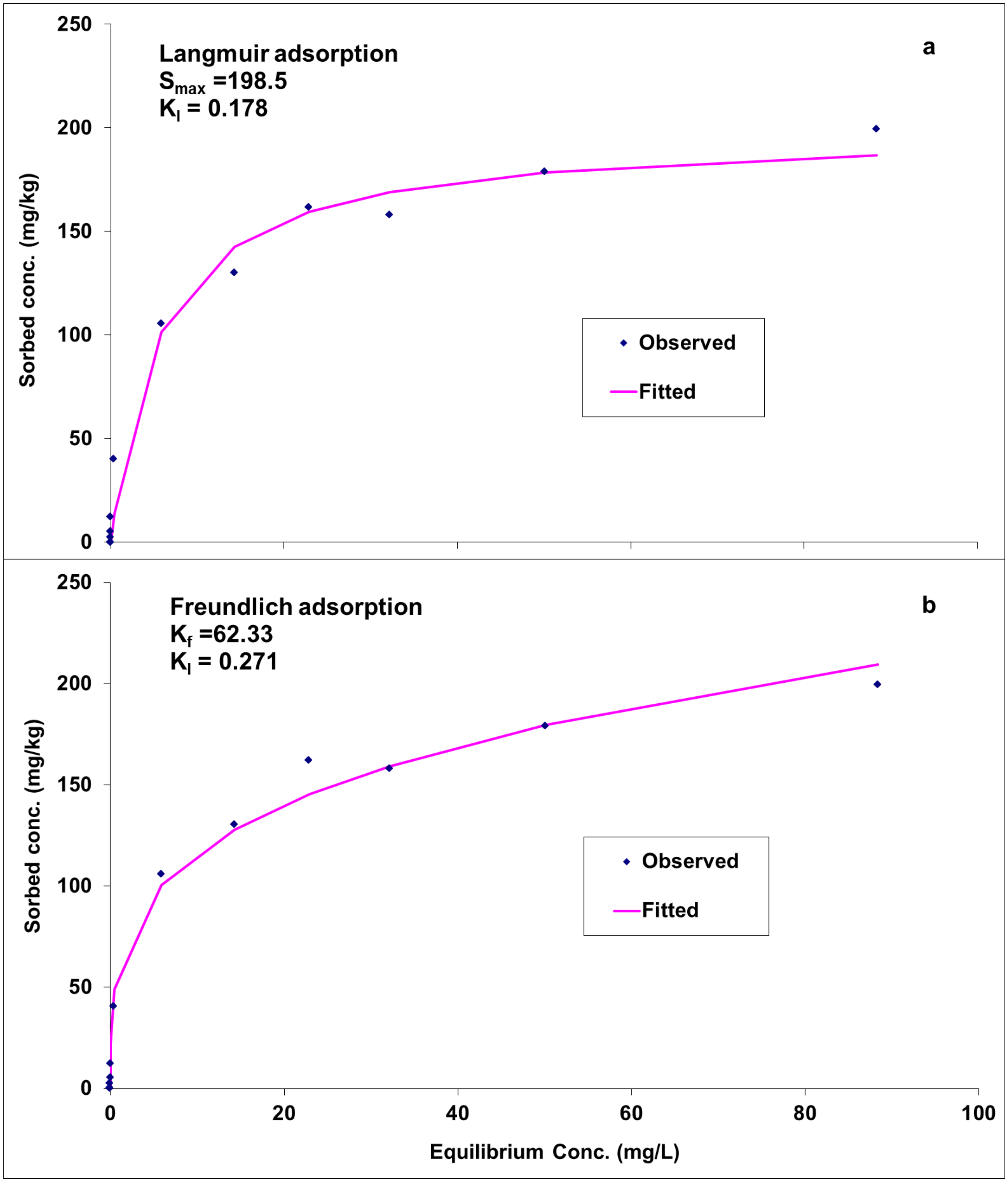


Figure 6.2. Batch experiment data fit with Langmuir and Freundlich adsortpion isotherm model using the excel spreadsheet developed by Bolster and Hornberger (2007).

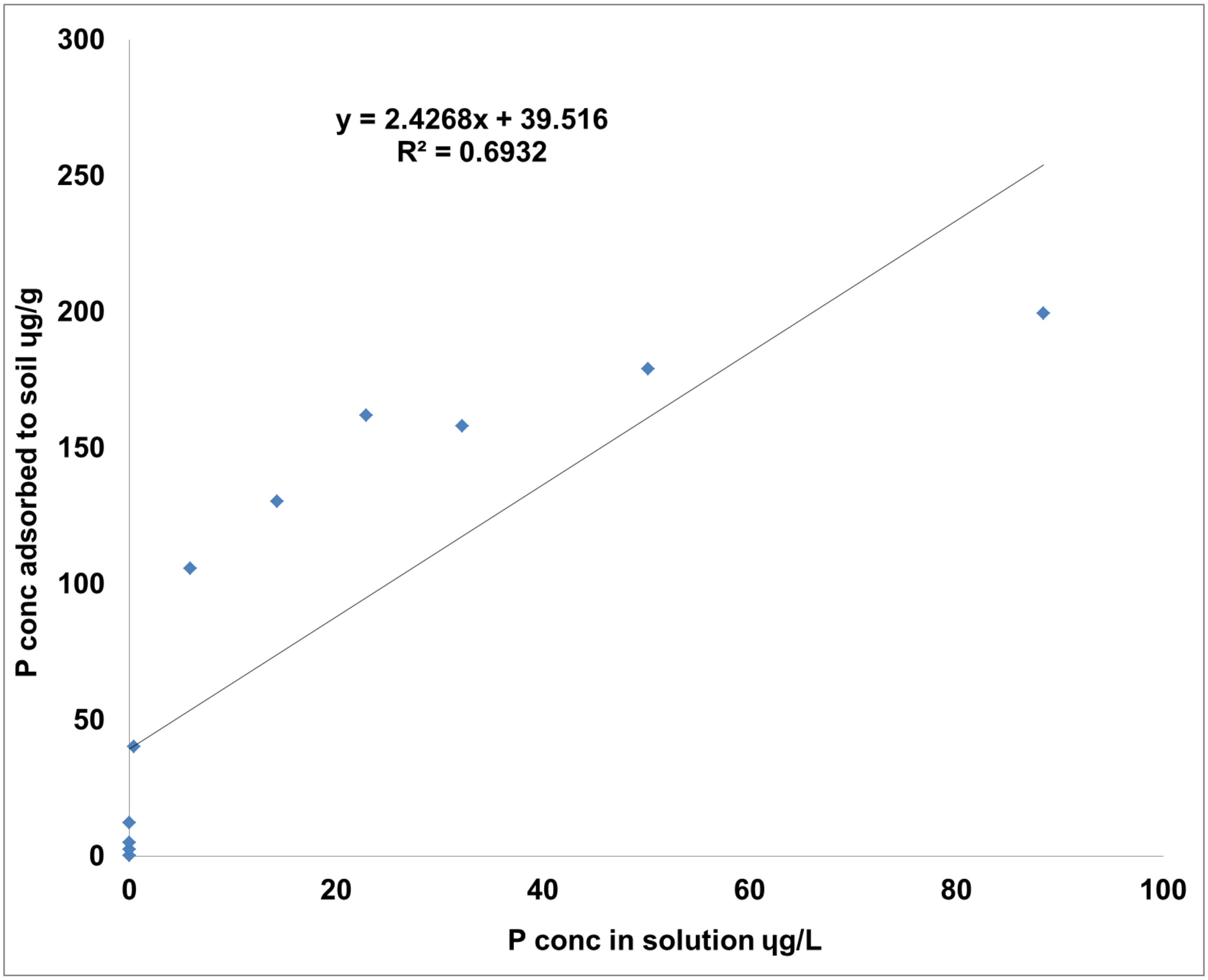


Figure 6.3. Batch experiment data fit with Linear model using the excel spreadsheet. All the data points were used in the model fit.

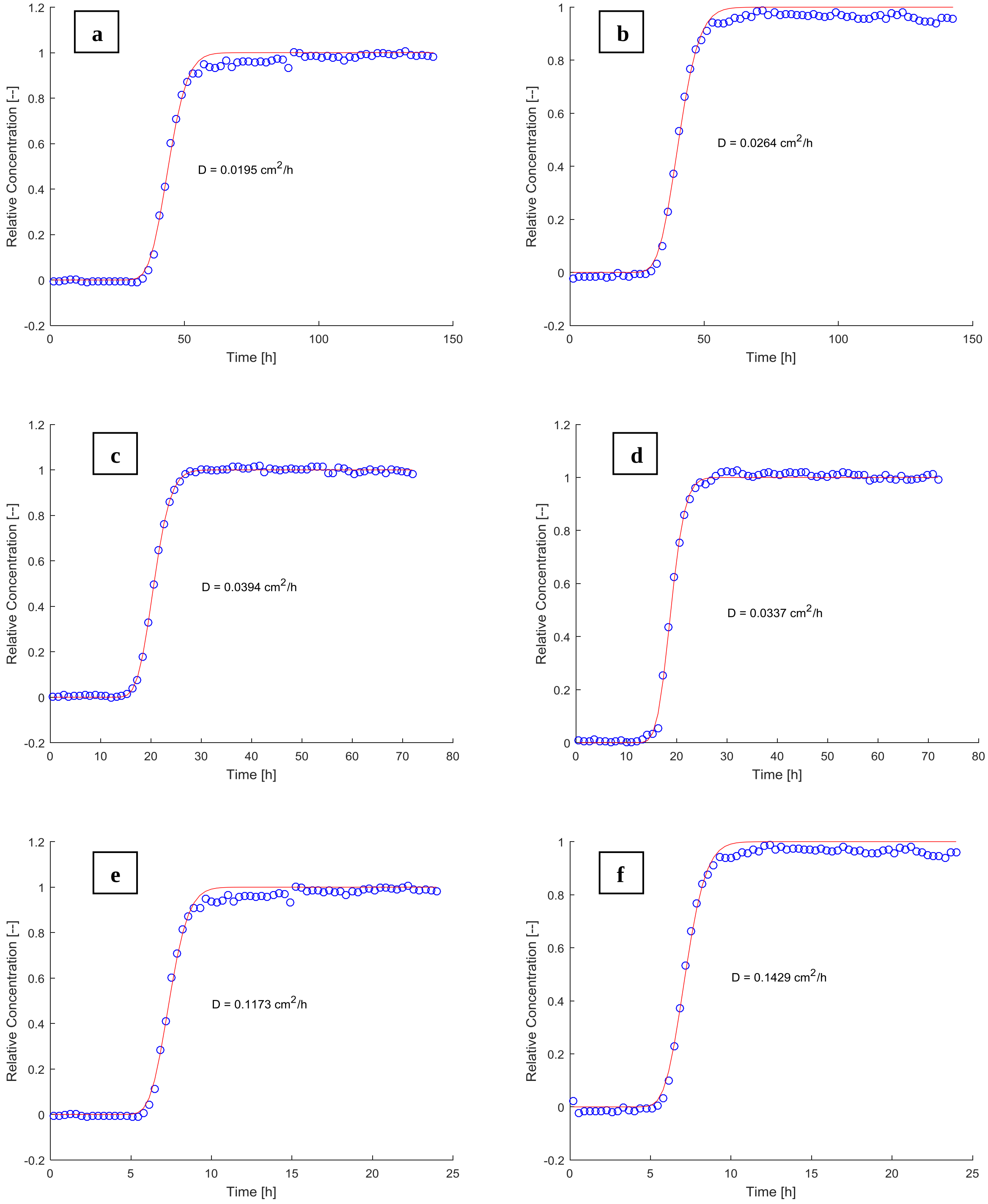


Figure 6.4. Estimation of dispersion coefficient (D = cm^2 hr^{-1}) using bromide breakthrough curve with data collected in a column leaching study.

a) Slow pore water velocity (SPWV)(0.21 cm hr^{-1})-rep 1	b) SPWV-rep 2
c) Medium pore water velocity (0.42 cm hr^{-1})-rep 1	d) MPWV-rep 2
e) Fast pore water velocity (1.25 cm hr^{-1})-rep1	f) FPWV-rep 2

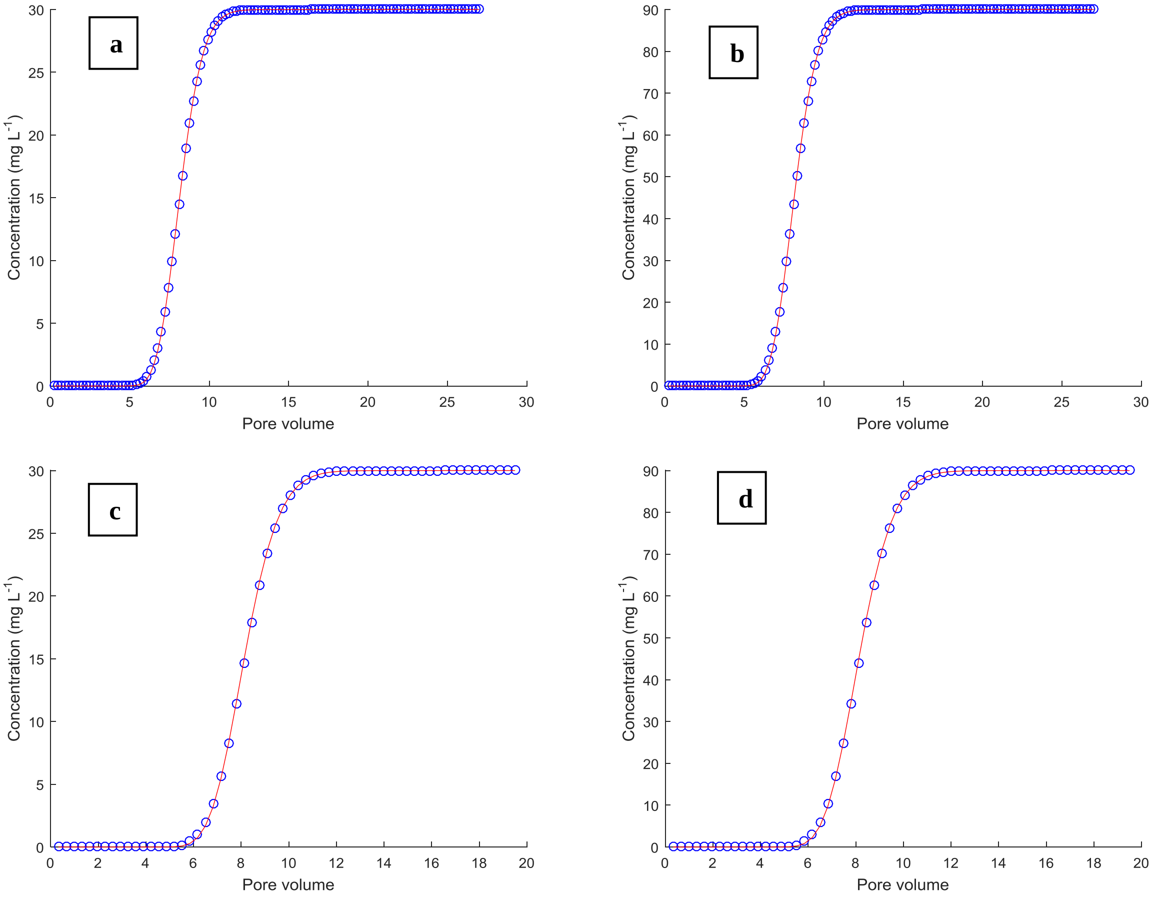


Figure 6.5. Linear adsorption isotherm with K_d = 2.4358 determined with batch experiment

a) Slow flow rate (Pore water velocity = 1.875), 30 mg kg^{-1} P concentration
b) Slow flow rate (Pore water velocity = 1.875), 90 mg kg^{-1} P concentration
c) Fast flow rate (Pore water velocity = 2.708), 30 mg kg^{-1} P concentration
d) Fast flow rate (Pore water velocity = 2.708), 90 mg kg^{-1} P concentration

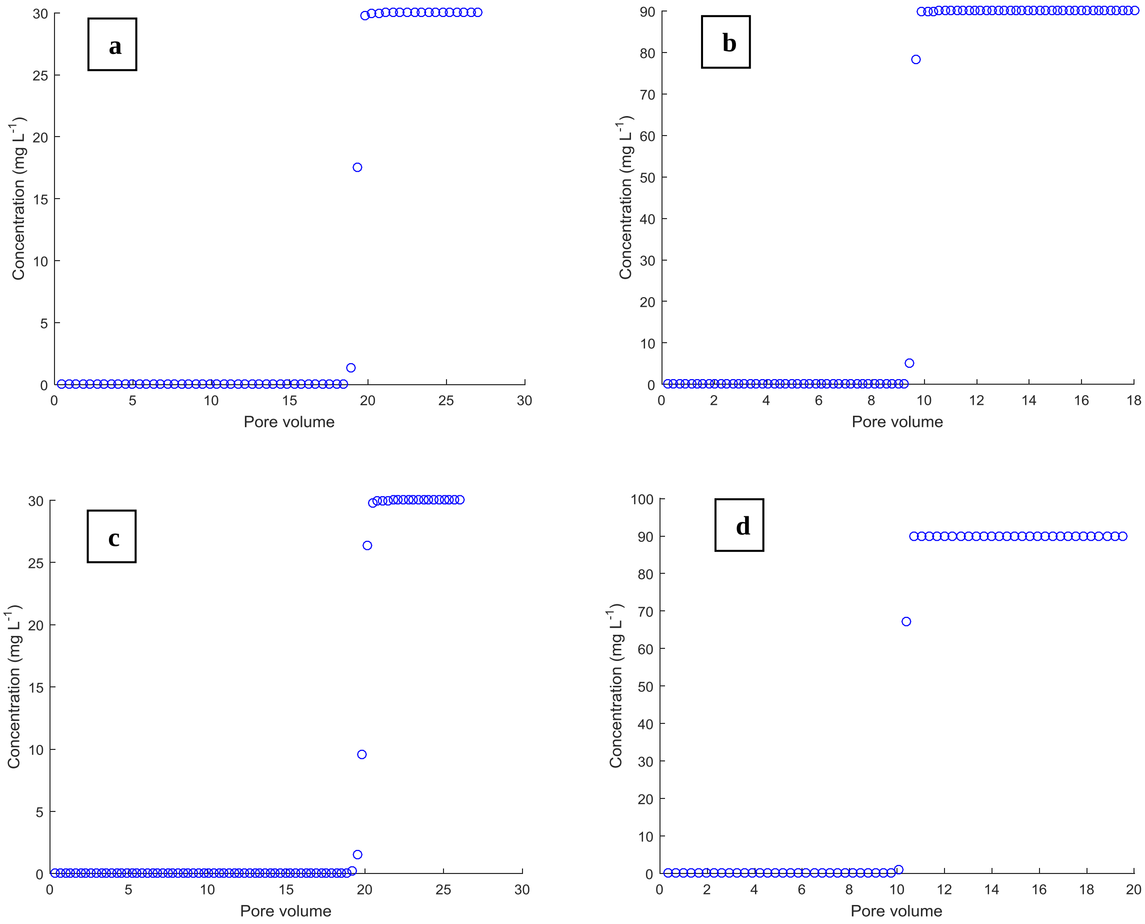


Figure 6.6. Langmuir adsorption isotherm with S_{max} = 198.5 and k_l = 0.178, determined with batch experiment

a) Slow flow rate (Pore water velocity = 1.875), 30 mg kg^{-1} P concentration
b) Slow flow rate (Pore water velocity = 1.875), 90 mg kg^{-1} P concentration
c) Fast flow rate (Pore water velocity = 2.708), 30 mg kg^{-1} P concentration
d) Fast flow rate (Pore water velocity = 2.708), 90 mg kg^{-1} P concentration

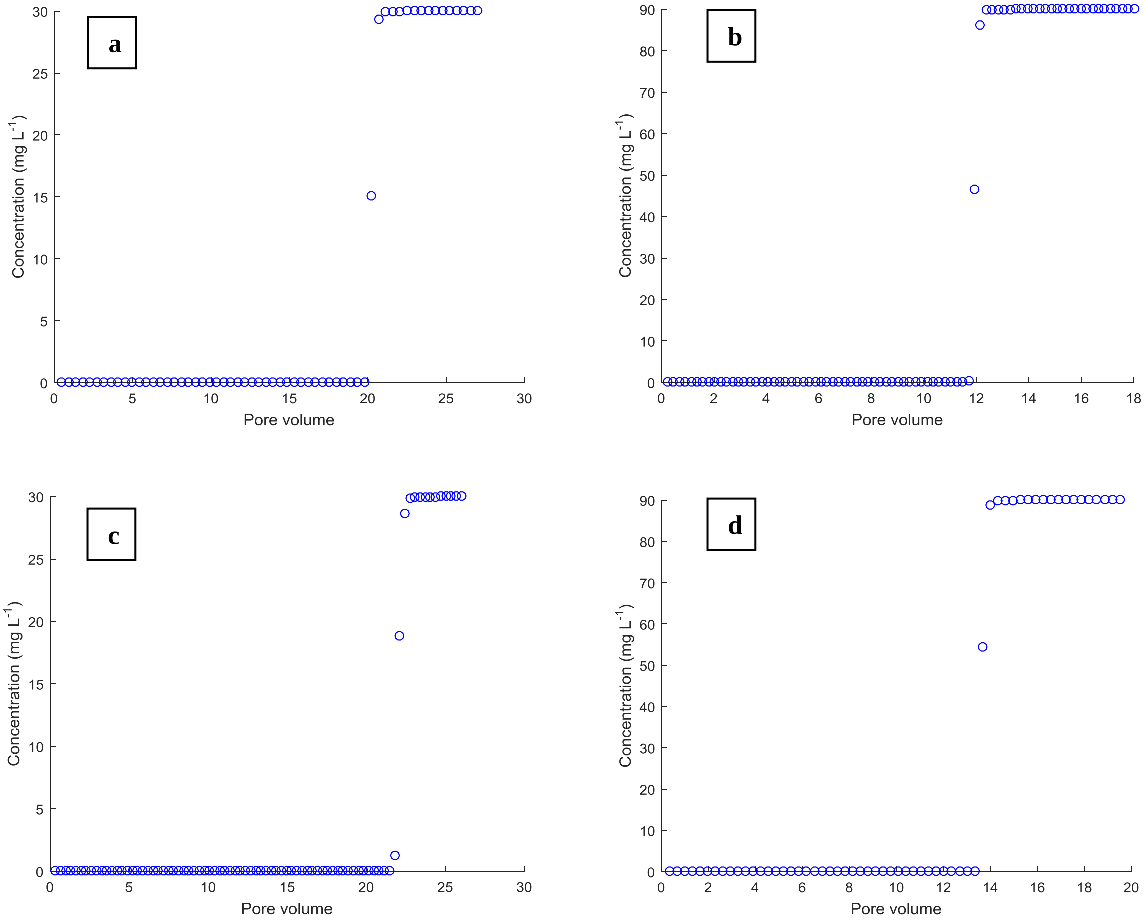


Figure 6.7. Freundlich adsorption isotherm with K_f = 62.33 and k_l = 0.271, determined with batch experiment

a) Slow flow rate (Pore water velocity = 1.875), 30 mg kg^{-1} P concentration
b) Slow flow rate (Pore water velocity = 1.875), 90 mg kg^{-1} P concentration
c) Fast flow rate (Pore water velocity = 2.708), 30 mg kg^{-1} P concentration
d) Fast flow rate (Pore water velocity = 2.708), 90 mg kg^{-1} P concentration

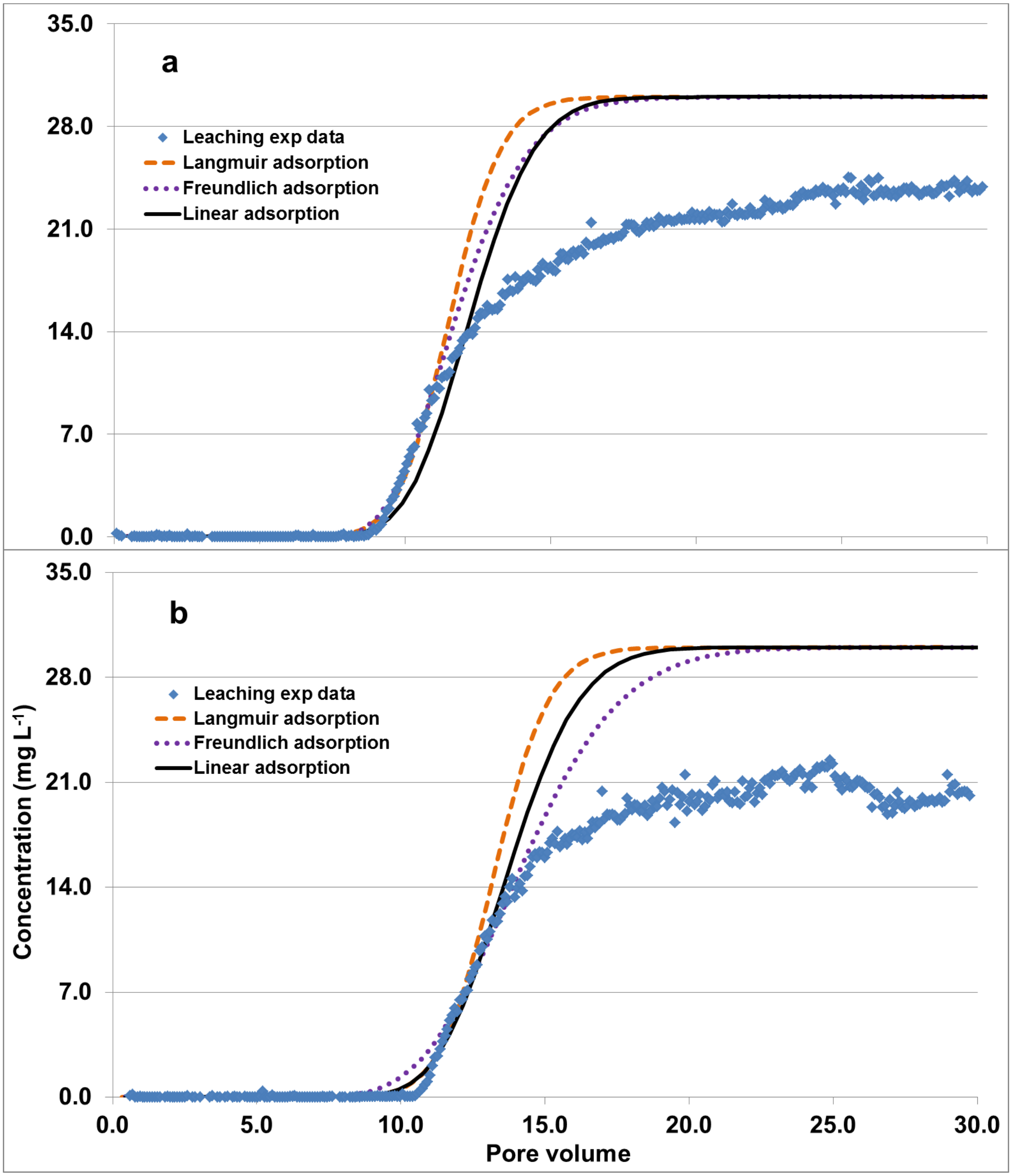


Figure 6.8. Fitting experimental data with linear and non-linear adsorption isotherm using advection-dispersion equation in MATLAB, slow flow rate 30 mg kg^{-1} P. a) Column 1 and b) Column 2

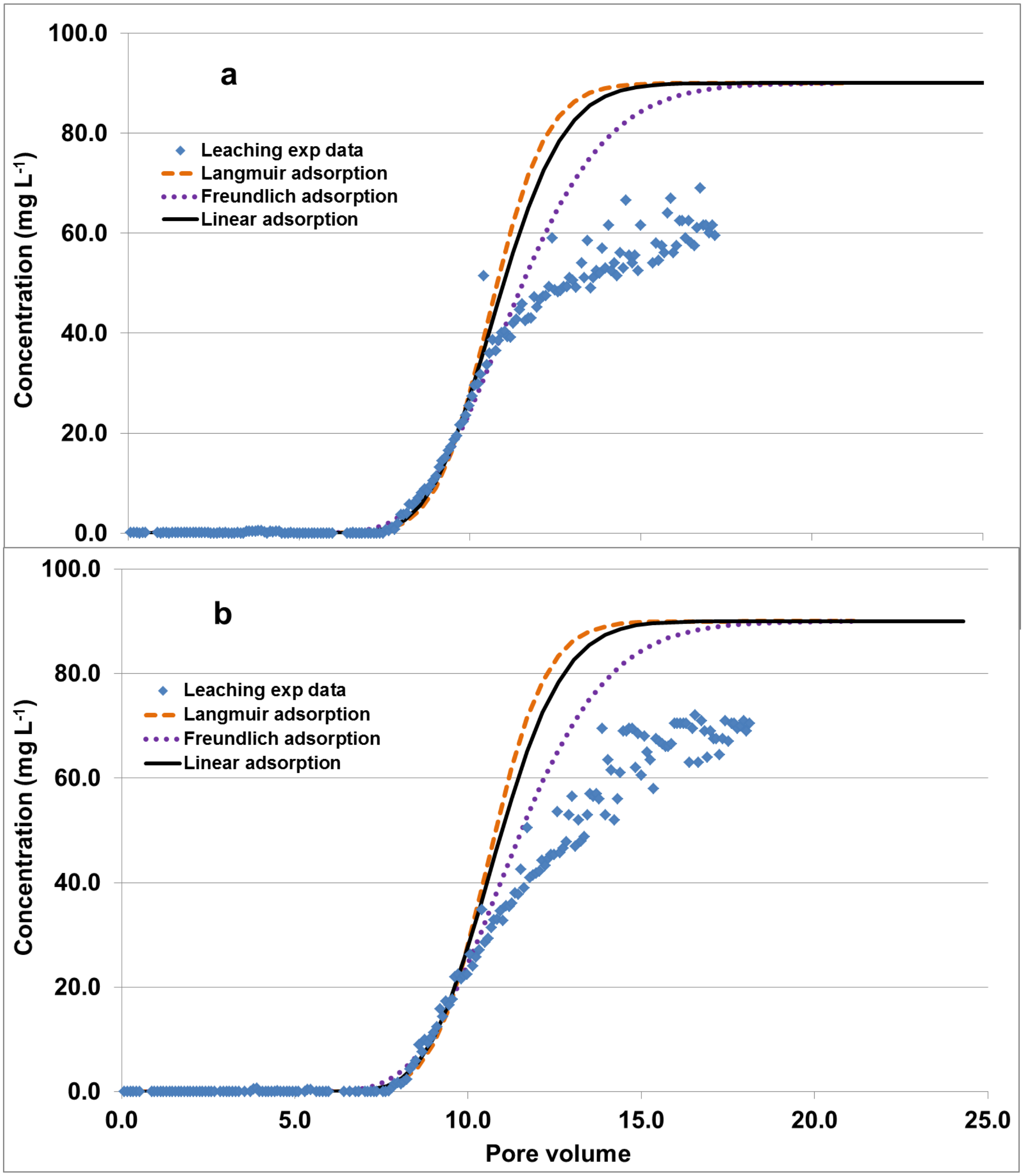


Figure 6.9. Fitting experimental data with linear and non-linear adsorption isotherm using advection-dispersion equation in MATLAB, slow flow rate 90 mg kg^{-1} P. a) Column 1 and b) Column 2

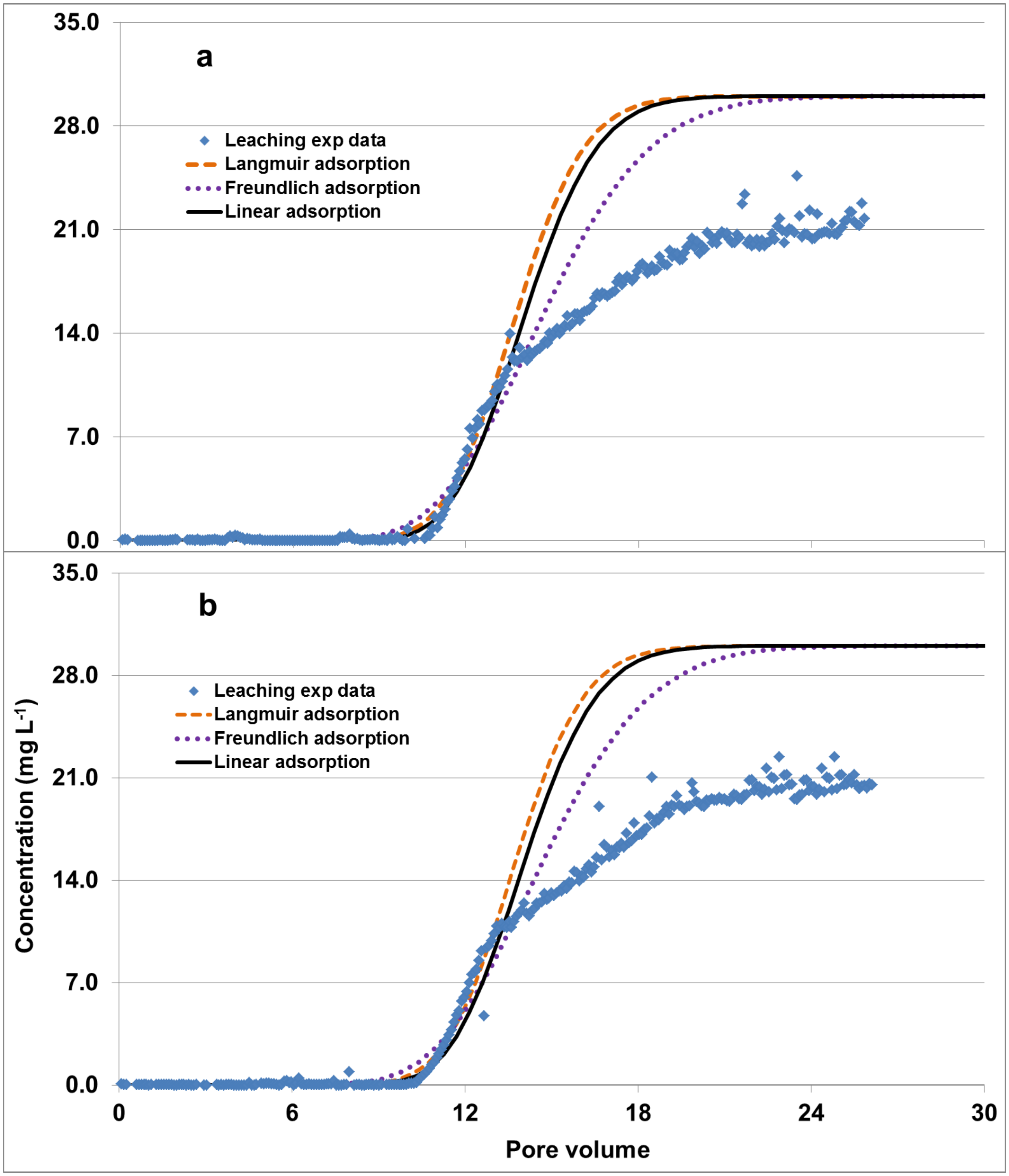


Figure 6.10. Fitting experimental data with linear and non-linear adsorption isotherm using advection-dispersion equation in MATLAB, fast flow rate 30 mg kg^{-1} P. a) Column 1 and b) Column 2

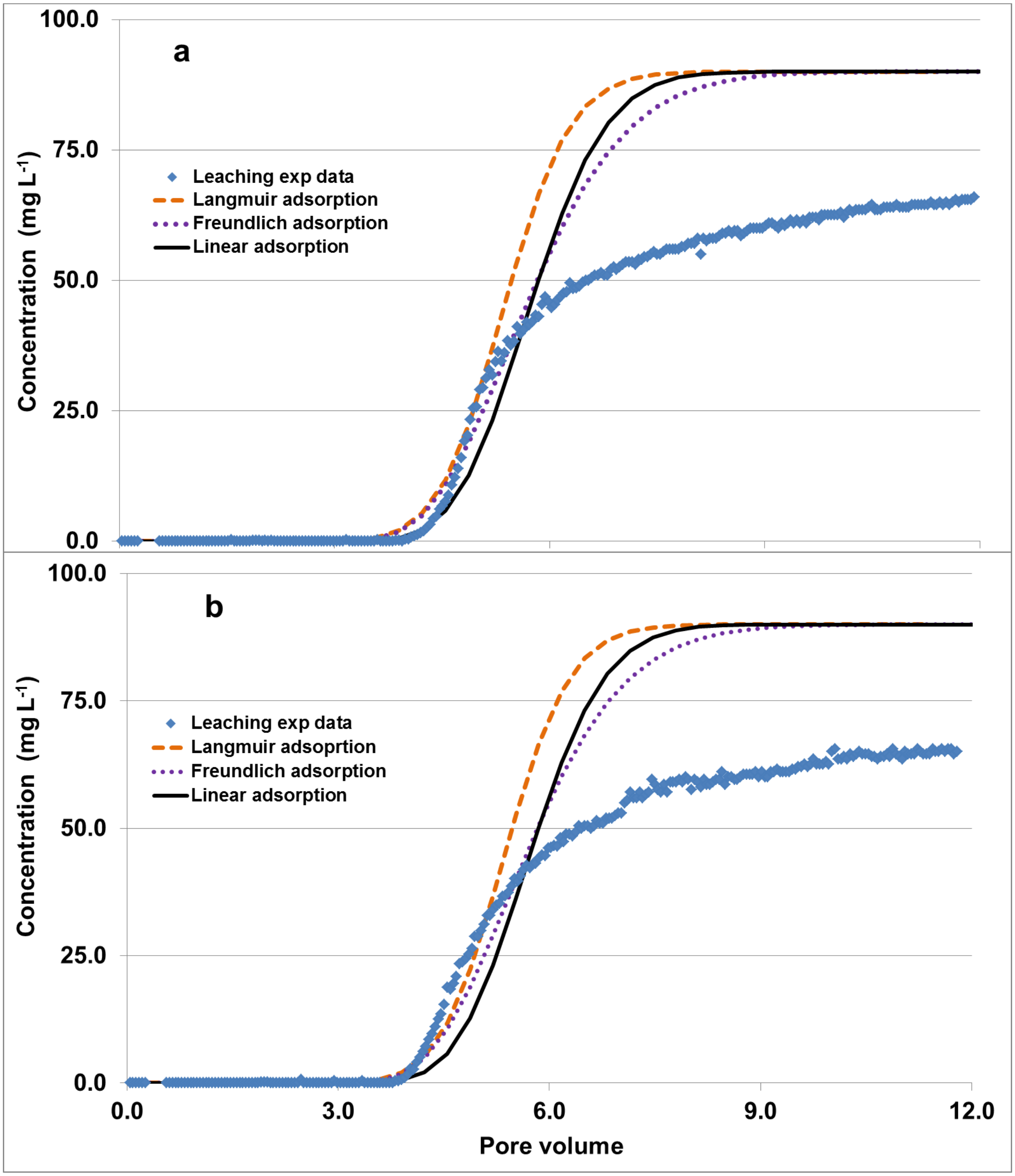


Figure 6.11. Fitting experimental data with linear and non-linear adsorption isotherm using advection-dispersion equation in MATLAB, fast flow rate 90 mg kg^{-1} P. a) Column 1 and b) Column 2

APPENDIX A. Map of the watersheds in the study sites

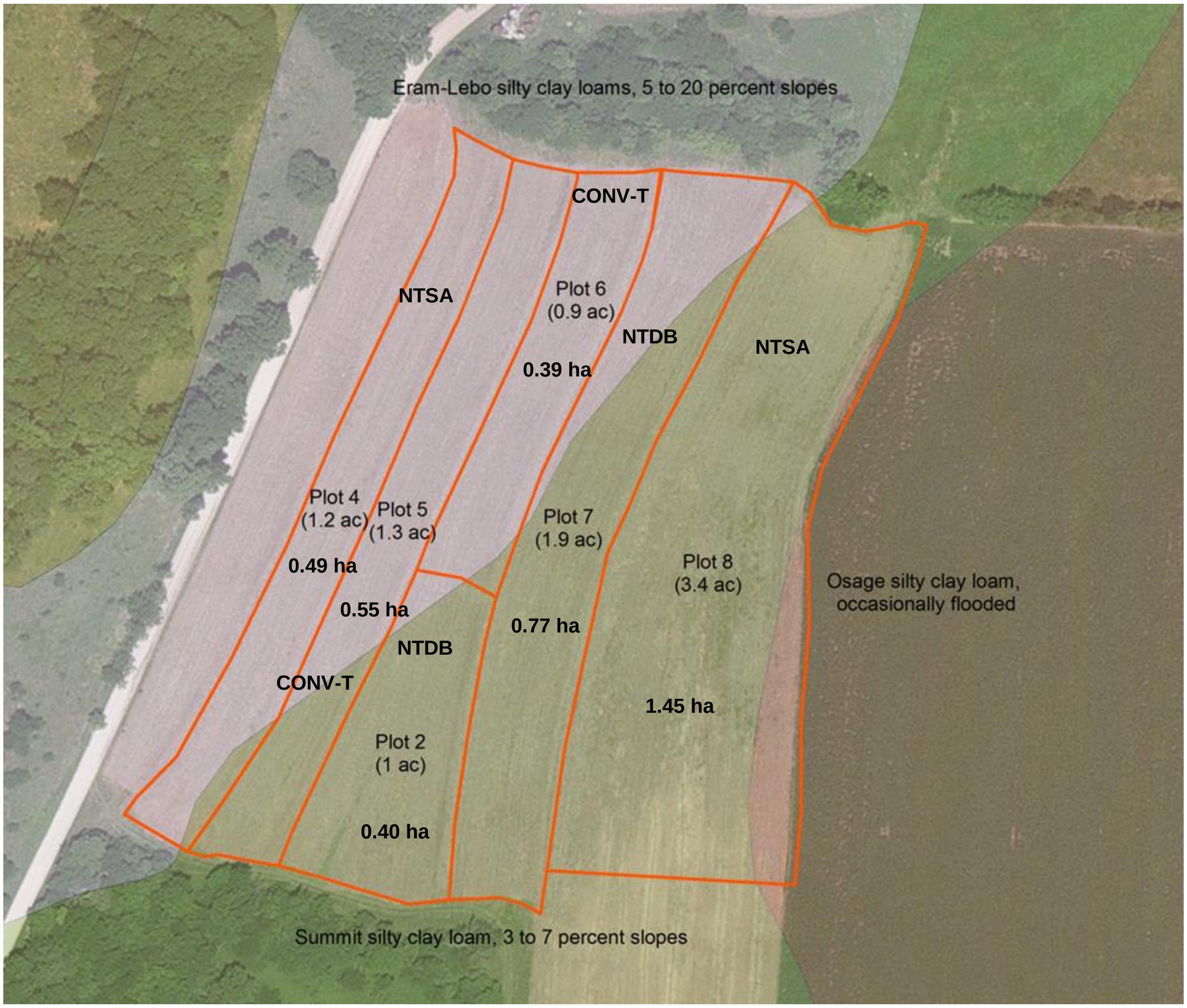


Figure A1. Watersheds layout at the Franklin County runoff study site. NTSA = No-till fertilizer surface applied; NTDB = No-till fertilizers sub-surface application; CONV-T = Conventional tillage - fertilizer incorporated. The slope of the site ranged from approximately 3.5 to 7%.

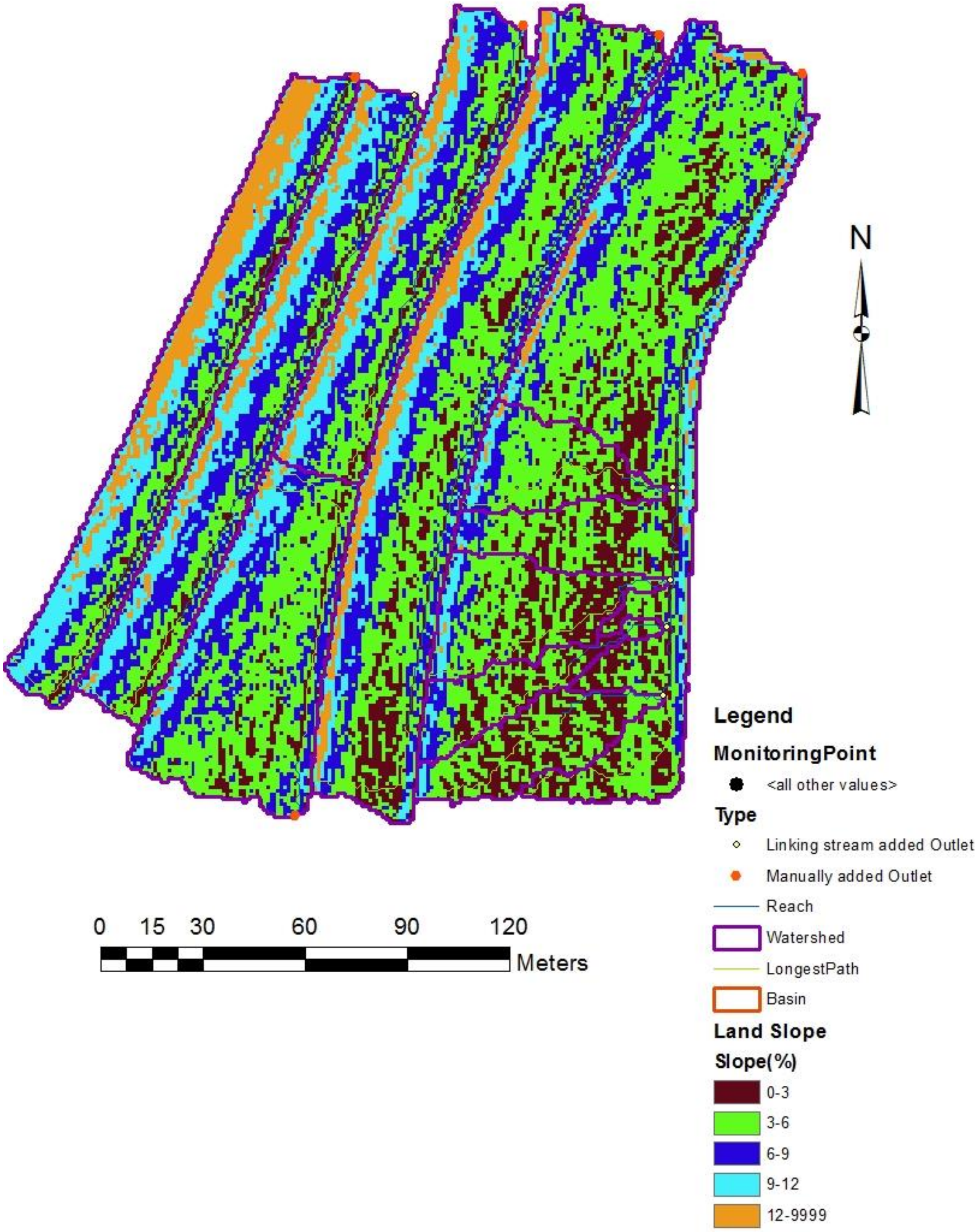


Figure A2. Watersheds delineated using ARC-APEX at the Franklin County runoff study site.

Figure A3: Watersheds layout at the Crawford County runoff study with management practices. Watersheds with nitrogen based turkey litter-notill treatment were not used in this study. The slope of the site was approximately 1%.

Table A: A.1 Key processes option available in the APEX model; the bold and italic was the one selected in our study

Component		Methods to estimate
Hydrology	Potential evapotranspiration	Penman-Monteith
		Penman
		Priestly-Taylor
		Hargreaves
		Baier-Robertson
	Peak runoff rate	Modified rational EQ stochastic peak rate estimate
		Modified rational EQ rigid peak rate estimate
		SCS TR55 peak rate estimate
		Options to SCS TR55 peak rate estimate
		a. Type I rainfall pattern
		b. Type 1A rainfall pattern
		c. ***Type 2 rainfall pattern***
		d. Type 3 rainfall pattern
	Surface runoff	***CN estimate of Q***
		Green and Ampt estimate of Q, rainfall exponential distribution, peak rainfall rate
		G&A Q, rainfall exponential distribution, peak rainfall input
		G&A Q, rainfall uniformly distribution, peak rainfall input
		G&A Q, rainfall input at time interval DTHY
Soil erosion		MUST- modified MUSLE theoretical based equation
		AOF- Onstad-Foster
		USLE- Universal soil loss equation
		MUSS small watershed MUSLE
		MUSLE Modified USLE
		MUSI Modified muscle with input parameters (see BUS(1))
		RUSLE Revised universal soil loss equation
		RUSLE2 Modified RUSLE
Nutrients	Enrichment ratio	Epic enrichment ration
		Gleams enrichment ratio
	Soluble P runoff estimate equation	Soluble P runoff estimate using GLEAMS pesticide equation
		Langmuir equation
	N and P plant uptake concentration	Smith curve
		S-curve

APEX user manual, Steglich and Williams et al. (2013)

APPENDIX B. Additional information on model parameters, and soil characteristics

Section 1: Description of Management Specific Sensitive Parameters

Soluble Runoff Coefficient (P8)

Parameter 8 (P8) determines the P concentration in runoff as a function of the P concentration in the soil (Williams et al 2012; Steglich and Williams 2013). The relationship between soil test P and P concentration in runoff could change with soil test P (Koopmans et al. 2002). Therefore, P8 could be different for high and low P rate application management systems. Increasing P8 in high P application managements decreases the dissolved P concentration in runoff. It suggests that for high P application the impact of soil test P on P loss can be decreased by increasing the value of P8. Thus, P8 should be considered as a parameter of interest especially in high soil test P, and poultry litter or manure application systems. It ranged from 4- 20 at Crawford and 10-20 at Franklin runoff study site (Table 2).

Soil Evaporation- Plant Cover Factor (P17)

Parameter 17 (P17) reduces the effect of plant cover as related to leaf area index (LAI) in regulating soil evaporation. The model computes evaporation from plants and soils separately (Ritchie, 1972). Soil evaporation depends on soil depth and water content. The potential soil water evaporation is estimated as a function of potential evaporation and leaf area index (LAI). Leaf area index is the area of the plant leaves relative to the soil surface. The LAI is simulated as a function of heat units, crop stress and crop development stages which is initially very small or zero (Williams et al. Williams et al. 2012). As, the LAI depends on type of crops grown, soil fertility, water content etc. it can differ from one management to another. Lower P17 increases effectiveness of the plant cover factor related to LAI and reduce runoff. Increasing this number reduces the effectiveness and increases runoff, sediment and phosphorus loss.

Biological Mixing Efficiency (P29)

The model calibration procedure indicated that parameter 29 (P29) should be 0.50 for no till (NTSA/NTDB) and 0.10 for conventional tillage (CONV-T) managements at Franklin site. But was less sensitive and was 0.50 for all management practices at Crawford site (Table 2). Parameter 29 determines the redistribution of soil constituents as a result of the activity of the biota in soil (e.g. earthworms). Biological mixing is performed at the end of every calendar year and specifies the fraction of materials (residue, nutrients, pesticides etc.) within the tillage depth that are mixed uniformly throughout that tillage depth (Williams et al 2012; Steglich and Williams 2013). In general if the management system shifts from conventional to conservation and no till, the biological mixing increases. However, it may not be sensitive if the soil is frequently mixed with tillage operations (Arnold et al. 2012).Therefore, biological mixing could be different based on the tillage system.

Coefficient adjusts microbial activity function in the top soil layer, parameter 69 (P69) and Microbial decay rate coefficient

RUSLE C-factor Coefficient (P46)

Parameter 46 (P46) is the coefficient in exponential residue function in residue factor. The crop residue factor (FRSD) calculates the crop management factor in APEX. FRSD is an exponential function of the above ground residue CVRS, where CVRS is the above ground residue (t ha-1). The default value for P46 is 0.75 (Williams et al. 2012). This factor estimates the effectiveness of surface residue to reduce erosion. Higher P46 value indicates greater effectiveness of the residue to reduce erosion and may be affected by slope of the watershed, type of residues, and surface roughness etc. In general, the effectiveness of residue should be higher (higher P46) for higher slopes and vice-versa. Also, the type of residue and surface roughness of the field affect the erosion. For instance, if the residue cover does not make a full contact to the ground or perched above the soil due to depression or uneven surface, rill erosion may still occur beneath the residue. Therefore, based on the type of residue, evenness of the soil surface and slope of the watershed, parameter 46 can differ by management.

RUSCLE C-factor Coefficient (P47)

Parameter 47 (P47) is a coefficient in exponential crop height function in biomass is one of the crop management factors in APEX. The growing biomass factor (FBIO) is an exponential function of the fraction ground cover by the growing crop (FGC) and crop height in m (CPHT). The FGC is calculated based on the standing live biomass of the crop in t ha^{-1}. The default value for P46 is 0.1 (Williams et al. 2012). Higher P47 value indicates greater effectiveness of the growing cover and crop height. Hence, decrease the overall sediment loss. The crop height and biomass not only depend on types of crops grown but also may be affected by soil water content, soil nutrients, soil texture, rooting depth, and organic matter etc. For instance, in a control (without any poultry litter/fertilizer application) system the crop growth and biomass may be substantially low due to nutrient deficiency compared to nitrogen rate poultry litter application management. Therefore, based on the type of crops grown, nutrients availability, organic matter content etc. parameter 46 and its effect on erosion may vary with management.

Coefficient Adjusts Microbial Activity Function in the Top Soil Layer (P69) and Microbial Decay Rate Coefficient (P70)

The parameter 69 (P69) adjusts factors controlling biological processes (CS) in the top soil layer due to microbial activity. The value of P69 is directly proportional to the CS value. Likewise, parameter 70 (P70) adjusts soil water-temperature-oxygen equation and is also used to calculate the combined factor controlling biological processes (CS) (Williams et al 2012; Steglich and Williams 2013). An increase in P69 and P70 increases the CS and the rate of mineralization of residue thus mobilizes and increases the availability of nutrients for transport and nutrient loadings in runoff and lateral flow. Parameter P69 and P70 are vital in a system where there is no addition of external input (fertilizer/poultry litter) as in CONT management to maintain the natural processes and nutrient cycling. These parameters also affect runoff and sediment loss to some extent. Therefore, these parameters could differ based on management such as crop residues, fertilizer, poultry litter application rates etc. (Table 2).

Coefficient regulating P flux between labile and active pool (parameter 84)

In APEX, the rate of flow between the soluble and active pools is a user defined input and is the same for each transfer direction. Based on the literature and APEX theoretical documentation and in the original paper on phosphorus cycling and transport by Jones et al. (1984), it recommended to set as 0.1. This will enable to a more rate of P fixation when fertilizer is added, but slower release of phosphorus from the active pool for plant uptake or after P has been removed by runoff. It might differ with the management practices, the sensitivity analysis indicated that it need to be increased (0.60) with conventional tillage when the inorganic fertilizer was applied.

Soluble Phosphorus Leaching KD Value (P96)

Parameter 96 (P96) is the phosphorus leaching kd value. It is a ratio of concentration of P in soil with concentration of P in water. Decreasing P (96) values in the model decreases the total P concentration in runoff by increasing the P leaching loss to soil profile and vice-versa. Parameter 96 is more important when P application exceeds the removal rate as in N rate poultry litter application and if there is a buildup of test P in soils. Therefore, P96 may differ by management practices and should be considered if the STP is high as in N rate applications and in tillage systems where P application is incorporated.

Section 2: Regional Model Development

The APEX model was parametrized, calibrated and validated using data from 2005-2008 and from 2011-2013 collected from 2005- 2008 and 2011- 2013 in a continuous grain sorghum cropping system. The nitrogen (N) rate poultry litter application (TLN) management was tested in this study. Data from 2005-2008 were used for calibration and data from 2011-2013 were used for validation of the model.

The Crawford runoff study was located in Crawford County, Kansas (37o 30’ N, 94o 59’ W). The soil series was Parsons Silt loam (fine, mixed thermic Mollic Albaqualf), which is a claypan soil in NRCS hydrologic group D, as confirmed by an on-site investigation (Donald Gastineau, unpublished data, 2013). There were 10 adjacent small watersheds 133m by 31m

(0.40 ha) in size with an approximate slope of 1%. Each watershed was separated on all sides by a soil berm to isolate runoff, with berms on the downslope end of the watershed angled toward a weir. The study was initiated in 1998 to investigate the effect of tillage fertilizer application method on water quality for a grain sorghum-soybean rotation. Poultry litter was applied from 2005 and the cropping system was changed to continuous sorghum. Additional details on site characteristics and data collection are available in Sweeney et al. (2012) and Zeimen et al. (2006).

Runoff was monitored from April through October or November. Runoff was not monitored during the winter months due to complications associated with freezing temperatures. Runoff data included runoff volume, sediment loss, total nitrogen (TN) loss, total P (TP) loss, and dissolved P (DP) loss for each runoff event, with some events including multiple days. The data were summed together if there was onsite precipitation recorded continuously for more than one day and was regarded as a single event. Measured data were reviewed for quality control and events with inexplicable data (i.e. runoff: rainfall ratio > 0.9) were omitted from the analysis.

The same procedure was used for sensitivity analysis, calibration and validation of the model with the TLN management as described in the chapter 2 materials and method section. There were 25 events for calibration and 26 events validation. The model parameters, range tested, uncalibrated and calibrated values selected were listed in Table A5.

RESULTS AND DISCUSSION

The results indicated that except for runoff the uncalibrated model did not meet the model performance criteria for sediment, TP and DP loss. The sediment loss was extremely over predicted by approximately 3500 % (Table A6; Figure 1A). The calibration improved the model performance and the runoff, TP and DP loss met the model performance criteria. Although, the r^2 and NSE did not meet the threshold criteria, the sediment loss was greatly improved as indicated by the p-bias (Table A6; Figure 1A). Similarly, the runoff, sediment, TP and DP loss all met the model performance criteria during validation. Overall, the results indicated that if properly calibrated the APEX model is capable of simulating runoff, TP and DP loss with similar management.

Table B: B.1 Archive soil (collected in 2000) analysis results before the initiation of the study at Franklin runoff study site

Managements	Depth (cm)	Bray P (ppm)	TP† (ppm)	TN‡ (ppm)	TN (%)	TC§ (%)	PSP¶	AEP#
NTDB (Watershed 2)	0 - 5.1	20	482	1508	0.18	2.10	0.28	19.10
	5.1 - 15.24	17	421	1406	0.16	1.90	0.29	16.46
NTSA (Watershed 4)	0 - 5.1	25	495	1498	0.20	2.22	0.31	23.50
	0 - 5.1- 15.24	10	431	1451	0.16	1.83	0.19	10.30
CONV-T (Watershed 5)	0 - 5.1	19	415	1258	0.18	1.97	0.30	18.22
	0 - 5.1 - 15.24	13	427	1452	0.16	1.90	0.24	12.94
CONV-T (Watershed 6)	0 - 5.1	21	385	1187	0.16	1.95	0.35	19.98
	0.05 - 15.24	11	465	1567	0.17	2.08	0.19	11.18
NTDB (Watershed 7)	0 - 5.1	21	450.6	1493.9	0.19	2.06	0.31	19.98
	0 - 5.1 - 15.24	6	343.6	1201.2	0.14	1.67	0.18	6.78
NTSA (Watershed 8)	0 - 5.1	27	484.1	1612.2	0.18	2.25	0.35	25.26
	0 - 5.1 - 15.24	11	366.9	1158.8	0.16	1.95	0.24	11.18

†TP = Total Phosphorus

‡TN = Total nitrogen

§TC = Total carbon

¶ PSP = Phosphorous sorption coefficient

#AEP = Anion exchangeable Phosphorus (Labile P)

Table B: B2. Profile particle size analysis, total nitrogen and total carbon percentage at Franklin runoff study site

Field/Watershed	Depth to the bottom layer (cm)	TN† %	TC‡ %	Sand %	Silt %	Clay %
NTDB (Watershed 2)	5.1	0.18	2.10	11	49	40
	19	0.16	1.90	11	49	40
	43	0.13	1.05	6	40	54
	67	0.12	0.75	6	40	54
	90	0.10	0.49	6	42	52
	152	0.09	0.37	7	39	54
NTSA (Watershed 4)	5.1	0.20	2.22	9	52	39
	16	0.16	1.83	9	52	39
	37	0.14	1.22	9	41	51
	68	0.10	0.74	8	40	53
	102	0.09	0.51	7	42	52
	133	0.09	0.45	7	41	52
CONV-T (Watershed 5)	5.1	0.18	1.97	10	49	41
	19	0.16	1.90	10	49	41
	44	0.12	0.95	8	37	55
	69	0.10	0.67	7	40	53
	105	0.09	0.44	7	40	53
	120	0.09	0.32	6	38	56
CONV-T (Watershed 6)	5.1	0.16	1.95	14	48	38
	20	0.17	2.08	10	48	42
	71	0.09	0.64	8	40	52
	120	0.07	0.49	6	42	52
NTDB (Watershed 7)	5.1	0.19	2.06	11	48	41
	16	0.14	1.67	11	48	41
	36	0.13	1.23	11	40	49
	75	0.10	0.72	8	40	52
	152	0.09	0.41	8	43	49
NTSA (Watershed 8)	5.1	0.18	2.25	12	56	32
	15	0.16	1.95	12	56	32
	34	0.15	1.87	12	50	38
	62	0.12	1.14	11	48	41
	99	0.09	0.69	10	49	41
	152	0.10	0.58	8	45	47

†TP = Total Phosphorus

‡TN = Total nitrogen

Table B: B3. Background soil analysis results before initiation of the study at Crawford runoff study site

Managements	Depth (cm)	Bray P (ppm)	TP† (ppm)	TN‡ (ppm)	TN (%)	TC§ (%)	PSP¶	AEP#
FERTC	0 - 7.6	8.8	435	1051	0.15	1.44	0.15	9.25
(Watershed 102)	7.6 - 20.3	7.4	296	727	0.12	1.18	0.20	8.03
	20.3 – 30.5	2.1	252	724	0.10	0.80	0.12	3.37
CONT	0 - 7.6	4.0	273	919	0.12	1.04	0.17	5.06
(Watershed 103)	7.6 - 20.3	3.4	225	636	0.10	0.90	0.18	4.52
	20.3 – 30.5	2.1	289	757	0.10	0.84	0.10	3.36
TLP	0 - 7.6	8.2	245	698	0.09	0.67	0.28	8.68
(Watershed 104)	7.6 - 20.3	2.7	252	540	0.09	0.68	0.12	3.85
	20.3 – 30.5	1.9	322	924	0.12	1.10	0.09	3.17
TLNC	0 - 7.6	7.6	346	1027	0.12	1.21	0.19	8.15
(Watershed 105)	7.6 - 20.3	5.6	221	670	0.10	1.01	0.25	6.40
	20.3 – 30.5	1.8	220	706	0.09	0.74	0.14	3.08
TLNC	0 - 7.6	43.7	666	1102	0.13	1.26	0.30	39.96
(Watershed 201)	7.6 - 20.3	28.1	375	711	0.10	1.02	0.37	26.26
	20.3 – 30.5	1.9	308	739	0.10	0.78	0.08	3.17
FERTC	0 - 7.6	9.6	298	926	0.12	1.11	0.26	9.95
(Watershed 203)	7.6 - 20.3	7.0	210	619	0.10	0.89	0.30	7.69
	20.3 – 30.5	1.7	191	636	0.08	0.67	0.17	3.01
TLPC	0 - 7.6	16.6	399	872	0.11	1.12	0.25	16.11
(Watershed 204)	7.6 - 20.3	11.8	261	602	0.10	0.92	0.30	11.88
	20.3 – 30.5	1.8	170	739	0.09	0.75	0.29	3.12
CONT	0 - 7.6	7.6	370	760	0.10	0.93	0.15	8.19
(Watershed 205)	7.6 - 20.3	5.6	260	553	0.09	0.80	0.18	6.44
	20.3 – 30.5	1.8	190	720	0.09	0.71	0.20	3.11

†TP = Total Phosphorus

‡TN^2 = Total nitrogen

§TC = Total carbon

¶ PSP = Phosphorous sorption coefficient

#AEP = Anion exchangeable Phosphorus (Labile P).

The PSP was estimated using PSP = 1/ ([(total phosphorus - organic phosphorus)/ (5*labile Phosphorus)] + 4/5) (Nelson and Parsons, 2006) and the AEP was estimated using regression equation (Mallarino and Atta, 2005).

Table B: B4. Profile particle size analysis, total nitrogen and total carbon percentage at Crawford runoff study site

Field/Watershed	Depth to the bottom layer (cm)	TP† %	TN‡ %	Sand %	Silt %	Clay %
FERTC (Watershed 102)	8	0.10	1.01	44	40	16
	19	0.10	0.73	26	28	46
	36	0.05	0.35	32	26	42
	60	0.06	0.30	46	18	36
TLNC (Watershed 105)	8	0.11	1.05	46	40	14
	22	0.09	0.67	22	30	48
	32	0.08	0.40	30	28	42
	60	0.05	0.33	48	20	32
	60	0.06	0.28	50	18	32
FERTC Watershed 203)	8	0.08	0.80	48	38	14
	19	0.11	0.75	26	28	46
	31	0.08	0.46	26	30	44
	60	0.07	0.37	36	28	36
TLPC (Watershed 204)	8	0.09	0.81	48	38	14
	20	0.11	0.95	22	28	50
	32	0.08	0.52	22	30	48
	60	0.06	0.32	34	30	36
CONT (Watershed 205)	8	0.09	0.78	54	34	12
	16	0.11	0.88	26	32	42
	29	0.08	0.52	26	32	42
	60	0.04	0.37	32	32	36
Average of watersheds (102, 105, 203, 204 and 205)	7	0.09	0.91	50	37	14
	19	0.10	0.78	26	29	46
	29	0.07	0.44	29	28	43
	60	0.06	0.33	41	24	35

†TP = Total Phosphorus

‡TN = Total nitrogen

Table B: B5. APEX model parameters tested during sensitivity analysis, calibration and their selected values at Crawford study sites for the regional model

Sensitive parameters†	Range tested‡	Un-calibrated values	Calibrated values selected
Parameters affecting runoff			0.02
Runoff CN residue adjustment parameter P[15]	0.0-0.3	0.00	
Soil evaporation plant cover factor P[17]	0.0-0.5	0.10	0.01
Water stress weighing coefficient P[38]	0.0-1.0	1.00	1.0
SCS CN index coefficient P[42]	0.3-2.5	1.00	2.5
Upper limit CN retention parameter P[44]	1.0-2.0	1.50	
Parameters affecting sediment			
Sediment routing coefficient P[19]	0.01-0.05	0.05	2.0
RUSLE C-factor coefficient residue factor P[46]	0.5-1.5	0.50	1.40
RUSLE C-factor coefficient biomass factor P[47]	0.5-1.5	0.50	0.10
Parameters affecting soil biological activity			
Biological mixing efficiency P[29]	0.1-0.5	0.10	0.50
Maximum depth for biological mixing P[31]	0.1-0.3	0.30	0.30
Coefficient adjusts microbial activity P[69]	0.1-1.0	1.00	0.5
Microbial decay rate coefficient P[70]	0.5-1.5	1.00	0.5
Parameters affecting total and dissolved Phosphorus			
Root growth soil strength P[2]	1.0-2.0	1.50	1.50
Soluble phosphorus runoff coefficient P[8]	10.0-20.0	15.0	10.0
P upward movement by evaporation coefficient P[59]	1- 20.0	1.00	1.00
Manure erosion equation coefficient P[62]	0.1-0.5	0.25	0.10
Manure erosion exponent P[68]	0.1-1.0	0.50	1.00
Standing dead fall rate coefficient P[76]	0.0001-0.1	0.01	0.001
	0.0001-0.001	0.0001	0.001
Coefficient. regulating P flux between labile and active pool P[84]	0.0001-0.001	0.0001	0.001
Soluble Phosphorus Leaching KD value P[96]	1-15	1	5

†CN, curve number; SCS, Soil Conservation Service ; RUSLE, Revised Universal Soil Loss Equation; KD, partition coefficient.

‡The parameter ranges specified in the APEX manual (Steglich and Williams, 2013).

Table B: B6. Model performance statistics for same managements at Crawford runoff study site

Forms of model tested	Management† (Watersheds)	Runoff			Sediment			Total Phosphorus			Dissolved Phosphorus		
		r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias	r^2	NSE	P-bias
Uncalibrated model	TLN (Watershed 101)	0.93	0.75	-1.01	0.10	-20478‡	-8370	0.84	0.60	3	0.82	0.37	-8
Calibration	TLN (Watershed 101)	0.88	0.79	-18	0.17	-1.64	-19	0.97	0.94	21	0.97	0.96	15
Validation	TLN (Watershed 101)	0.74	0.70	24	0.60	0.49	53	0.90	0.86	-8	0.95	0.80	-24

†TLN = No till; nitrogen rate poultry litter application.

Model performance threshold criteria for Runoff loss = 0.50, 0.30, ±35 % for r^2, NSE, and PBIAS respectively; Sediment, TP and DP loss = = 0.50, 0.30, ±60 % for r^2, NSE, and PBIAS respectively.

‡Bolded values indicate the model performance that did not meet the threshold criteria.

APPENDIX C. Full model runs results for total phosphorus, and sediment loss with poultry litter and different management practices, Crawford runoff study site

Appendix C: C1. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a continuous corn-corn rotation

Phosphorus rates	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT[2]	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %
JANUARY APPLICATION															
0	1.3	1.4	8	2.0	1.8	-10	3.3	2.5	-30	6.0	4.0	-49	11.3	7.0	-62
25	2.0	2.8	27	2.7	3.2	15	4.0	3.9	-3	6.7	5.4	-23	12.1	8.5	-42
50	2.7	4.1	35	3.4	4.5	25	4.7	5.3	11	7.4	6.9	-8	12.8	10.0	-28
100	4.1	7.1	42	4.8	7.5	36	6.2	8.4	26	8.9	10.0	11	14.4	13.2	-9
200	7.1	13.7	48	7.8	14.2	45	9.2	15.1	39	12.0	16.8	29	17.5	20.1	13
APRIL APPLICATION															
0	1.4	2.0	32	1.9	2.4	20	3.0	3.2	4	5.3	4.8	-11	9.8	7.9	-24
25	1.8	2.3	20	2.4	2.7	9	3.6	3.4	-6	5.8	4.8	-23	10.4	7.6	-38
50	2.3	3.2	28	2.9	3.6	20	4.1	4.3	6	6.4	5.8	-10	11.0	8.6	-27
100	3.3	5.3	37	3.9	5.7	32	5.1	6.5	22	7.4	8.0	7	12.1	10.9	-10
200	5.5	10.4	47	6.1	10.8	43	7.3	11.6	37	9.7	13.2	27	14.4	16.2	11
OCTOBER APPLICATION															
0	1.2	1.4	10	1.9	1.8	-6	3.2	2.6	-23	5.8	4.2	-38	11.0	7.4	-49
25	1.6	2.2	26	2.3	2.7	14	3.6	3.5	-3	6.4	5.3	-20	11.8	8.8	-34
50	2.0	3.1	35	2.7	3.5	25	4.0	4.4	9	6.7	6.2	-8	12.2	9.8	-24
100	2.7	4.9	45	3.4	5.4	37	4.7	6.3	25	7.5	8.1	8	13.0	11.8	-10
200	4.1	8.7	53	4.8	9.2	48	6.1	10.1	39	8.9	12.0	26	14.5	15.8	9
NOVEMBER APPLICATION															
0	1.3	1.4	7	1.9	1.7	-10	3.2	2.5	-30	5.9	4.0	-46	11.1	7.1	-58
25	1.7	2.2	22	2.4	2.6	8	3.7	3.4	-10	6.4	5.0	-29	11.9	8.2	-44
50	2.1	3.1	30	2.8	3.5	19	4.2	4.3	3	6.9	6.0	-16	12.4	9.3	-34
100	3.0	4.9	39	3.7	5.4	32	5.0	6.2	19	7.8	7.9	2	13.3	11.3	-17
200	4.7	9.1	48	5.4	9.5	44	6.7	10.4	35	9.5	12.2	22	15.1	15.7	4

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

Appendix C: C2. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a continuous corn-soybean rotation

Phosphorus rates	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT[2]	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %
JANUARY APPLICATION															
0	1.1	1.3	9	1.9	2.1	7	3.1	3.1	-2	5.5	5.0	-9	10.3	9.0	-14
25	1.6	2.2	27	2.3	2.9	22	3.4	3.8	11	5.8	5.7	-1	10.4	9.5	-10
50	2.0	3.1	36	2.6	3.8	30	3.8	4.7	19	6.1	6.6	7	10.8	10.4	-4
100	2.7	4.8	44	3.3	5.5	40	4.5	6.5	30	6.9	8.4	18	11.5	12.2	5
200	4.2	8.6	51	4.8	9.3	48	6.0	10.3	41	8.4	12.2	31	13.2	16.1	18
APRIL APPLICATION															
0	1.3	1.3	-4	2.1	2.1	0	3.1	3.1	-1	5.1	5.1	-1	9.2	9.0	-2
25	1.6	2.1	21	2.3	2.9	18	3.5	3.8	8	5.7	5.7	-1	10.3	9.1	-13
50	2.0	2.9	31	2.7	3.7	27	3.8	4.6	17	6.1	6.5	6	10.6	9.5	-12
100	2.8	4.7	41	3.4	5.4	36	4.6	6.4	28	6.9	8.3	17	11.5	10.5	-9
200	4.3	8.5	49	5.0	9.3	46	6.2	10.3	40	8.6	12.2	30	13.3	12.5	-6
OCTOBER APPLICATION															
0	1.3	1.2	-1	2.0	2.0	1	3.0	3.0	0	5.1	5.0	-1	9.1	9.0	-1
25	1.3	1.8	24	2.1	2.5	17	3.2	3.4	7	5.4	5.3	-3	10.0	9.1	-10
50	1.6	2.3	30	2.2	3.0	24	3.4	3.9	13	5.6	5.8	2	10.2	9.5	-7
100	2.0	3.2	39	2.6	3.9	33	3.7	4.8	22	6.0	6.7	10	10.6	10.5	-1
200	2.7	5.1	47	3.3	5.7	42	4.5	6.7	33	6.8	8.6	21	11.5	12.5	8
NOVEMBER APPLICATION															
0	1.3	1.2	-1	2.0	2.0	0.52	3.0	3.0	0	5.0	5.0	-1	9.1	9.0	-1
25	1.4	1.8	23	2.1	2.5	16.73	3.3	3.5	6	5.5	5.3	-4	10.1	9.1	-12
50	1.7	2.4	29	2.3	3.0	23.66	3.5	4.0	13	5.8	5.8	1	10.3	9.6	-8
100	2.1	3.4	38	2.7	4.1	32.67	3.9	5.0	22	6.2	6.9	10	10.8	10.7	-2
200	3.0	5.6	47	3.6	6.2	42.11	4.8	7.2	33	7.2	9.1	21	11.9	13.0	8

[†] INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

Appendix C: C3. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation

Phosphorus rates	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT[2]	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %
JANUARY APPLICATION															
0	1.6	1.5	-3	2.3	2.3	-1	3.7	3.7	-2	6.4	6.3	-2	11.9	11.6	-3
25	1.8	2.6	30	2.7	3.4	22	4.3	4.7	10	7.5	7.4	-1	13.9	12.7	-10
50	2.2	3.7	39	3.1	4.5	31	4.7	5.8	19	7.9	8.5	7	14.4	13.8	-4
100	3.1	5.9	47	4.0	6.7	41	5.6	8.1	31	8.8	10.8	18	15.3	16.2	6
200	4.9	10.7	54	5.8	11.5	50	7.4	12.9	43	10.6	15.6	32	17.1	21.1	19
APRIL APPLICATION															
0	1.6	1.5	-5	2.4	2.3	-1	3.7	3.7	-2	6.4	6.3	-3	11.9	11.6	-3
25	1.9	2.6	26	2.8	3.4	18	4.4	4.7	8	7.5	7.4	-2	13.9	12.7	-9
50	2.4	3.7	35	3.2	4.5	27	4.8	5.8	17	8.0	8.5	5	14.4	13.9	-3
100	3.4	6.1	45	4.2	6.7	37	5.8	8.1	28	9.0	10.8	16	15.4	16.5	6
200	5.5	11.5	53	6.3	11.5	45	7.9	12.9	39	11.1	15.6	29	17.5	22.1	21
JUNE APPLICATION															
0	1.6	1.5	-2	2.4	2.4	0	3.7	3.7	-1	6.4	6.3	-2	11.9	11.6	-2
25	1.8	2.1	17	2.6	2.9	12	4.0	4.2	6	6.9	6.9	0	12.7	12.2	-4
50	2.0	2.7	25	2.8	3.5	19	4.3	4.8	12	7.2	7.5	4	12.9	12.8	-1
100	2.6	3.9	34	3.3	4.7	29	4.8	6.0	20	7.7	8.7	11	13.5	14.0	4
200	3.8	6.6	42	4.6	7.4	38	6.1	8.8	31	9.0	11.5	22	14.8	16.8	12
OCTOBER APPLICATION															
0	1.5	1.5	-3	2.3	2.3	-1	3.7	3.6	-2	6.4	6.3	-2	11.9	11.5	-3
25	1.6	2.1	25	2.4	2.9	17	4.0	4.2	6	7.1	6.9	-4	13.5	12.2	-10
50	1.8	2.7	33	2.6	3.5	24	4.2	4.8	12	7.4	7.5	1	13.7	12.8	-7
100	2.3	3.8	41	3.1	4.6	34	4.7	6.0	22	7.8	8.7	10	14.2	14.1	-1
200	3.1	6.2	49	4.0	7.0	43	5.6	8.3	33	8.7	11.1	21	15.1	16.6	9
NOVEMBER APPLICATION															
0	1.5	1.5	-2	2.3	2.3	-1	3.7	3.6	-2	6.4	6.3	-2	11.9	11.5	-3
25	1.6	2.1	24	2.5	2.9	16	4.1	4.3	5	7.3	6.9	-5	13.7	12.3	-11
50	1.9	2.8	32	2.7	3.6	24	4.3	4.9	12	7.5	7.6	1	13.9	12.9	-8
100	2.4	4.1	41	3.2	4.9	34	4.8	6.2	22	8.0	8.9	10	14.5	14.4	-1
200	3.4	6.8	49	4.3	7.6	44	5.9	9.0	35	9.1	11.7	22	15.5	17.2	10

[†] INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

Appendix C: C4. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a continuous corn-winter wheat-soybean rotation

Phosphorus rates	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT[2]	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %	INC	NT	± %
JANUARY APPLICATION															
0	0.7	0.8	14	1.3	1.4	9	2.1	2.0	-3	3.7	3.3	-13	7.0	5.8	-20
25	1.0	1.6	34	1.6	2.1	26	2.4	2.7	13	4.0	4.0	0	7.2	6.5	-11
50	1.4	2.3	41	1.9	2.8	35	2.7	3.5	23	4.3	4.7	9	7.6	7.2	-4
100	2.0	3.9	48	2.5	4.4	44	3.3	5.1	35	4.9	6.3	22	8.2	8.9	7
200	3.3	7.2	55	3.8	7.8	52	4.6	8.4	46	6.2	9.7	36	9.5	12.3	22
APRIL APPLICATION															
0	0.8	0.8	-4	1.4	1.4	0	2.0	2.0	-1	3.3	3.3	-1	6.0	5.8	-2
25	1.1	1.5	26	1.6	2.0	21	2.4	2.7	10	4.0	3.9	-1	7.1	6.1	-16
50	1.4	2.2	35	1.9	2.7	30	2.7	3.4	20	4.3	4.6	8	7.4	6.5	-13
100	2.1	3.7	44	2.5	4.2	40	3.3	4.8	31	4.9	6.1	20	8.0	7.4	-9
200	3.4	7.0	52	3.8	7.5	49	4.6	8.2	43	6.2	9.5	34	9.4	9.1	-4
OCTOBER APPLICATION															
0	0.7	0.8	17	1.2	1.4	11	2.0	2.0	0	3.6	3.3	-10	6.8	5.8	-16
25	0.9	1.2	30	1.3	1.7	22	2.1	2.4	10	3.7	3.6	-2	6.8	6.1	-12
50	1.0	1.7	37	1.5	2.1	30	2.3	2.8	18	3.8	4.0	4	7.0	6.5	-7
100	1.4	2.5	45	1.8	2.9	39	2.6	3.6	28	4.1	4.8	14	7.3	7.4	1
200	3.6	4.1	13	4.2	4.5	7	5.5	5.2	-6	8.1	6.5	-25	13.2	9.1	-46
NOVEMBER APPLICATION															
0	0.7	0.8	15	1.2	1.4	9	2.0	2.0	-2	3.7	3.3	-12	6.9	5.8	-19
25	0.9	1.3	29	1.4	1.8	21	2.2	2.4	8	3.8	3.6	-4	7.0	6.1	-14
50	1.1	1.7	36	1.6	2.2	29	2.4	2.8	16	4.0	4.1	3	7.2	6.6	-9
100	1.5	2.6	44	1.9	3.1	38	2.7	3.7	27	4.3	5.0	14	7.5	7.5	0
200	2.2	4.5	52	2.6	5.0	47	3.4	5.6	39	5.0	6.9	27	8.3	9.5	13

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C5. Average annual runoff loss with different soil test phosphorus, application rates, and timings in a continuous corn rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	172	140	172	140	172	140	172	140	172	140
25	172	142	172	142	172	142	172	142	172	142
50	172	143	172	143	172	143	172	143	172	143
100	172	144	172	144	172	144	172	144	172	144
200	172	145	172	145	172	145	172	145	172	145
APRIL APPLICATION										
0	156	143	156	143	156	143	156	143	156	143
25	156	137	156	137	156	137	156	137	156	137
50	156	137	156	137	156	137	156	137	156	137
100	156	138	156	138	156	138	156	138	156	138
200	156	139	156	139	156	139	156	139	156	139
OCTOBER APPLICATION										
0	165	143	165	143	165	143	165	143	165	143
25	165	150	165	150	165	150	165	150	165	150
50	165	151	165	151	165	151	165	151	165	151
100	164	153	164	153	164	153	164	153	164	153
200	163	155	163	155	163	155	163	155	163	155
NOVEMBER APPLICATION										
0	170	141	170	141	170	141	170	141	170	141
25	170	145	170	145	170	145	170	145	170	145
50	170	146	170	146	170	146	170	146	170	146
100	169	148	169	148	169	148	169	148	169	148
200	169	151	169	151	169	151	169	151	169	151

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C6. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a continuous corn rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01
25	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02
50	0.60	0.02	0.60	0.02	0.60	0.02	0.60	0.02	0.60	0.02
100	0.63	0.02	0.63	0.02	0.63	0.02	0.63	0.02	0.63	0.02
200	0.68	0.03	0.68	0.03	0.68	0.03	0.68	0.03	0.68	0.03
APRIL APPLICATION										
0	0.47	0.03	0.47	0.03	0.47	0.03	0.47	0.03	0.47	0.03
25	0.57	0.01	0.57	0.01	0.57	0.01	0.57	0.01	0.57	0.01
50	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
100	0.63	0.01	0.63	0.01	0.63	0.01	0.63	0.01	0.63	0.01
200	0.70	0.02	0.70	0.02	0.70	0.02	0.70	0.02	0.70	0.02
OCTOBER APPLICATION										
0	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01
25	0.62	0.04	0.62	0.04	0.62	0.04	0.62	0.04	0.62	0.04
50	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05
100	0.69	0.07	0.69	0.07	0.69	0.07	0.69	0.07	0.69	0.07
200	0.74	0.10	0.74	0.10	0.74	0.10	0.74	0.10	0.74	0.10
NOVEMBER APPLICATION										
0	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01	0.27	0.01
25	0.60	0.02	0.60	0.02	0.60	0.02	0.60	0.02	0.60	0.02
50	0.62	0.03	0.62	0.03	0.62	0.03	0.62	0.03	0.62	0.03
100	0.67	0.04	0.67	0.04	0.67	0.04	0.67	0.04	0.67	0.04
200	0.73	0.06	0.73	0.06	0.73	0.06	0.73	0.06	0.73	0.06

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C7. Average annual runoff loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	151	144	151	144	151	144	151	144	151	144
25	149	140	149	140	149	140	149	140	149	140
50	148	140	148	140	148	140	148	140	148	140
100	148	140	148	140	148	140	148	140	148	140
200	149	141	149	141	149	141	149	141	149	141
APRIL APPLICATION										
0	147	143	147	143	147	143	147	143	147	143
25	144	139	144	139	144	139	144	139	144	139
50	144	139	144	139	144	139	144	139	144	139
100	144	140	144	140	144	140	144	140	144	140
200	146	142	146	142	146	142	146	142	146	142
OCTOBER APPLICATION										
0	146	144	146	144	146	144	146	144	146	144
25	143	140	143	140	143	140	143	140	143	140
50	143	140	143	140	143	140	143	140	143	140
100	142	140	142	140	142	140	142	140	142	140
200	143	141	143	141	143	141	143	141	143	141
NOVEMBER APPLICATION										
0	149	144	149	144	149	144	149	144	149	144
25	146	140	146	140	146	140	146	140	146	140
50	146	140	146	140	146	140	146	140	146	140
100	145	140	145	140	145	140	145	140	145	140
200	146	141	146	141	146	141	146	141	146	141

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C8. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	0.23	0.02	0.23	0.02	0.23	0.02	0.23	0.02	0.23	0.02
25	0.24	0.02	0.24	0.02	0.24	0.02	0.24	0.02	0.24	0.02
50	0.24	0.02	0.24	0.02	0.24	0.02	0.24	0.02	0.24	0.02
100	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
200	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
APRIL APPLICATION										
0	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
25	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
50	0.26	0.02	0.26	0.02	0.26	0.02	0.26	0.02	0.26	0.02
100	0.28	0.02	0.28	0.02	0.28	0.02	0.28	0.02	0.28	0.02
200	0.30	0.03	0.30	0.03	0.30	0.03	0.30	0.03	0.30	0.03
OCTOBER APPLICATION										
0	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
25	0.21	0.02	0.21	0.02	0.21	0.02	0.21	0.02	0.21	0.02
50	0.22	0.02	0.22	0.02	0.22	0.02	0.22	0.02	0.22	0.02
100	0.24	0.03	0.24	0.03	0.24	0.03	0.24	0.03	0.24	0.03
200	0.26	0.03	0.26	0.03	0.26	0.03	0.26	0.03	0.26	0.03
NOVEMBER APPLICATION										
0	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
25	0.22	0.02	0.22	0.02	0.22	0.02	0.22	0.02	0.22	0.02
50	0.23	0.02	0.23	0.02	0.23	0.02	0.23	0.02	0.23	0.02
100	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02	0.25	0.02
200	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: A9. Average annual runoff loss with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	170	163	170	163	170	163	170	163	170	163
25	183	163	183	163	183	163	183	163	183	163
50	183	164	183	164	183	164	183	164	183	164
100	183	164	183	164	183	164	183	164	183	164
200	182	165	182	165	182	165	182	165	182	165
APRIL APPLICATION										
0	170	163	170	163	170	163	170	163	170	163
25	169	163	169	163	169	163	169	163	169	163
50	169	164	169	164	169	164	169	164	169	164
100	168	164	168	164	168	164	168	164	168	164
200	167	165	167	165	167	165	167	165	167	165
JUNE APPLICATION										
0	170	163	170	163	170	163	170	163	170	163
25	169	163	169	163	169	163	169	163	169	163
50	169	163	169	163	169	163	169	163	169	163
100	169	163	169	163	169	163	169	163	169	163
200	170	163	170	163	170	163	170	163	170	163
OCTOBER APPLICATION										
0	170	163	170	163	170	163	170	163	170	163
25	192	163	192	163	192	163	192	163	192	163
50	192	164	192	164	192	164	192	164	192	164
100	191	164	191	164	191	164	191	164	191	164
200	189	165	189	165	189	165	189	165	189	165
NOVEMBER APPLICATION										
0	170	163	170	163	170	163	170	163	170	163
25	192	163	192	163	192	163	192	163	192	163
50	192	164	192	164	192	164	192	164	192	164
100	191	164	191	164	191	164	191	164	191	164
200	189	165	189	165	189	165	189	165	189	165

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: A10. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a grain sorghum -soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	0.16	0.08	0.16	0.08	0.16	0.08	0.16	0.08	0.08	163
25	0.91	0.09	0.91	0.09	0.91	0.09	0.91	0.09	0.09	163
50	0.92	0.09	0.92	0.09	0.92	0.09	0.92	0.09	0.09	164
100	0.95	0.10	0.95	0.10	0.95	0.10	0.95	0.10	0.10	164
200	0.99	0.11	0.99	0.11	0.99	0.11	0.99	0.11	0.11	165
APRIL APPLICATION										
0	0.16	0.08	0.16	0.08	0.16	0.08	0.16	0.08	0.08	163
25	1.04	0.09	1.04	0.09	1.04	0.09	1.04	0.09	0.09	163
50	1.07	0.09	1.07	0.09	1.07	0.09	1.07	0.09	0.09	164
100	1.11	0.10	1.11	0.10	1.11	0.10	1.11	0.10	0.10	164
200	1.16	0.13	1.16	0.13	1.16	0.13	1.16	0.13	0.13	165
JUNE APPLICATION										
0	0.16	0.08	0.16	0.08	0.16	0.08	0.16	0.08	0.08	163
25	0.73	0.08	0.73	0.08	0.73	0.08	0.73	0.08	0.08	163
50	0.74	0.09	0.74	0.09	0.74	0.09	0.74	0.09	0.09	163
100	0.76	0.09	0.76	0.09	0.76	0.09	0.76	0.09	0.09	163
200	0.79	0.10	0.79	0.10	0.79	0.10	0.79	0.10	0.10	163
OCTOBER APPLICATION										
0	0.16	0.08	0.16	0.08	0.16	0.08	0.16	0.08	0.08	163
25	0.97	0.09	0.97	0.09	0.97	0.09	0.97	0.09	0.09	163
50	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.10	0.10	164
100	1.04	0.11	1.04	0.11	1.04	0.11	1.04	0.11	0.11	164
200	1.10	0.15	1.10	0.15	1.10	0.15	1.10	0.15	0.15	165
NOVEMBER APPLICATION										
0	0.16	0.08	0.16	0.08	0.16	0.08	0.16	0.08	0.08	163
25	0.92	0.09	0.92	0.09	0.92	0.09	0.92	0.09	0.09	163
50	0.95	0.09	0.95	0.09	0.95	0.09	0.95	0.09	0.09	164
100	1.01	0.11	1.01	0.11	1.01	0.11	1.01	0.11	0.11	164
200	1.09	0.13	1.09	0.13	1.09	0.13	1.09	0.13	0.13	165

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C11. Average annual runoff loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	96	92	96	92	96	92	96	92	96	92
25	95	91	95	91	95	91	95	91	95	91
50	95	91	95	91	95	91	95	91	95	91
100	95	91	95	91	95	91	95	91	95	91
200	94	91	94	91	94	91	94	91	94	91
APRIL APPLICATION										
0	96	92	96	92	96	92	96	92	96	92
25	95	91	95	91	95	91	95	91	95	91
50	95	91	95	91	95	91	95	91	95	91
100	95	91	95	91	95	91	95	91	95	91
200	95	92	95	92	95	92	95	92	95	92
OCTOBER APPLICATION										
0	91	92	91	92	91	92	91	92	91	92
25	90	91	90	91	90	91	90	91	90	91
50	89	91	89	91	89	91	89	91	89	91
100	89	91	89	91	89	91	89	91	89	91
200	88	91	88	91	88	91	88	91	88	91
NOVEMBER APPLICATION										
0	94	92	94	92	94	92	94	92	94	92
25	92	91	92	91	92	91	92	91	92	91
50	92	91	92	91	92	91	92	91	92	91
100	91	91	91	91	91	91	91	91	91	91
200	91	91	91	91	91	91	91	91	91	91

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX C: C12. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm		50 ppm		100 ppm		200 ppm		400 ppm	
	INC†	NT	INC	NT	INC	NT	INC	NT	INC	NT
JANUARY APPLICATION										
0	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01
25	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01
50	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01
100	0.12	0.01	0.12	0.01	0.12	0.01	0.12	0.01	0.12	0.01
200	0.13	0.01	0.13	0.01	0.13	0.01	0.13	0.01	0.13	0.01
APRIL APPLICATION										
0	0.23	0.01	0.23	0.01	0.23	0.01	0.23	0.01	0.23	0.01
25	0.14	0.01	0.14	0.01	0.14	0.01	0.14	0.01	0.14	0.01
50	0.15	0.01	0.15	0.01	0.15	0.01	0.15	0.01	0.15	0.01
100	0.16	0.01	0.16	0.01	0.16	0.01	0.16	0.01	0.16	0.01
200	0.18	0.01	0.18	0.01	0.18	0.01	0.18	0.01	0.18	0.01
OCTOBER APPLICATION										
0	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01
25	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01
50	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01
100	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01
200	0.31	0.01	0.31	0.01	0.31	0.01	0.31	0.01	0.31	0.01
NOVEMBER APPLICATION										
0	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01	0.09	0.01
25	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01
50	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01	0.10	0.01
100	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01	0.11	0.01
200	0.12	0.01	0.12	0.01	0.12	0.01	0.12	0.01	0.12	0.01

†INC= Poultry litter incorporated with chisel-disk-field cultivate; NT = No till-Surface broadcast

APPENDIX D. Full model runs results for total phosphorus, and sediment loss with different management practices, Franklin runoff study site

Watershed 8

Appendix D: D1. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a continuous-corn rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	1.1	0.9	0.61	-12	1.6	1.2	0.9	-31	2.5	1.6	1.3	-55	4.5	2.5	2.2	-78	8.3	4.2	4.1	-96
25	1.6	2.1	0.61	23	2.1	2.3	0.9	10	3.1	2.8	1.3	-11	5.0	3.7	2.2	-37	8.9	5.4	4.1	-64
50	2.2	3.2	0.61	33	2.7	3.5	0.9	23	3.6	3.9	1.3	7	5.6	4.8	2.2	-16	9.4	6.5	4.1	-44
75	2.7	4.3	0.61	38	3.2	4.6	0.9	30	4.2	5.0	1.3	17	6.1	5.9	2.2	-4	10.0	7.7	4.1	-30
APRIL APPLICATION																				
0	1.1	1.0	0.61	-10	1.6	1.2	0.8	-25	2.5	1.7	1.3	-47	4.3	2.6	2.1	-68	7.9	4.3	3.9	-84
25	1.6	2.0	0.60	21	2.0	2.2	0.9	9	3.0	2.7	1.3	-10	4.8	3.6	2.2	-34	8.4	5.3	4.0	-59
50	2.0	3.0	0.61	32	2.5	3.2	0.9	23	3.4	3.7	1.3	7	5.2	4.5	2.2	-15	8.9	6.3	4.0	-41
75	2.5	4.0	0.62	37	3.0	4.2	0.9	30	3.9	4.7	1.3	17	5.7	5.5	2.2	-3	9.3	7.3	4.0	-29
OCTOBER APPLICATION																				
0	1.0	0.9	0.61	-16	1.5	1.1	0.8	-36	2.5	1.6	1.3	-59	4.4	2.4	2.2	-81	8.3	4.2	3.9	-97
25	1.4	1.6	0.64	12	1.9	1.8	0.9	-4	2.9	2.3	1.4	-27	4.9	3.2	2.3	-53	8.9	5.0	4.1	-76
50	1.7	2.2	0.67	23	2.2	2.5	0.9	10	3.2	2.9	1.4	-10	5.2	3.9	2.3	-35	9.2	5.7	4.2	-62
75	2.1	2.9	0.70	29	2.6	3.1	0.9	18	3.6	3.6	1.4	1	5.6	4.5	2.3	-23	9.6	6.4	4.2	-51
NOVEMBER APPLICATION																				
0	1.0	0.9	0.62	-17	1.5	1.1	0.8	-36	2.5	1.6	1.3	-60	4.5	2.5	2.1	-82	8.4	4.2	3.9	-99
25	1.4	1.6	0.65	13	1.9	1.9	0.9	-3	3.0	2.4	1.4	-26	5.0	3.3	2.3	-52	9.0	5.1	4.1	-77
50	1.8	2.4	0.67	24	2.3	2.6	0.9	12	3.3	3.1	1.4	-8	5.3	4.0	2.3	-34	9.3	5.8	4.1	-61
75	2.2	3.1	0.70	30	2.7	3.4	0.9	20	3.7	3.8	1.4	3	5.7	4.7	2.3	-21	9.7	6.5	4.2	-49

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D2. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 8

Phosphorus application	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
rates (Kg ha^{-1})	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	0.6	0.6	0.6	-3	1.1	1.1	1.0	0	1.7	1.6	1.5	-9	3.1	2.6	2.6	-16	5.7	4.7	4.6	-21
25	1.0	1.3	0.6	27	1.4	1.8	1.0	22	2.1	2.3	1.6	11	3.4	3.4	2.6	-1	6.0	5.4	4.8	-11
50	1.3	2.0	0.6	36	1.7	2.5	1.0	32	2.4	3.0	1.6	21	3.7	4.1	2.7	9	6.4	6.1	4.8	-4
75	1.6	2.8	0.7	41	2.0	3.2	1.1	37	2.7	3.7	1.6	28	4.0	4.8	2.7	16	6.7	6.8	4.8	2
APRIL APPLICATION																				
0	0.6	0.6	0.6	-7	1.1	1.1	1.0	-2	1.8	1.6	1.5	-9	3.1	2.6	2.6	-16	5.6	4.7	4.6	-20
25	1.0	1.3	0.6	24	1.4	1.8	1.0	20	2.1	2.3	1.6	10	3.4	3.3	2.6	-1	6.0	5.4	4.8	-10
50	1.3	2.0	0.7	34	1.7	2.5	1.0	30	2.4	3.0	1.6	20	3.7	4.0	2.7	9	6.3	6.1	4.8	-3
75	1.6	2.7	0.7	39	2.0	3.1	1.1	36	2.7	3.7	1.6	27	4.0	4.7	2.7	15	6.6	6.8	4.8	3
OCTOBER APPLICATION																				
0	0.6	0.6	0.5	1	1.0	1.1	1.0	2	1.7	1.6	1.5	-7	3.0	2.6	2.6	-14	5.6	4.7	4.6	-19
25	0.8	1.0	0.6	22	1.2	1.5	1.0	16	1.9	2.0	1.6	5	3.2	3.1	2.6	-5	5.8	5.1	4.8	-14
50	1.1	1.5	0.7	29	1.4	1.9	1.1	24	2.1	2.4	1.6	13	3.4	3.5	2.7	2	6.0	5.5	4.8	-9
75	1.3	1.9	0.7	34	1.6	2.3	1.1	29	2.3	2.8	1.6	19	3.6	3.9	2.7	7	6.2	6.0	4.8	-4
NOVEMBER APPLICATION																				
0	0.6	0.6	0.5	-1	1.1	1.1	1.0	0	1.7	1.6	1.5	-9	3.0	2.6	2.6	-16	5.7	4.7	4.6	-21
25	0.9	1.1	0.6	22	1.3	1.5	1.0	16	2.0	2.1	1.6	5	3.3	3.1	2.6	-6	5.9	5.2	4.8	-14
50	1.1	1.6	0.7	30	1.5	2.0	1.1	25	2.2	2.5	1.6	14	3.5	3.6	2.7	2	6.1	5.6	4.8	-9
75	1.3	2.1	0.7	35	1.7	2.5	1.1	30	2.4	3.0	1.6	20	3.7	4.0	2.7	8	6.4	6.1	4.8	-4

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D3. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	1.0	0.7	0.7	-37	1.7	1.2	1.2	-39	2.9	1.9	1.9	-51	5.3	3.3	3.3	-60	10.1	6.1	6.0	-66
25	1.5	1.8	0.8	16	2.1	2.2	1.2	4	3.3	2.9	1.9	-14	5.7	4.3	3.3	-33	10.5	7.1	6.2	-49
50	2.0	2.8	0.8	30	2.6	3.3	1.2	20	3.8	4.0	1.9	4	6.2	5.3	3.4	-16	11.0	8.1	6.2	-36
75	2.4	3.8	0.8	37	3.1	4.3	1.2	29	4.3	5.0	2.0	14	6.7	6.4	3.4	-5	11.5	9.1	6.3	-26
APRIL APPLICATION																				
0	1.1	0.8	0.7	-51	1.9	1.2	1.2	-51	3.1	1.9	1.9	-64	5.7	3.3	3.3	-71	10.8	6.1	6.1	-77
25	1.6	1.8	0.8	11	2.3	2.3	1.2	-1	3.6	2.9	1.9	-23	6.2	4.4	3.4	-40	11.3	7.2	6.3	-57
50	2.1	2.9	0.8	27	2.8	3.4	1.2	17	4.1	4.0	1.9	-3	6.7	5.5	3.4	-22	11.8	8.3	6.3	-42
75	2.6	4.0	0.8	35	3.3	4.4	1.3	26	4.6	5.0	2.0	8	7.1	6.5	3.4	-9	12.3	9.3	6.3	-31
JUNE APPLICATION																				
0	1.0	0.8	0.7	-25	1.5	1.2	1.2	-23	2.5	1.9	1.9	-29	4.4	3.3	3.3	-33	8.3	6.1	6.0	-36
25	1.3	1.4	0.8	11	1.8	1.9	1.2	4	2.8	2.6	1.9	-8	4.7	4.0	3.3	-19	8.6	6.7	6.1	-27
50	1.6	2.1	0.8	24	2.1	2.5	1.2	17	3.1	3.2	1.9	4	5.0	4.6	3.3	-9	8.9	7.4	6.1	-20
75	1.9	2.7	0.8	32	2.4	3.2	1.2	24	3.4	3.9	1.9	13	5.3	5.2	3.3	-1	9.1	8.0	6.1	-14
OCTOBER APPLICATION																				
0	1.0	0.7	0.7	-33	1.6	1.2	1.2	-36	2.8	1.9	1.9	-48	5.2	3.3	3.3	-58	5.2	3.3	6.0	-58
25	1.3	1.3	0.8	5	1.9	1.8	1.2	-7	3.1	2.5	1.9	-25	5.5	3.9	3.4	-41	5.5	3.9	6.2	-41
50	1.6	1.9	0.8	19	2.2	2.4	1.2	7	3.4	3.1	2.0	-10	5.8	4.5	3.4	-29	5.8	4.5	6.3	-29
75	1.9	2.5	0.9	26	2.5	3.0	1.3	16	3.7	3.7	2.0	0	6.1	5.1	3.4	-20	6.1	5.1	6.3	-20
NOVEMBER APPLICATION																				
0	1.0	0.7	0.7	-36	1.7	1.2	1.2	-38	2.9	1.9	1.9	-51	5.3	3.3	3.3	-60	10.1	6.1	6.0	-66
25	1.3	1.4	0.8	6	2.0	1.9	1.2	-6	3.2	2.6	1.9	-24	5.6	3.9	3.4	-42	10.4	6.7	6.2	-55
50	1.7	2.1	0.8	20	2.3	2.5	1.3	9	3.5	3.2	2.0	-9	5.9	4.6	3.4	-28	10.7	7.4	6.3	-45
75	2.0	2.7	0.9	28	2.6	3.2	1.3	18	3.8	3.9	2.0	1	6.2	5.3	3.5	-18	11.0	8.0	6.3	-37

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D4. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	0.2	0.2	0.2	13	0.5	0.6	0.5	13	0.8	0.8	0.8	2	1.4	1.3	1.3	-7	2.6	2.3	2.3	-13
25	0.4	0.6	0.2	40	0.7	1.0	0.5	33	1.0	1.3	0.8	22	1.6	1.8	1.3	9	2.8	2.8	2.3	-2
50	0.6	1.1	0.3	44	0.8	1.4	0.5	41	1.2	1.7	0.8	31	1.8	2.2	1.3	19	3.0	3.2	2.3	6
75	0.8	1.6	0.3	47	1.0	1.9	0.5	45	1.3	2.1	0.8	37	1.9	2.6	1.3	25	3.2	3.6	2.3	12
APRIL APPLICATION																				
0	0.2	0.2	0.2	5	0.5	0.6	0.5	10	0.8	0.8	0.8	1	1.4	1.3	1.3	-7	2.6	2.3	2.3	-13
25	0.4	0.7	0.2	37	0.7	1.0	0.5	32	1.0	1.3	0.8	22	1.6	1.8	1.3	10	2.8	2.8	2.3	-1
50	0.7	1.2	0.3	44	0.9	1.5	0.5	41	1.2	1.7	0.8	32	1.8	2.2	1.3	20	3.0	3.3	2.3	8
75	0.9	1.6	0.3	48	1.1	1.9	0.5	45	1.4	2.2	0.8	38	2.0	2.7	1.3	27	3.2	3.7	2.3	14
OCTOBER APPLICATION																				
0	0.1	0.2	0.2	22	0.5	0.6	0.5	17	0.8	0.8	0.8	7	1.3	1.3	1.3	-2	2.5	2.3	2.3	-8
25	0.3	0.5	0.2	39	0.6	0.8	0.5	30	0.9	1.1	0.8	18	1.5	1.6	1.3	7	2.6	2.6	2.3	-2
50	0.5	0.8	0.3	41	0.7	1.0	0.5	36	1.0	1.3	0.8	26	1.6	1.8	1.3	14	2.7	2.8	2.3	3
75	0.6	1.0	0.3	44	0.8	1.3	0.6	40	1.1	1.5	0.8	31	1.7	2.0	1.3	19	2.8	3.1	2.4	7
NOVEMBER APPLICATION																				
0	0.2	0.2	0.2	17	0.5	0.6	0.5	14	0.8	0.8	0.8	3	1.4	1.3	1.3	-6	2.6	2.3	2.3	-12
25	0.3	0.5	0.2	37	0.6	0.8	0.5	29	0.9	1.1	0.8	17	1.5	1.6	1.3	5	2.7	2.6	2.3	-5
50	0.5	0.8	0.3	40	0.7	1.1	0.5	36	1.0	1.4	0.8	25	1.6	1.9	1.3	13	2.8	2.9	2.4	1
75	0.6	1.1	0.3	44	0.8	1.4	0.6	40	1.1	1.6	0.8	30	1.8	2.1	1.3	18	3.0	3.2	2.4	6

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D5. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a continuous corn rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	125	100	104	125	100	104	125	100	104	125	100	104	125	100	104
25	126	102	104	126	102	104	126	102	104	126	102	104	126	102	104
50	126	102	104	126	102	104	126	102	104	126	102	104	126	102	104
75	126	102	104	126	102	104	126	102	104	126	102	104	126	102	104
APRIL APPLICATION															
0	117	100	100	117	100	100	117	100	100	117	100	100	117	100	100
25	118	101	103	118	101	103	118	101	103	118	101	103	118	101	103
50	118	101	103	118	101	103	118	101	103	118	101	103	118	101	103
75	118	101	103	118	101	103	118	101	103	118	101	103	118	101	103
OCTOBER APPLICATION															
0	122	101	100	122	101	100	122	101	100	122	101	100	122	101	100
25	122	104	104	122	104	104	122	104	104	122	104	104	122	104	104
50	122	104	104	122	104	104	122	104	104	122	104	104	122	104	104
75	122	104	104	122	104	104	122	104	104	122	104	104	122	104	104
NOVEMBER APPLICATION															
0	126	101	99	126	101	99	126	101	99	126	101	99	126	101	99
25	126	103	104	126	103	104	126	103	104	126	103	104	126	103	104
50	126	103	104	126	103	104	126	103	104	126	103	104	126	103	104
75	126	103	104	126	103	104	126	103	104	126	103	104	126	103	104

[†] INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D6. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a continuous corn rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	0.410	0.002	0.004	0.410	0.002	0.004	0.410	0.002	0.004	0.410	0.002	0.004	0.410	0.002	0.004
25	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004
50	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004
75	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004	0.414	0.003	0.004
APRIL APPLICATION															
0	0.430	0.002	0.002	0.430	0.002	0.002	0.430	0.002	0.002	0.430	0.002	0.002	0.430	0.002	0.002
25	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004
50	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004
75	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004	0.437	0.002	0.004
OCTOBER APPLICATION															
0	0.413	0.002	0.001	0.413	0.002	0.001	0.413	0.002	0.001	0.413	0.002	0.001	0.413	0.002	0.001
25	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004
50	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004
75	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004	0.445	0.004	0.004
NOVEMBER APPLICATION															
0	0.406	0.002	0.001	0.406	0.002	0.001	0.406	0.002	0.001	0.406	0.002	0.001	0.406	0.002	0.001
25	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004
50	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004
75	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004	0.433	0.004	0.004

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D7. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 8

Phosphorus application	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
rates (Kg ha^{-1})	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	117	111	111	117	111	111	117	111	111	117	111	111	117	111	111
25	118	112	113	118	112	113	118	112	113	118	112	113	118	112	113
50	118	112	113	118	112	113	118	112	113	118	112	113	118	112	113
75	118	112	113	118	112	113	118	112	113	118	112	113	118	112	113
APRIL APPLICATION															
0	116	111	111	116	111	111	116	111	111	116	111	111	116	111	111
25	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113
50	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113
75	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113
OCTOBER APPLICATION															
0	114	111	111	114	111	111	114	111	111	114	111	111	114	111	111
25	116	112	113	116	112	113	116	112	113	116	112	113	116	112	113
50	116	112	113	116	112	113	116	112	113	116	112	113	116	112	113
75	116	112	113	116	112	113	116	112	113	116	112	113	116	112	113
NOVEMBER APPLICATION															
0	116	111	111	116	111	111	116	111	111	116	111	111	116	111	111
25	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113
50	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113
75	117	112	113	117	112	113	117	112	113	117	112	113	117	112	113

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D8. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC†	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	0.094	0.004	0.005	0.094	0.004	0.005	0.094	0.004	0.005	0.094	0.004	0.005	0.094	0.004	0.005
25	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006
50	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006
75	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006	0.094	0.005	0.006
APRIL APPLICATION															
0	0.109	0.004	0.005	0.109	0.004	0.005	0.109	0.004	0.005	0.109	0.004	0.005	0.109	0.004	0.005
25	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007
50	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007
75	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007	0.109	0.005	0.007
OCTOBER APPLICATION															
0	0.086	0.004	0.004	0.086	0.004	0.004	0.086	0.004	0.004	0.086	0.004	0.004	0.086	0.004	0.004
25	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006
50	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006
75	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006	0.086	0.005	0.006
NOVEMBER APPLICATION															
0	0.092	0.004	0.005	0.092	0.004	0.005	0.092	0.004	0.005	0.092	0.004	0.005	0.092	0.004	0.005
25	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006
50	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006
75	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006	0.092	0.005	0.006

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D9. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC†	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	124	119	119	124	119	119	124	119	119	124	119	119	124	119	119
25	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
50	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
75	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
APRIL APPLICATION															
0	124	119	119	124	119	119	124	119	119	124	119	119	124	119	119
25	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
50	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
75	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
JUNE APPLICATION															
0	121	119	119	121	119	119	121	119	119	121	119	119	121	119	119
25	121	119	119	121	119	119	121	119	119	121	119	119	121	119	119
50	121	119	119	121	119	119	121	119	119	121	119	119	121	119	119
75	121	119	119	121	119	119	121	119	119	121	119	119	121	119	119
OCTOBER APPLICATION															
0	122	119	119	122	119	119	122	119	119	122	119	119	122	119	119
25	122	119	120	122	119	120	122	119	120	122	119	120	122	119	120
50	122	119	120	122	119	120	122	119	120	122	119	120	122	119	120
75	122	119	120	122	119	120	122	119	120	122	119	120	122	119	120
NOVEMBER APPLICATION															
0	124	119	119	124	119	119	124	119	119	124	119	119	124	119	119
25	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
50	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120
75	124	119	120	124	119	120	124	119	120	124	119	120	124	119	120

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D10. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a grain sorghum - soybean rotation, watershed 8

Phosphorus application rates	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
(Kg ha^{-1})	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	0.600	0.05	0.05	0.600	0.05	0.05	0.600	0.05	0.05	0.600	0.05	0.05	0.600	0.05	0.05
25	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07
50	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07
75	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07	0.600	0.05	0.07
APRIL APPLICATION															
0	0.760	0.06	0.06	0.760	0.06	0.06	0.760	0.06	0.06	0.760	0.06	0.06	0.760	0.06	0.06
25	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08
50	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08
75	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08	0.760	0.06	0.08
JUNE APPLICATION															
0	0.403	0.05	0.05	0.403	0.05	0.05	0.403	0.05	0.05	0.403	0.05	0.05	0.403	0.05	0.05
25	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06
50	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06
75	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06	0.403	0.05	0.06
OCTOBER APPLICATION															
0	0.570	0.05	0.05	0.570	0.05	0.05	0.570	0.05	0.05	0.570	0.05	0.05	0.570	0.05	0.05
25	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07
50	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07
75	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07	0.570	0.05	0.07
NOVEMBER APPLICATION															
0	0.586	0.05	0.05	0.586	0.05	0.05	0.586	0.05	0.05	0.586	0.05	0.05	0.586	0.05	0.05
25	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07
50	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07
75	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07	0.586	0.05	0.07

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D11. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation

Phosphorus application	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
rates (Kg ha^{-1})	INC†	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	66	63	63	66	63	63	66	63	63	66	63	63	66	63	63
25	66	64	64	66	64	64	66	64	64	66	64	64	66	64	64
50	66	64	64	66	64	64	66	64	64	66	64	64	66	64	64
75	66	64	64	66	64	64	66	64	64	66	64	64	66	64	64
APRIL APPLICATION															
0	66	63	63	66	63	63	66	63	63	66	63	63	66	63	63
25	67	64	64	67	64	64	67	64	64	67	64	64	67	64	64
50	67	64	64	67	64	64	67	64	64	67	64	64	67	64	64
75	67	64	64	67	64	64	67	64	64	67	64	64	67	64	64
OCTOBER APPLICATION															
0	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63
25	63	64	64	63	64	64	63	64	64	63	64	64	63	64	64
50	63	64	64	63	64	64	63	64	64	63	64	64	63	64	64
75	63	64	64	63	64	64	63	64	64	63	64	64	63	64	64
NOVEMBER APPLICATION															
0	65	63	63	65	63	63	65	63	63	65	63	63	65	63	63
25	65	64	64	65	64	64	65	64	64	65	64	64	65	64	64
50	65	64	64	65	64	64	65	64	64	65	64	64	65	64	64
75	65	64	64	65	64	64	65	64	64	65	64	64	65	64	64

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D12. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat--soybean rotation, watershed 8

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
JANUARY APPLICATION															
0	0.020	0.0003	0.051	0.020	0.0003	0.051	0.020	0.0003	0.051	0.020	0.0003	0.051	0.020	0.0003	0.051
25	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066
50	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066
75	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066	0.020	0.0003	0.066
APRIL APPLICATION															
0	0.027	0.0004	0.057	0.027	0.0004	0.057	0.027	0.0004	0.057	0.027	0.0004	0.057	0.027	0.0004	0.057
25	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076
50	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076
75	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076	0.027	0.0004	0.076
OCTOBER APPLICATION															
0	0.016	0.0004	0.051	0.016	0.0004	0.051	0.016	0.0004	0.051	0.016	0.0004	0.051	0.016	0.0004	0.051
25	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065
50	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065
75	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065	0.016	0.0004	0.065
NOVEMBER APPLICATION															
0	0.018	0.0004	0.051	0.018	0.0004	0.051	0.018	0.0004	0.051	0.018	0.0004	0.051	0.018	0.0004	0.051
25	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065
50	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065
75	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065	0.018	0.0004	0.065

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Watershed 4

Appendix D: D13. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a continuous-corn rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	2.2	0.9	0.71	-136	3.3	1.2	1.0	-180	5.4	1.6	1.5	-231	9.6	2.5	2.4	-279	18.1	4.4	4.4	-315
25	3.1	2.0	0.71	-51	4.1	2.3	1.0	-82	6.3	2.7	1.5	-129	10.5	3.7	2.4	-187	19.0	5.5	4.4	-244
50	3.9	3.1	0.71	-27	5.0	3.4	1.0	-50	7.1	3.8	1.5	-87	11.4	4.7	2.4	-140	19.8	6.6	4.4	-202
75	4.8	4.2	0.71	-15	5.9	4.4	1.0	-33	8.0	4.9	1.5	-64	12.3	5.8	2.4	-111	20.7	7.7	4.4	-171
APRIL APPLICATION																				
0	1.8	1.0	0.64	-90	2.7	1.2	0.9	-125	4.4	1.6	1.3	-167	7.8	2.5	2.2	-208	14.5	4.3	4.0	-239
25	2.7	1.9	0.69	-40	3.6	2.2	0.9	-65	5.2	2.6	1.4	-102	8.6	3.5	2.3	-149	15.4	5.2	4.2	-194
50	3.5	2.9	0.72	-24	4.4	3.1	1.0	-42	6.1	3.5	1.4	-72	9.5	4.4	2.4	-115	16.3	6.2	4.2	-163
75	4.4	3.8	0.76	-15	5.2	4.0	1.0	-30	6.9	4.5	1.5	-55	10.3	5.3	2.4	-93	17.1	7.1	4.2	-140
OCTOBER APPLICATION																				
0	1.7	0.8	0.64	-108	2.7	1.1	0.9	-144	4.4	1.6	1.3	-183	7.9	2.5	2.3	-218	15.0	4.4	4.2	-244
25	2.4	1.5	0.73	-57	3.4	1.8	1.0	-89	5.2	2.3	1.5	-131	9.0	3.2	2.5	-177	16.5	5.2	4.6	-217
50	2.9	2.2	0.78	-35	3.9	2.4	1.0	-61	5.8	2.9	1.6	-98	9.5	3.9	2.6	-145	17.1	5.8	4.7	-192
75	3.5	2.8	0.84	-23	4.4	3.1	1.1	-44	6.3	3.6	1.6	-78	10.1	4.5	2.7	-122	17.6	6.5	4.7	-171
NOVEMBER APPLICATION																				
0	1.8	0.8	0.64	-112	2.7	1.1	0.9	-148	4.5	1.6	1.3	-189	8.1	2.5	2.3	-226	15.2	4.3	4.1	-253
25	2.5	1.6	0.72	-55	3.4	1.8	1.0	-85	5.3	2.3	1.5	-127	9.0	3.3	2.5	-175	16.4	5.2	4.5	-217
50	3.1	2.3	0.78	-33	4.0	2.5	1.0	-58	5.9	3.0	1.5	-94	9.6	4.0	2.6	-141	17.0	5.9	4.6	-190
75	3.7	3.0	0.83	-22	4.6	3.3	1.1	-42	6.5	3.7	1.6	-74	10.2	4.7	2.6	-118	17.6	6.6	4.6	-168

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D14. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	0.7	0.6	0.6	-10	1.1	1.0	0.9	-11	1.8	1.5	1.5	-20	3.2	2.5	2.5	-28	6.0	4.5	4.5	-33
25	1.0	1.3	0.7	21	1.4	1.7	1.0	14	2.1	2.2	1.5	2	3.5	3.2	2.5	-12	6.4	5.2	4.6	-23
50	1.3	2.0	0.8	31	1.7	2.3	1.1	26	2.4	2.8	1.6	14	3.8	3.8	2.6	-1	6.7	5.8	4.6	-15
75	1.7	2.6	0.8	37	2.0	3.0	1.1	32	2.7	3.5	1.6	21	4.1	4.5	2.6	7	7.0	6.5	4.7	-8
APRIL APPLICATION																				
0	0.7	0.6	0.6	-14	1.1	1.0	1.0	-13	1.8	1.5	1.5	-21	3.2	2.5	2.5	-27	6.0	4.5	4.5	-31
25	1.1	1.3	0.7	18	1.5	1.7	1.0	13	2.1	2.2	1.5	0	3.5	3.1	2.5	-12	6.3	5.1	4.5	-23
50	1.4	1.9	0.8	29	1.7	2.3	1.1	24	2.4	2.8	1.6	13	3.8	3.8	2.6	-1	6.6	5.8	4.6	-15
75	1.7	2.6	0.8	36	2.0	2.9	1.1	31	2.7	3.4	1.6	20	4.1	4.4	2.6	7	6.9	6.4	4.6	-8
OCTOBER APPLICATION																				
0	0.6	0.6	0.6	-5	1.1	1.0	0.9	-8	1.8	1.5	1.4	-17	3.1	2.5	2.5	-24	5.8	4.5	4.5	-29
25	0.9	1.0	0.7	15	1.3	1.4	1.0	8	2.0	1.9	1.5	-4	3.3	2.9	2.5	-15	6.0	4.9	4.6	-24
50	1.1	1.4	0.8	25	1.5	1.8	1.1	18	2.1	2.3	1.6	6	3.5	3.3	2.6	-7	6.2	5.3	4.6	-19
75	1.3	1.8	0.8	31	1.6	2.2	1.1	24	2.3	2.7	1.6	12	3.7	3.7	2.6	-1	6.4	5.6	4.7	-14
NOVEMBER APPLICATION																				
0	0.7	0.6	0.6	-8	1.1	1.0	0.9	-10	1.8	1.5	1.5	-19	3.2	2.5	2.5	-27	5.9	4.5	4.5	-31
25	0.9	1.1	0.7	15	1.3	1.4	1.0	8	2.0	1.9	1.5	-4	3.4	2.9	2.5	-16	6.2	4.9	4.6	-26
50	1.1	1.5	0.8	25	1.5	1.9	1.1	18	2.2	2.4	1.6	6	3.6	3.4	2.6	-8	6.4	5.3	4.6	-20
75	1.4	2.0	0.8	31	1.1	1.0	1.1	-10	2.4	2.8	1.6	13	3.8	3.8	2.6	-1	6.6	5.8	4.7	-14

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D15. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation, watershed 4

Phosphorus	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
application rates (Kg ha^{-1})	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC †	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	1.3	0.8	0.8	-69	1.3	0.8	0.8	-67	2.0	1.2	1.2	-68	2.9	2.0	1.9	-49	7.3	3.4	3.4	-112
25	1.8	1.8	0.9	-1	1.6	1.4	0.8	-14	2.3	1.8	1.3	-31	3.2	2.6	2.0	-25	7.8	4.5	3.6	-74
50	2.3	2.8	0.9	18	2.0	2.1	0.9	5	2.6	2.4	1.4	-12	3.5	3.2	2.0	-10	8.3	5.5	3.7	-50
75	2.8	3.8	1.0	27	2.3	2.7	1.0	15	3.0	2.9	1.4	0	3.8	3.8	2.1	0	8.8	6.6	3.7	-34
APRIL APPLICATION																				
0	1.5	0.8	0.8	-86	2.1	1.2	1.2	-73	2.1	1.2	1.2	-72	3.5	1.9	1.9	-82	5.2	3.4	3.4	-54
25	2.0	1.8	0.9	-8	2.6	2.2	1.3	-17	2.4	1.8	1.3	-35	3.8	2.5	2.0	-52	5.5	4.0	3.5	-38
50	2.5	2.9	0.9	14	3.1	3.2	1.4	4	2.8	2.4	1.4	-16	4.1	3.1	2.1	-34	5.8	4.6	3.5	-26
75	3.0	3.9	1.0	24	3.6	4.2	1.4	15	3.1	2.9	1.4	-5	4.4	3.7	2.2	-21	6.1	5.2	3.5	-17
JUNE APPLICATION																				
0	1.1	0.8	0.8	-42	1.8	1.2	1.2	-41	2.9	2.0	1.9	-49	5.2	3.4	3.4	-54	9.8	6.3	6.2	-57
25	1.4	1.4	0.8	-2	2.1	1.9	1.2	-11	3.2	2.6	2.0	-25	5.5	4.0	3.5	-38	10.1	6.9	6.4	-47
50	1.7	2.0	0.9	14	2.4	2.5	1.3	4	3.5	3.2	2.0	-10	5.8	4.6	3.5	-26	10.4	7.5	6.4	-39
75	2.0	2.6	0.9	23	2.7	3.1	1.3	14	3.8	3.8	2.1	0	6.1	5.2	3.5	-17	10.7	8.1	6.5	-33
OCTOBER APPLICATION																				
0	1.1	0.8	0.8	-42	2.4	1.3	1.2	-88	3.6	1.9	1.9	-87	3.6	1.9	1.9	-86	3.6	1.9	3.3	-86
25	1.4	1.4	0.8	-2	2.9	2.3	1.3	-24	4.1	2.9	2.0	-40	3.9	2.6	2.0	-52	3.9	2.6	3.5	-52
50	1.7	2.0	0.9	14	3.4	3.3	1.4	0	4.6	3.9	2.1	-17	4.3	3.2	2.1	-32	4.3	3.2	3.6	-32
75	2.0	2.6	0.9	23	3.9	4.4	1.4	12	5.1	4.9	2.2	-3	4.6	3.9	2.2	-19	4.6	3.9	3.7	-19
NOVEMBER APPLICATION																				
0	1.3	0.8	0.7	-63	1.8	1.2	1.2	-41	4.0	2.0	1.9	-102	6.7	3.4	3.4	-98	6.6	3.4	3.3	-81
25	1.6	1.4	0.8	-15	2.1	1.9	1.2	-11	4.5	3.0	2.1	-49	7.2	4.4	3.6	-64	6.9	4.0	3.6	-64
50	1.9	1.9	0.9	3	2.4	2.5	1.3	4	5.0	4.1	2.1	-23	7.6	5.4	3.6	-42	7.3	4.7	3.6	-51
75	2.2	2.5	1.0	14	2.7	3.1	1.3	14	5.5	5.1	2.2	-8	8.1	6.4	3.7	-28	13.6	8.2	6.7	-60

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D16. Average annual total phosphorus loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm				50 ppm				100 ppm				200 ppm				400 ppm			
	INC†	NT	SSA	± %‡	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC†	NT	SSA	± %	INC	NT	SSA	± %
JANUARY APPLICATION																				
0	0.3	0.3	0.3	0	0.5	0.5	0.5	0	0.9	0.8	0.8	-11	1.6	1.3	1.3	-20	3.0	2.4	2.3	-26
25	0.5	0.7	0.3	30	0.7	1.0	0.5	25	1.1	1.2	0.8	12	1.8	1.8	1.3	-2	3.2	2.8	2.4	-14
50	0.7	1.2	0.4	39	0.9	1.4	0.6	35	1.3	1.7	0.8	24	2.0	2.2	1.4	10	3.4	3.2	2.4	-5
75	0.9	1.6	0.4	44	1.1	1.8	0.6	40	1.4	2.1	0.9	30	2.1	2.6	1.4	17	3.5	3.6	2.4	2
APRIL APPLICATION																				
0	0.3	0.3	0.3	-7	0.6	0.6	0.5	-3	0.9	0.8	0.8	-13	1.6	1.3	1.3	-21	3.0	2.4	2.3	-27
25	0.5	0.8	0.3	28	0.8	1.0	0.5	24	1.1	1.3	0.8	12	1.8	1.8	1.3	-2	3.2	2.8	2.4	-14
50	0.7	1.2	0.4	39	0.9	1.4	0.6	34	1.3	1.7	0.8	24	2.0	2.2	1.4	10	3.4	3.2	2.4	-4
75	0.9	1.7	0.4	44	1.1	1.9	0.6	40	1.5	2.1	0.9	31	2.2	2.7	1.4	18	3.6	3.7	2.4	3
OCTOBER APPLICATION																				
0	0.2	0.3	0.2	11	0.5	0.5	0.5	6	0.8	0.8	0.8	-5	1.5	1.3	1.3	-14	2.8	2.4	2.3	-19
25	0.4	0.6	0.3	28	0.6	0.8	0.5	21	0.9	1.0	0.8	9	1.6	1.6	1.3	-3	2.9	2.6	2.4	-13
50	0.5	0.8	0.4	35	0.7	1.0	0.6	29	1.1	1.3	0.8	18	1.7	1.8	1.4	5	3.0	2.8	2.4	-7
75	0.6	1.1	0.4	40	0.8	1.3	0.6	34	1.2	1.5	0.9	24	1.8	2.0	1.4	11	3.1	3.1	2.4	-2
NOVEMBER APPLICATION																				
0	0.3	0.3	0.2	6	0.5	0.5	0.5	2	0.9	0.8	0.8	-8	1.6	1.3	1.3	-17	2.9	2.4	2.3	-23
25	0.4	0.6	0.3	27	0.6	0.8	0.5	20	1.0	1.1	0.8	8	1.7	1.6	1.3	-5	3.0	2.6	2.4	-16
50	0.6	0.9	0.4	35	0.8	1.1	0.6	29	1.1	1.3	0.8	17	1.8	1.9	1.4	4	3.2	2.9	2.4	-9
75	0.7	1.2	0.4	40	0.9	1.4	0.6	34	1.2	1.6	0.9	23	1.9	2.1	1.4	10	3.3	3.2	2.4	-4

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application. ‡ The percent differences in the table were calculated only for incorporation and no-till surface broadcast.

Appendix D: D17. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a continuous corn rotation, watershed 4

Phosphorus application	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
rates (Kg ha^{-1})	INC†	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	192	96	100	192	96	100	192	96	100	192	96	100	192	96	100
25	190	97	100	190	97	100	190	97	100	190	97	100	190	97	100
50	190	97	100	190	97	100	190	97	100	190	97	100	190	97	100
75	190	97	100	190	97	100	190	97	100	190	97	100	190	97	100
APRIL APPLICATION															
0	186	95	95	186	95	95	186	95	95	186	95	95	186	95	95
25	184	96	98	184	96	98	184	96	98	184	96	98	184	96	98
50	184	96	98	184	96	98	184	96	98	184	96	98	184	96	98
75	184	96	98	184	96	98	184	96	98	184	96	98	184	96	98
OCTOBER APPLICATION															
0	184	97	97	184	97	97	184	97	97	184	97	97	184	97	97
25	183	100	101	183	100	101	183	100	101	183	100	101	183	100	101
50	183	100	101	183	100	101	183	100	101	183	100	101	183	100	101
75	183	100	101	183	100	101	183	100	101	183	100	101	183	100	101
NOVEMBER APPLICATION															
0	190	96	96	190	96	96	190	96	96	190	96	96	190	96	96
25	189	99	101	189	99	101	189	99	101	189	99	101	189	99	101
50	189	99	101	189	99	101	189	99	101	189	99	101	189	99	101
75	189	99	101	189	99	101	189	99	101	189	99	101	189	99	101

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D18. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a continuous corn rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	1.38	0.01	0.02	1.38	0.01	0.02	1.38	0.01	0.02	1.38	0.01	0.02	1.38	0.01	0.02
25	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02
50	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02
75	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02	1.39	0.01	0.02
APRIL APPLICATION															
0	0.97	0.01	0.01	0.97	0.01	0.01	0.97	0.01	0.01	0.97	0.01	0.01	0.97	0.01	0.01
25	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01
50	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01
75	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01	1.00	0.01	0.01
OCTOBER APPLICATION															
0	0.90	0.01	0.01	0.90	0.01	0.01	0.90	0.01	0.01	0.90	0.01	0.01	0.90	0.01	0.01
25	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03
50	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03
75	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03	1.07	0.02	0.03
NOVEMBER APPLICATION															
0	0.93	0.01	0.01	0.93	0.01	0.01	0.93	0.01	0.01	0.93	0.01	0.01	0.93	0.01	0.01
25	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02
50	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02
75	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02	1.03	0.02	0.02

[†] INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: 19. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
25	110	104	104	110	104	104	110	104	104	110	104	104	110	104	104
50	110	104	104	110	104	104	110	104	104	110	104	104	110	104	104
75	110	104	104	110	104	104	110	104	104	110	104	104	110	104	104
APRIL APPLICAION															
0	108	104	104	108	104	104	108	104	104	108	104	104	108	104	104
25	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
50	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
75	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
OCTOBER APPLICATION															
0	106	104	104	106	104	104	106	104	104	106	104	104	106	104	104
25	107	104	104	107	104	104	107	104	104	107	104	104	107	104	104
50	107	104	104	107	104	104	107	104	104	107	104	104	107	104	104
75	107	104	104	107	104	104	107	104	104	107	104	104	107	104	104
NOVEMBER APPLICATION															
0	108	104	104	108	104	104	108	104	104	108	104	104	108	104	104
25	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
50	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104
75	109	104	104	109	104	104	109	104	104	109	104	104	109	104	104

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D20. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
0	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01
25	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01
50	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01
75	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01	0.16	0.01	0.01
APRIL APPLICATION															
0	0.17	0.01	0.01	0.17	0.01	0.01	0.17	0.01	0.01	0.17	0.01	0.01	0.17	0.01	0.01
25	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01
50	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01
75	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01	0.18	0.01	0.01
OCTOBER APPLICATION															
0	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01
25	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01
50	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01
75	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01	0.14	0.01	0.01
NOVEMBER APPLICTION															
0	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01
25	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01
50	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01
75	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01	0.15	0.01	0.01

[†] INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D21. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation, watershed 4

Phosphorus application	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
rates (Kg ha^{-1})	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	119	113	113	118	113	113	116	113	113	115	113	113	119	113	113
25	119	113	114	118	113	114	119	113	114	115	113	114	119	113	114
50	119	113	114	118	113	114	119	113	114	115	113	114	119	113	114
75	119	113	114	118	113	114	119	113	114	115	113	114	119	113	114
APRIL APPLICATION															
0	119	113	113	119	113	113	118	113	113	116	113	113	115	113	113
25	119	113	114	119	113	114	118	113	114	116	113	114	115	113	114
50	119	113	114	119	113	114	118	113	114	116	113	114	115	113	114
75	119	113	114	119	113	114	118	113	114	116	113	114	115	113	114
JUNE APPLICATION															
0	115	113	113	115	113	113	115	113	113	115	113	113	115	113	113
25	115	113	113	115	113	113	115	113	113	115	113	113	115	113	113
50	115	113	113	115	113	113	115	113	113	115	113	113	115	113	113
75	115	113	113	115	113	113	115	113	113	115	113	113	115	113	113
OCTOBER APPLICATION															
0	115	113	113	119	113	113	119	113	113	118	113	113	116	113	113
25	115	113	113	119	113	113	119	113	113	118	113	113	116	113	113
50	115	113	113	119	113	113	119	113	113	118	113	113	116	113	113
75	115	113	113	119	113	113	119	113	113	118	113	113	116	113	113
NOVEMBER APPLICATION															
0	116	113	113	115	113	113	119	113	113	119	113	113	118	113	113
25	116	113	114	115	113	114	119	113	114	119	113	114	118	113	114
50	116	113	114	115	113	114	119	113	114	119	113	114	118	113	114
75	116	113	114	115	113	114	119	113	114	119	113	114	118	113	114

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D22. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a grain sorghum-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	0.97	0.10	0.10	0.94	0.10	0.10	0.91	0.10	0.10	0.64	0.10	0.10	1.20	0.11	0.11
25	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14
50	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14
75	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14
APRIL APPLICATION															
0	1.20	0.11	0.11	0.97	0.10	0.10	0.94	0.10	0.10	0.91	0.10	0.10	0.64	0.10	0.10
25	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12
50	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12
75	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12	0.64	0.10	0.12
JUNE APPLICATION															
0	0.64	0.10	0.10	0.64	0.10	0.10	0.64	0.10	0.10	0.64	0.10	0.10	0.64	0.10	0.10
25	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12
50	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12
75	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12	0.64	0.10	0.12
OCTOBER APPLICATION															
0	0.64	0.10	0.10	1.20	0.11	0.11	0.97	0.10	0.10	0.94	0.10	0.10	0.91	0.10	0.10
25	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12
50	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12
75	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12	0.91	0.10	0.12
NOVMBER APPLICATION															
0	0.91	0.10	0.10	0.64	0.10	0.10	1.20	0.11	0.11	0.97	0.10	0.10	0.94	0.10	0.10
25	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12
50	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12
75	0.91	0.10	0.12	0.64	0.10	0.12	1.20	0.11	0.14	0.97	0.10	0.13	0.94	0.10	0.12

[†] INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D23. Average annual runoff loss (mm) with different soil test phosphorus, application rates, and timings in a corn-winter wheat - soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC†	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	65	61	61	65	61	61	65	61	61	65	61	61	65	61	61
25	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
50	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
75	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
APRIL APPLICATION															
0	65	61	61	65	61	61	65	61	61	65	61	61	65	61	61
25	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
50	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
75	65	61	62	65	61	62	65	61	62	65	61	62	65	61	62
OCTOBER APPLICATION															
0	62	61	61	62	61	61	62	61	61	62	61	61	62	61	61
25	62	61	62	62	61	62	62	61	62	62	61	62	62	61	62
50	62	61	62	62	61	62	62	61	62	62	61	62	62	61	62
75	62	61	62	62	61	62	62	61	62	62	61	62	62	61	62
0	63	61	61	63	61	61	63	61	61	63	61	61	63	61	61
NOVEMBER APPLICATION															
25	63	61	62	63	61	62	63	61	62	63	61	62	63	61	62
50	63	61	62	63	61	62	63	61	62	63	61	62	63	61	62
75	63	61	62	63	61	62	63	61	62	63	61	62	63	61	62

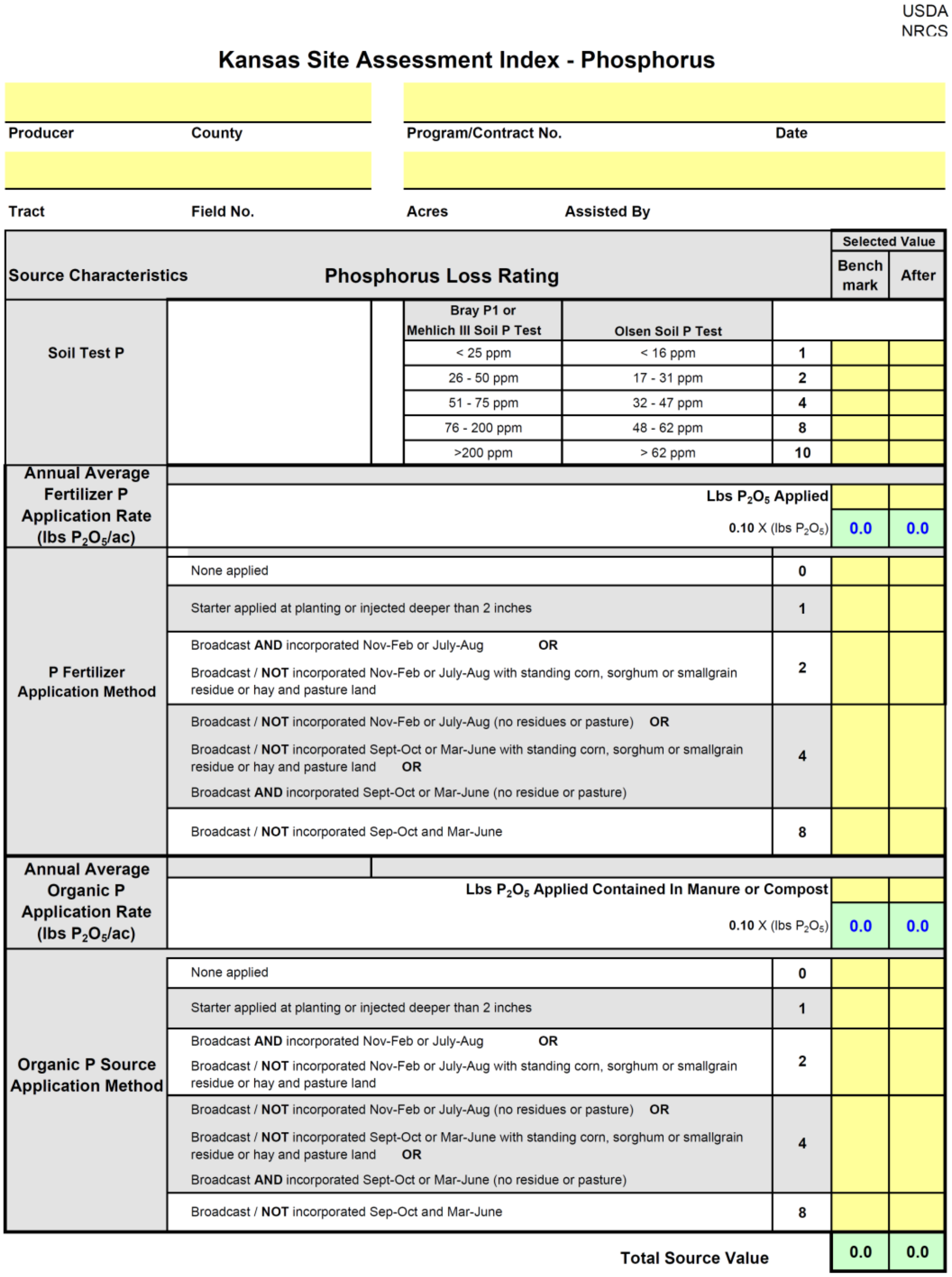
†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

Appendix D: D24. Average annual sediment loss with different soil test phosphorus, application rates, and timings in a corn-winter wheat-soybean rotation, watershed 4

Phosphorus application rates (Kg ha^{-1})	25 ppm			50 ppm			100 ppm			200 ppm			400 ppm		
	INC[†]	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA	INC	NT	SSA
JANUARY APPLICATION															
0	0.050	0.002	0.002	0.050	0.002	0.002	0.050	0.002	0.002	0.050	0.002	0.002	0.050	0.002	0.002
25	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003
50	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003
75	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003	0.050	0.002	0.003
APRIL APPLICATION															
0	0.063	0.002	0.002	0.063	0.002	0.002	0.063	0.002	0.002	0.063	0.002	0.002	0.063	0.002	0.002
25	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003
50	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003
75	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003	0.063	0.002	0.003
OCTOBER APPLICATION															
0	0.042	0.002	0.002	0.042	0.002	0.002	0.042	0.002	0.002	0.042	0.002	0.002	0.042	0.002	0.002
25	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003
50	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003
75	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003	0.042	0.002	0.003
NOVEMBER APPLICATION															
0	0.046	0.002	0.002	0.046	0.002	0.002	0.046	0.002	0.002	0.046	0.002	0.002	0.046	0.002	0.002
25	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003
50	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003	0.046	0.002	0.003
75	0.046	0.002	0.33	0.046	0.002	0.16	0.046	0.002	0.15	0.046	0.002	0.15	0.046	0.002	0.15

†INC= Fertilizer incorporated with chisel-disk-field cultivate; NT = No till-surface broadcast; SSA = no till-sub-surface application

APPENDIX E. Description of Kansas multiplicative model, phosphorus index ratings and average annual TP loss



USDA
NRCS

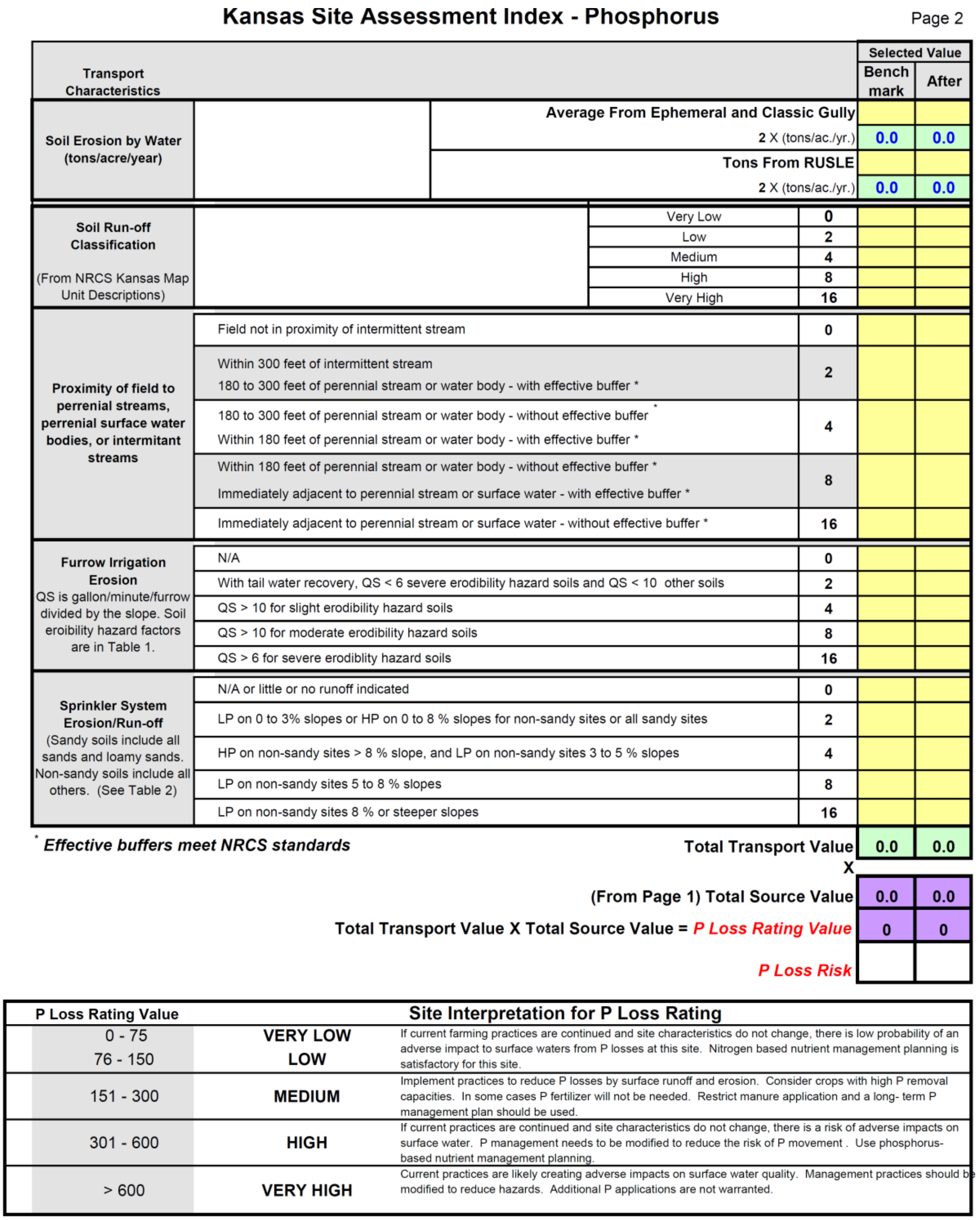
Kansas Site Assessment Index - Phosphorus

Producer County Program/Contract No. Date

Tract Field No. Acres Assisted By

Source Characteristics	Phosphorus Loss Rating			Selected Value: Bench mark	Selected Value: After
Soil Test P	Bray P1 or Mehlich III Soil P Test	Olsen Soil P Test			
	< 25 ppm	< 16 ppm	1		
	26 - 50 ppm	17 - 31 ppm	2		
	51 - 75 ppm	32 - 47 ppm	4		
	76 - 200 ppm	48 - 62 ppm	8		
	>200 ppm	> 62 ppm	10		
Annual Average Fertilizer P Application Rate (lbs P_2O_5/ac)			Lbs P_2O_5 Applied		
			0.10 X (lbs P_2O_5)	0.0	0.0
P Fertilizer Application Method	None applied		0		
	Starter applied at planting or injected deeper than 2 inches		1		
	Broadcast **AND** incorporated Nov-Feb or July-Aug **OR** Broadcast / **NOT** incorporated Nov-Feb or July-Aug with standing corn, sorghum or smallgrain residue or hay and pasture land		2		
	Broadcast / **NOT** incorporated Nov-Feb or July-Aug (no residues or pasture) **OR** Broadcast / **NOT** incorporated Sept-Oct or Mar-June with standing corn, sorghum or smallgrain residue or hay and pasture land **OR** Broadcast **AND** incorporated Sept-Oct or Mar-June (no residue or pasture)		4		
	Broadcast / **NOT** incorporated Sep-Oct and Mar-June		8		
Annual Average Organic P Application Rate (lbs P_2O_5/ac)			Lbs P_2O_5 Applied Contained In Manure or Compost		
			0.10 X (lbs P_2O_5)	0.0	0.0
Organic P Source Application Method	None applied		0		
	Starter applied at planting or injected deeper than 2 inches		1		
	Broadcast **AND** incorporated Nov-Feb or July-Aug **OR** Broadcast / **NOT** incorporated Nov-Feb or July-Aug with standing corn, sorghum or smallgrain residue or hay and pasture land		2		
	Broadcast / **NOT** incorporated Nov-Feb or July-Aug (no residues or pasture) **OR** Broadcast / **NOT** incorporated Sept-Oct or Mar-June with standing corn, sorghum or smallgrain residue or hay and pasture land **OR** Broadcast **AND** incorporated Sept-Oct or Mar-June (no residue or pasture)		4		
	Broadcast / **NOT** incorporated Sep-Oct and Mar-June		8		
			Total Source Value	0.0	0.0

Figure E1. Page 1 of the Kansas P index containing the categories and computation of the source factor. Index values for soil test P, P fertilizer application method, and organic P source application method are selected from the categorical classification based on field characteristics. Index values for P fertilizer application rate and Organic P application rate are computed as 0.1*(P application rate). The total source value is the sum of the index values for all five source factors. *Source:* https://efotg.sc.egov.usda.gov/references/public/KS/phosphorusIndex2008.xls



Kansas Site Assessment Index - Phosphorus Page 2

Transport Characteristics			Selected Value: Bench mark	Selected Value: After
Soil Erosion by Water (tons/acre/year)	**Average From Ephemeral and Classic Gully**			
	2 X (tons/ac./yr.)		0.0	0.0
	Tons From RUSLE			
	2 X (tons/ac./yr.)		0.0	0.0
Soil Run-off Classification (From NRCS Kansas Map Unit Descriptions)	Very Low	**0**		
	Low	**2**		
	Medium	**4**		
	High	**8**		
	Very High	**16**		
Proximity of field to perrenial streams, perrenial surface water bodies, or intermitant streams	Field not in proximity of intermittent stream	**0**		
	Within 300 feet of intermittent stream 180 to 300 feet of perennial stream or water body - with effective buffer *	**2**		
	180 to 300 feet of perennial stream or water body - without effective buffer * Within 180 feet of perennial stream or water body - with effective buffer *	**4**		
	Within 180 feet of perennial stream or water body - without effective buffer * Immediately adjacent to perennial stream or surface water - with effective buffer *	**8**		
	Immediately adjacent to perennial stream or surface water - without effective buffer *	**16**		
Furrow Irrigation Erosion QS is gallon/minute/furrow divided by the slope. Soil eroibility hazard factors are in Table 1.	N/A	**0**		
	With tail water recovery, QS < 6 severe erodibility hazard soils and QS < 10 other soils	**2**		
	QS > 10 for slight erodibility hazard soils	**4**		
	QS > 10 for moderate erodibility hazard soils	**8**		
	QS > 6 for severe erodiblity hazard soils	**16**		
Sprinkler System Erosion/Run-off (Sandy soils include all sands and loamy sands. Non-sandy soils include all others. (See Table 2)	N/A or little or no runoff indicated	**0**		
	LP on 0 to 3% slopes or HP on 0 to 8 % slopes for non-sandy sites or all sandy sites	**2**		
	HP on non-sandy sites > 8 % slope, and LP on non-sandy sites 3 to 5 % slopes	**4**		
	LP on non-sandy sites 5 to 8 % slopes	**8**		
	LP on non-sandy sites 8 % or steeper slopes	**16**		

* ***Effective buffers meet NRCS standards***

	Bench mark	After
Total Transport Value	0.0	0.0
X		
(From Page 1) Total Source Value	0.0	0.0
Total Transport Value X Total Source Value = ***P Loss Rating Value***	0	0
P Loss Risk		

P Loss Rating Value		Site Interpretation for P Loss Rating
0 - 75 76 - 150	**VERY LOW** **LOW**	If current farming practices are continued and site characteristics do not change, there is low probability of an adverse impact to surface waters from P losses at this site. Nitrogen based nutrient management planning is satisfactory for this site.
151 - 300	**MEDIUM**	Implement practices to reduce P losses by surface runoff and erosion. Consider crops with high P removal capacities. In some cases P fertilizer will not be needed. Restrict manure application and a long- term P management plan should be used.
301 - 600	**HIGH**	If current practices are continued and site characteristics do not change, there is a risk of adverse impacts on surface water. P management needs to be modified to reduce the risk of P movement . Use phosphorus-based nutrient management planning.
> 600	**VERY HIGH**	Current practices are likely creating adverse impacts on surface water quality. Management practices should be modified to reduce hazards. Additional P applications are not warranted.

Source: https://efotg.sc.egov.usda.gov/references/public/KS/phosphorusIndex2008.xls

Figure E2. Page 21 of the Kansas P index containing the categories and computation of the transport factor. Index values for soil runoff classification, proximity of field to a waterbody, furrow irrigation erosion, and sprinkler system erosion are selected from the categorical classification based on field characteristics. The index value for soil erosion is computed as 2*(soil erosion rate). The total transport value is the sum of index values for all five transport factors. ***Source:*** **https://efotg.sc.egov.usda.gov/references/public/KS/phosphorusIndex2008.xls**

Revised universal soil loss equation (RUSLE 2)

The RUSLE model was used to estimate the sediment and runoff loss for management scenarios used to evaluate the KS-PI and CPI. The sediment loss with the RUSLE2 can be estimated as follows

Sediment loss (tons ac^{-1} yr^{-1}) = R x K x L x S x C x PE =

where, R = Climate erodibility factor

K = Soil erodibility factor measured under a standard condition

L = Slope length

S = Slope steepness

C = Cover management factor

P = Erosion control practices or support factor

Climate erodibility (R) - It is also known as erosivity index and calculated from an annual summation of rainfall energy of a storm and its maximum 30 minute intensity.

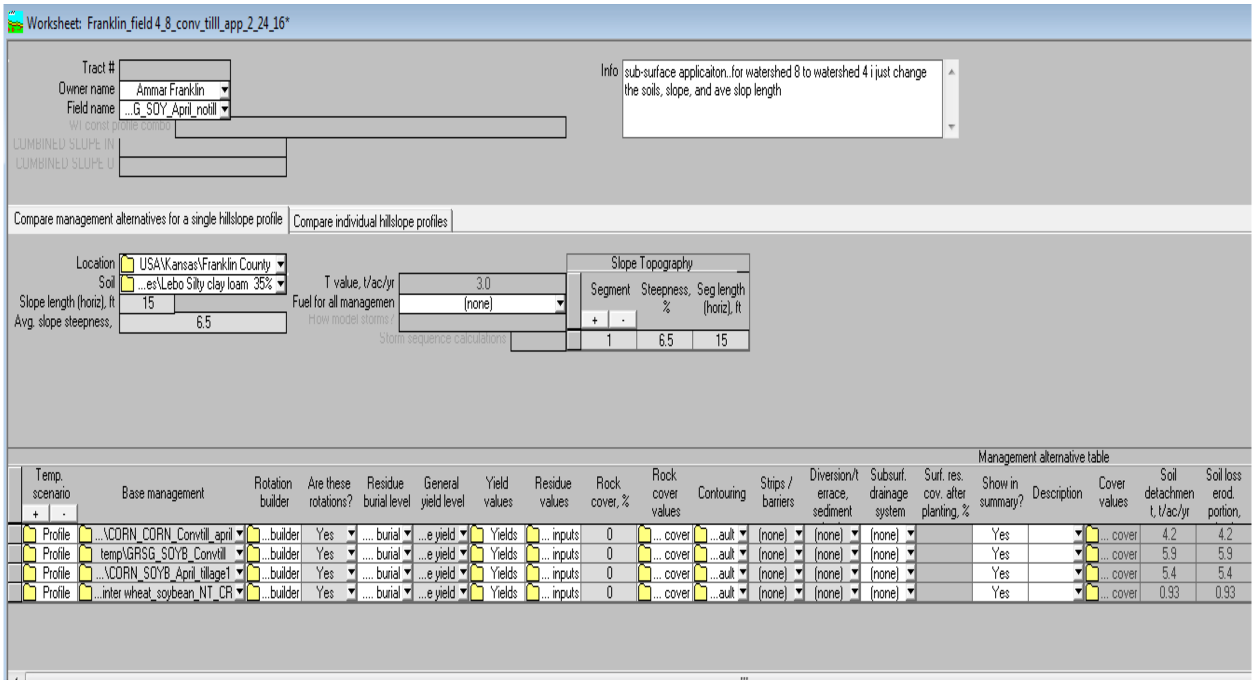
Soil erodibility factor (K) - It is the inherent susceptibility of soils to erosion. Soil texture, organic content, structural stability etc. affect the soil erodibility.

Slope length and steepness factor (S and L) - In general longer slopes accumulate runoff from larger areas and steeper slopes produce higher overland flow velocities. Erosion is more sensitive to steepness than length.

Cover management factor (C) - Cropping sequence, tillage, crop residue, and yield affect the cover management factor. In general, continuous row crops increase C factor while increase in yield, including small grains in rotation and higher residue decrease C factor. Likewise, tillage operation such as no-till and ridge till decrease C factor while spring and fall tillage increase C factor.

Erosion control practices or support factor (PE) - Different conservation practices such as terraces, contouring, strip cropping, etc may reduce soil loss and erosion control factor consider those practices.

The more details on RUSLE2 and the model software can be found in USDA-ARS website http://www.ars.usda.gov/Research/docs.htm?docid=6010



Worksheet: Franklin_field 4_8_conv_tilll_app_2_24_16*

Tract #
Owner name: Ammar Franklin
Field name: ...G_SOY_April_notill
WI const profile combo
COMBINED SLOPE IN
COMBINED SLOPE O

Info: sub-surface applicaiton..for watershed 8 to watershed 4 i just change the soils, slope, and ave slop length

Location: USA\Kansas\Franklin County
Soil: ...es\Lebo Silty clay loam 35%
Slope length (horiz), ft: 15
Avg. slope steepness, 6.5
T value, t/ac/yr: 3.0
Fuel for all managemen: (none)
How model storms?
Storm sequence calculations

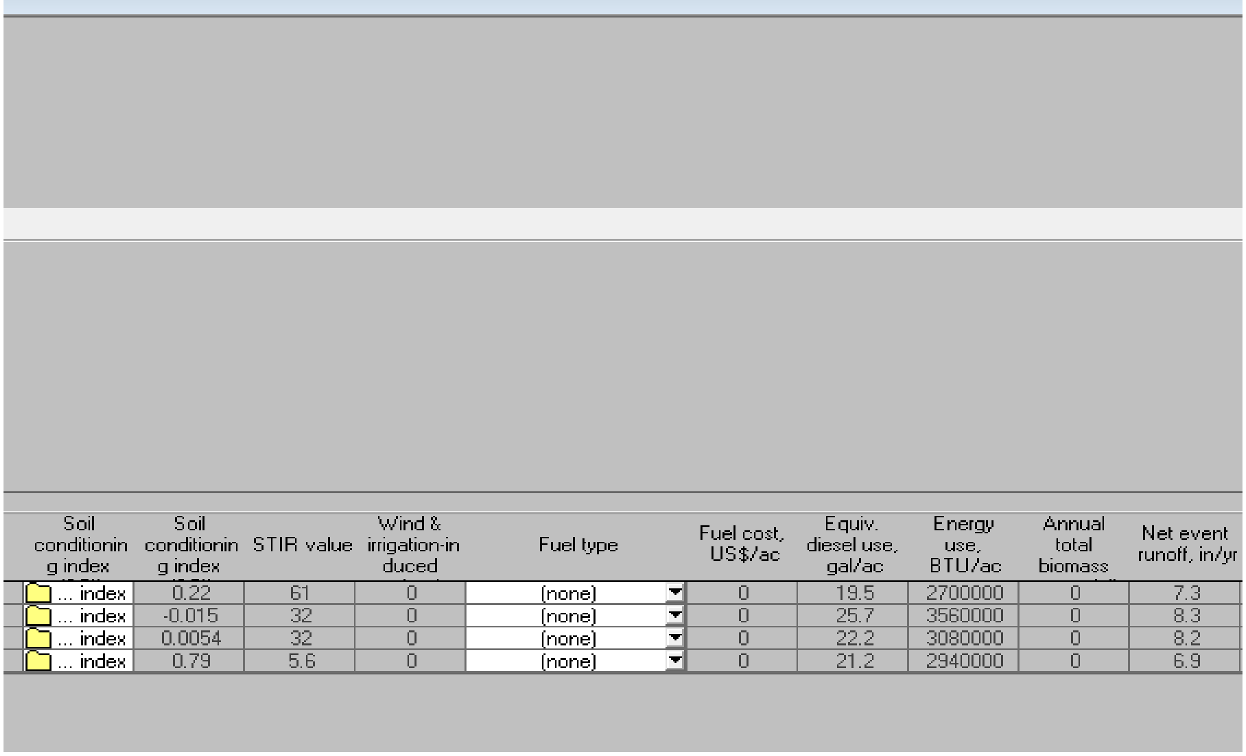
Slope Topography

Segment	Steepness, %	Seg length (horiz), ft
1	6.5	15

Management alternative table

Temp. scenario	Base management	Rotation builder	Are these rotations?	Residue burial level	General yield level	Yield values	Residue values	Rock cover, %	Rock cover values	Contouring	Strips / barriers	Diversion/terrace, sediment	Subsurf. drainage system	Surf. res. cov. after planting, %	Show in summary?	Description	Cover values	Soil detachment, t/ac/yr	Soil loss erod. portion,
Profile	...\CORN_CORN_Convtill_april	...builder	Yes	.... burial	...e yield	Yields	... inputs	0	... cover	...ault	(none)	(none)	(none)		Yes		... cover	4.2	4.2
Profile	temp\GRSG_SOYB_Convtill	...builder	Yes	.... burial	...e yield	Yields	... inputs	0	... cover	...ault	(none)	(none)	(none)		Yes		... cover	5.9	5.9
Profile	...\CORN_SOYB_April_tillage1	...builder	Yes	.... burial	...e yield	Yields	... inputs	0	... cover	...ault	(none)	(none)	(none)		Yes		... cover	5.4	5.4
Profile	...inter wheat_soybean_NT_CR	...builder	Yes	.... burial	...e yield	Yields	... inputs	0	... cover	...ault	(none)	(none)	(none)		Yes		... cover	0.93	0.93

Figure: E3. The RUSLE2 worksheet used to estimate sediment loss for different management practices.



Soil conditioning index	Soil conditioning index	STIR value	Wind & irrigation-induced	Fuel type	Fuel cost, US$/ac	Equiv. diesel use, gal/ac	Energy use, BTU/ac	Annual total biomass	Net event runoff, in/yr
... index	0.22	61	0	(none)	0	19.5	2700000	0	7.3
... index	-0.015	32	0	(none)	0	25.7	3560000	0	8.3
... index	0.0054	32	0	(none)	0	22.2	3080000	0	8.2
... index	0.79	5.6	0	(none)	0	21.2	2940000	0	6.9

Figure: E4. The RUSLE2 worksheet used to estimate runoff loss for different management practices continuation of Figure E3.

FRANKLIN SITE - watershed 8 (W -8)

Appendix E: E1. Total phosphorus loss (Kg ha^{-1}) and P-index values in continuous corn rotation; phosphorus surface broadcast in a no-till system, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.9	100	1.0	166	0.9	166	0.9	100
25	25	2.1	270	2.0	336	1.6	336	1.6	270
25	50	3.2	440	3.0	507	2.2	507	2.4	440
25	75	4.3	610	4.0	677	2.9	677	3.1	610
50	0	1.2	133	1.2	200	1.1	200	1.1	133
50	25	2.3	303	2.2	370	1.8	370	1.9	303
50	50	3.5	473	3.2	540	2.5	540	2.6	473
50	75	4.6	643	4.2	710	3.1	710	3.4	643
100	0	1.6	333	1.7	399	1.6	399	1.6	333
100	25	2.8	503	2.7	569	2.3	569	2.4	503
100	50	3.9	673	3.7	739	2.9	739	3.1	673
100	75	5.0	843	4.7	910	3.6	910	3.8	843
200	0	2.5	333	2.6	399	2.4	399	2.5	333
200	25	3.7	503	3.6	569	3.2	569	3.3	503
200	50	4.8	673	4.5	739	3.9	739	4.0	673
200	75	5.9	843	5.5	910	4.5	910	4.7	843
400	0	4.2	399	4.3	466	4.2	466	4.2	399
400	25	5.4	569	5.3	636	5.0	636	5.1	569
400	50	6.5	739	6.3	806	5.7	806	5.8	739
400	75	7.7	910	7.3	976	6.4	976	6.5	910

Appendix E: E2. Total phosphorus loss (Kg ha^{-1})and P-index values in corn-soybean rotation; phosphorus surface broadcast in a no-till system, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.6	103	0.6	172	0.6	172	0.6	103
25	25	1.3	191	1.3	260	1.0	260	1.1	191
25	50	2.0	279	2.0	348	1.5	348	1.6	279
25	75	2.8	367	2.7	436	1.9	436	2.1	367
50	0	1.1	138	1.1	206	1.1	206	1.1	138
50	25	1.8	225	1.8	294	1.5	294	1.5	225
50	50	2.5	313	2.5	382	1.9	382	2.0	313
50	75	3.2	401	3.1	470	2.3	470	2.5	401
100	0	1.6	344	1.6	413	1.6	413	1.6	344
100	25	2.3	432	2.3	501	2.0	501	2.1	432
100	50	3.0	520	3.0	589	2.4	589	2.5	520
100	75	3.7	608	3.7	676	2.8	676	3.0	608
200	0	2.6	344	2.6	413	2.6	413	2.6	344
200	25	3.4	432	3.3	501	3.1	501	3.1	432
200	50	4.1	520	4.0	589	3.5	589	3.6	520
200	75	4.8	608	4.7	676	3.9	676	4.0	608
400	0	4.7	413	4.7	482	4.7	482	4.7	413
400	25	5.4	501	5.4	569	5.1	569	5.2	501
400	50	6.1	589	6.1	657	5.5	657	5.6	589
400	75	6.8	676	6.8	745	6.0	745	6.1	676

Appendix E: E3. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn winter wheat-soybean rotation; phosphorus surface broadcast in a no-till system, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.2	100	0.2	167	0.2	167	0.2	100
25	25	0.6	185	0.7	252	0.5	252	0.5	185
25	50	1.1	270	1.2	337	0.8	337	0.8	270
25	75	1.6	355	1.6	422	1.0	422	1.1	355
50	0	0.6	133	0.6	200	0.6	200	0.6	133
50	25	1.0	218	1.0	285	0.8	285	0.8	218
50	50	1.4	304	1.5	370	1.0	370	1.1	304
50	75	1.9	389	1.9	455	1.3	455	1.4	389
100	0	0.8	333	0.8	400	0.8	400	0.8	333
100	25	1.3	418	1.3	485	1.1	485	1.1	418
100	50	1.7	503	1.7	570	1.3	570	1.4	503
100	75	2.1	589	2.2	655	1.5	655	1.6	589
200	0	1.3	333	1.3	400	1.3	400	1.3	333
200	25	1.8	418	1.8	485	1.6	485	1.6	418
200	50	2.2	503	2.2	570	1.8	570	1.9	503
200	75	2.6	589	2.7	655	2.0	655	2.1	589
400	0	2.3	400	2.3	466	2.3	466	2.3	400
400	25	2.8	485	2.8	552	2.6	552	2.6	485
400	50	3.2	570	3.3	637	2.8	637	2.9	570
400	75	3.6	655	3.7	722	3.1	722	3.2	655

Appendix E: E4. Total phosphorus loss (Kg ha^{-1})and P-index values in grain sorghum-soybean rotation with phosphorus surface broadcast and no-till system, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.7	104	0.8	174	0.8	174	0.7	174	0.7	104
25	25	1.8	193	1.8	263	1.4	263	1.3	263	1.4	193
25	50	2.8	282	2.9	352	2.1	352	1.9	352	2.1	282
25	75	3.8	371	4.0	441	2.7	441	2.5	441	2.7	371
50	0	1.2	139	1.2	209	1.2	209	1.2	209	1.2	139
50	25	2.2	228	2.3	298	1.9	298	1.8	298	1.9	228
50	50	3.3	317	3.4	387	2.5	387	2.4	387	2.5	317
50	75	4.3	406	4.4	476	3.2	476	3.0	476	3.2	406
100	0	1.9	348	1.9	418	1.9	418	1.9	418	1.9	348
100	25	2.9	437	3.0	507	2.6	507	2.5	507	2.6	437
100	50	4.0	526	4.1	595	3.2	595	3.1	595	3.2	526
100	75	5.0	615	5.2	684	3.9	684	3.7	684	3.9	615
200	0	3.3	348	3.3	418	3.3	418	3.3	418	3.3	348
200	25	4.3	437	4.4	507	4.0	507	3.9	507	3.9	437
200	50	5.3	526	5.5	595	4.6	595	4.5	595	4.6	526
200	75	6.4	615	6.5	684	5.2	684	5.1	684	5.3	615
400	0	6.1	418	6.1	487	6.1	487	6.1	487	6.1	418
400	25	7.1	507	7.2	576	6.7	576	6.6	576	6.7	507
400	50	8.1	595	8.3	665	7.4	665	7.2	665	7.4	595
400	75	9.1	684	9.3	754	8.0	754	7.8	754	8.0	684

Appendix E: E5. Total phosphorus (Kg ha^{-1}) loss and P-index values in continuous corn rotation; phosphorus incorporated with tillage, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.6	117	0.6	195	0.6	195	0.6	117
25	25	1.0	316	1.0	394	0.8	394	0.9	316
25	50	1.3	516	1.3	594	1.1	594	1.1	516
25	75	1.6	715	1.6	793	1.3	793	1.3	715
50	0	1.1	156	1.1	234	1.0	234	1.1	156
50	25	1.4	355	1.4	433	1.2	433	1.3	355
50	50	1.7	555	1.7	633	1.4	633	1.5	555
50	75	2.0	754	2.0	832	1.6	832	1.7	754
100	0	1.7	390	1.8	468	1.7	468	1.7	390
100	25	2.1	589	2.1	667	1.9	667	2.0	589
100	50	2.4	789	2.4	867	2.1	867	2.2	789
100	75	2.7	988	2.7	1066	2.3	1066	2.4	988
200	0	3.1	390	3.1	468	3.0	468	3.0	390
200	25	3.4	589	3.4	667	3.2	667	3.3	589
200	50	3.7	789	3.7	867	3.4	867	3.5	789
200	75	4.0	988	4.0	1066	3.6	1066	3.7	988
400	0	5.7	468	5.6	546	5.6	546	5.7	468
400	25	6.0	667	6.0	745	5.8	745	5.9	667
400	50	6.4	867	6.3	945	6.0	945	6.1	867
400	75	6.7	1066	6.6	1144	6.2	1144	6.4	1066

Appendix E: E6. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-soybean rotation; phosphorus incorporated with tillage, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.6	125	0.6	209	0.6	209	0.6	125
25	25	1.0	232	1.0	316	0.8	316	0.9	232
25	50	1.3	339	1.3	423	1.1	423	1.1	339
25	75	1.6	446	1.6	529	1.3	529	1.3	446
50	0	1.1	167	1.1	251	1.0	251	1.1	167
50	25	1.4	274	1.4	358	1.2	358	1.3	274
50	50	1.7	381	1.7	464	1.4	464	1.5	381
50	75	2.0	488	2.0	571	1.6	571	1.7	488
100	0	1.7	418	1.8	502	1.7	502	1.7	418
100	25	2.1	525	2.1	608	1.9	608	2.0	525
100	50	2.4	632	2.4	715	2.1	715	2.2	632
100	75	2.7	738	2.7	822	2.3	822	2.4	738
200	0	3.1	418	3.1	502	3.0	502	3.0	418
200	25	3.4	525	3.4	608	3.2	608	3.3	525
200	50	3.7	632	3.7	715	3.4	715	3.5	632
200	75	4.0	738	4.0	822	3.6	822	3.7	738
400	0	5.7	502	5.6	585	5.6	585	5.7	502
400	25	6.0	608	6.0	692	5.8	692	5.9	608
400	50	6.4	715	6.3	799	6.0	799	6.1	715
400	75	6.7	822	6.6	906	6.2	906	6.4	822

Appendix E: E7. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-winter wheat-soybean rotation; phosphorus incorporated with tillage, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.2	108	0.2	180	0.1	180	0.2	108
25	25	0.4	200	0.4	272	0.3	272	0.3	200
25	50	0.6	292	0.7	364	0.5	364	0.5	292
25	75	0.8	384	0.9	456	0.6	456	0.6	384
50	0	0.5	144	0.5	216	0.5	216	0.5	144
50	25	0.7	236	0.7	308	0.6	308	0.6	236
50	50	0.8	328	0.9	400	0.7	400	0.7	328
50	75	1.0	420	1.1	492	0.8	492	0.8	420
100	0	0.8	360	0.8	432	0.8	432	0.8	360
100	25	1.0	452	1.0	524	0.9	524	0.9	452
100	50	1.2	544	1.2	616	1.0	616	1.0	544
100	75	1.3	636	1.4	708	1.1	708	1.1	636
200	0	1.4	360	1.4	432	1.3	432	1.4	360
200	25	1.6	452	1.6	524	1.5	524	1.5	452
200	50	1.8	544	1.8	616	1.6	616	1.6	544
200	75	1.9	636	2.0	708	1.7	708	1.8	636
400	0	2.6	432	2.6	504	2.5	504	2.6	432
400	25	2.8	524	2.8	596	2.6	596	2.7	524
400	50	3.0	616	3.0	688	2.7	688	2.8	616
400	75	3.2	708	3.2	780	2.8	780	3.0	708

Appendix E: E8. Total phosphorus loss (Kg ha^{-1}) and P-index values in grain sorghum-soybean rotation; phosphorus incorporated with tillage, Franklin W-8

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.0	128	1.1	214	1.0	214	1.0	214	1.0	128
25	25	1.5	238	1.6	323	1.3	323	1.3	323	1.3	238
25	50	2.0	347	2.1	433	1.6	433	1.6	433	1.7	347
25	75	2.4	456	2.6	542	1.9	542	1.9	542	2.0	456
50	0	1.7	171	1.9	257	1.5	257	1.6	257	1.7	171
50	25	2.1	281	2.3	366	1.8	366	1.9	366	2.0	281
50	50	2.6	390	2.8	476	2.1	476	2.2	476	2.3	390
50	75	3.1	499	3.3	585	2.4	585	2.5	585	2.6	499
100	0	2.9	428	3.1	514	2.5	514	2.8	514	2.9	428
100	25	3.3	537	3.6	623	2.8	623	3.1	623	3.2	537
100	50	3.8	647	4.1	732	3.1	732	3.4	732	3.5	647
100	75	4.3	756	4.6	842	3.4	842	3.7	842	3.8	756
200	0	5.3	428	5.7	514	4.4	514	5.2	514	5.3	428
200	25	5.7	537	6.2	623	4.7	623	5.5	623	5.6	537
200	50	6.2	647	6.7	732	5.0	732	5.8	732	5.9	647
200	75	6.7	756	7.1	842	5.3	842	6.1	842	6.2	756
400	0	10.1	514	10.8	599	8.3	599	9.9	599	10.1	514
400	25	10.5	623	11.3	709	8.6	709	10.2	709	10.4	623
400	50	11.0	732	11.8	818	8.9	818	10.5	818	10.7	732
400	75	11.5	842	12.3	927	9.1	927	10.8	927	11.0	842

FRANKLIN SITE watershed 4 (W -4)

Appendix E: E9. Total phosphorus loss (Kg ha^{-1}) and P-index values in continuous corn rotation; phosphorus surface broadcast in a no-till system, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.9	102	1.0	170	0.8	170	0.8	102
25	25	2.0	275	1.9	343	1.5	343	1.6	275
25	50	3.1	449	2.9	517	2.2	517	2.3	449
25	75	4.2	622	3.8	690	2.8	690	3.0	622
50	0	1.2	136	1.2	204	1.1	204	1.1	136
50	25	2.3	309	2.2	377	1.8	377	1.8	309
50	50	3.4	483	3.1	551	2.4	551	2.5	483
50	75	4.4	656	4.0	724	3.1	724	3.3	656
100	0	1.6	340	1.6	408	1.6	408	1.6	340
100	25	2.7	513	2.6	581	2.3	581	2.3	513
100	50	3.8	687	3.5	755	2.9	755	3.0	687
100	75	4.9	860	4.5	928	3.6	928	3.7	860
200	0	2.5	340	2.5	408	2.5	408	2.5	340
200	25	3.7	513	3.5	581	3.2	581	3.3	513
200	50	4.7	687	4.4	755	3.9	755	4.0	687
200	75	5.8	860	5.3	928	4.5	928	4.7	860
400	0	4.4	408	4.3	475	4.4	475	4.3	408
400	25	5.5	581	5.2	649	5.2	649	5.2	581
400	50	6.6	755	6.2	823	5.8	823	5.9	755
400	75	7.7	928	7.1	996	6.5	996	6.6	928

Appendix E: E10. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-soybean rotation; phosphorus surface broadcast in a no-till system, , Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.6	106	0.6	177	0.6	177	0.6	106
25	25	1.3	197	1.3	267	1.0	267	1.1	197
25	50	2.0	287	1.9	358	1.4	358	1.5	287
25	75	2.6	378	2.6	448	1.8	448	2.0	378
50	0	1.0	142	1.0	212	1.0	212	1.0	142
50	25	1.7	232	1.7	303	1.4	303	1.4	232
50	50	2.3	322	2.3	393	1.8	393	1.9	322
50	75	3.0	413	2.9	484	2.2	484	2.3	413
100	0	1.5	354	1.5	425	1.5	425	1.5	354
100	25	2.2	444	2.2	515	1.9	515	1.9	444
100	50	2.8	535	2.8	606	2.3	606	2.4	535
100	75	3.5	625	3.4	696	2.7	696	2.8	625
200	0	2.5	354	2.5	425	2.5	425	2.5	354
200	25	3.2	444	3.1	515	2.9	515	2.9	444
200	50	3.8	535	3.8	606	3.3	606	3.4	535
200	75	4.5	625	4.4	696	3.7	696	3.8	625
400	0	4.5	425	4.5	496	4.5	496	4.5	425
400	25	5.2	515	5.1	586	4.9	586	4.9	515
400	50	5.8	606	5.8	676	5.3	676	5.3	606
400	75	6.5	696	6.4	767	5.6	767	5.8	696

Appendix E: E11. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn winter wheat-soybean rotation; phosphorus surface broadcast in a no-till system, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.3	102	0.3	169	0.3	169	0.3	102
25	25	0.7	188	0.8	256	0.6	256	0.6	188
25	50	1.2	275	1.2	342	0.8	342	0.9	275
25	75	1.6	361	1.7	429	1.1	429	1.2	361
50	0	0.5	135	0.6	203	0.5	203	0.5	135
50	25	1.0	222	1.0	290	0.8	290	0.8	222
50	50	1.4	308	1.4	376	1.0	376	1.1	308
50	75	1.8	395	1.9	463	1.3	463	1.4	395
100	0	0.8	339	0.8	406	0.8	406	0.8	339
100	25	1.2	425	1.3	493	1.0	493	1.1	425
100	50	1.7	512	1.7	579	1.3	579	1.3	512
100	75	2.1	598	2.1	666	1.5	666	1.6	598
200	0	1.3	339	1.3	406	1.3	406	1.3	339
200	25	1.8	425	1.8	493	1.6	493	1.6	425
200	50	2.2	512	2.2	579	1.8	579	1.9	512
200	75	2.6	598	2.7	666	2.0	666	2.1	598
400	0	2.4	406	2.4	474	2.4	474	2.4	406
400	25	2.8	493	2.8	561	2.6	561	2.6	493
400	50	3.2	579	3.2	647	2.8	647	2.9	579
400	75	3.6	666	3.7	734	3.1	734	3.2	666

Appendix E: E12. Total phosphorus loss (Kg ha^{-1}) and P-index values in grain sorghum-soybean rotation with phosphorus surface broadcast and no-till system, , Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.8	108	0.8	180	0.8	180	0.8	180	0.8	108
25	25	1.8	200	1.8	272	1.4	272	1.4	272	1.4	200
25	50	2.8	292	2.9	364	2.0	364	1.9	364	2.1	292
25	75	3.8	384	3.9	456	2.6	456	2.5	456	2.7	384
50	0	1.2	144	1.3	216	1.2	216	1.2	216	1.2	144
50	25	2.2	236	2.3	308	1.9	308	1.8	308	1.9	236
50	50	3.2	328	3.3	400	2.5	400	2.4	400	2.5	328
50	75	4.2	420	4.4	492	3.1	492	2.9	492	3.1	420
100	0	1.9	360	2.0	432	2.0	432	1.9	432	1.9	360
100	25	2.9	452	3.0	524	2.6	524	2.5	524	2.6	452
100	50	3.9	544	4.1	616	3.2	616	3.1	616	3.2	544
100	75	4.9	636	5.1	708	3.8	708	3.7	708	3.9	636
200	0	3.4	360	3.4	432	3.4	432	3.4	432	3.4	360
200	25	4.4	452	4.5	524	4.0	524	3.9	524	4.0	452
200	50	5.4	544	5.5	616	4.6	616	4.5	616	4.7	544
200	75	6.4	636	6.6	708	5.2	708	5.1	708	5.3	636
400	0	6.2	432	6.3	504	6.3	504	6.2	504	6.2	432
400	25	7.2	524	7.4	596	6.9	596	6.8	596	6.9	524
400	50	8.2	616	8.4	688	7.5	688	7.4	688	7.5	616
400	75	9.2	708	9.5	780	8.1	780	8.0	780	8.2	708

Appendix E: E13. Total phosphorus loss (Kg ha^{-1}) and P-index values in continuous corn rotation; phosphorus incorporated with tillage,, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	2.2	121	1.8	202	1.7	202	1.8	121
25	25	3.1	328	2.7	408	2.4	408	2.5	328
25	50	3.9	534	3.5	615	2.9	615	3.1	534
25	75	4.8	741	4.4	821	3.5	821	3.7	741
50	0	3.3	162	2.7	242	2.7	242	2.7	162
50	25	4.1	368	3.6	449	3.4	449	3.4	368
50	50	5.0	574	4.4	655	3.9	655	4.0	574
50	75	5.9	781	5.2	862	4.4	862	4.6	781
100	0	5.4	404	4.4	485	4.4	485	4.5	404
100	25	6.3	610	5.2	691	5.2	691	5.3	610
100	50	7.1	817	6.1	898	5.8	898	5.9	817
100	75	8.0	1023	6.9	1104	6.3	1104	6.5	1023
200	0	9.6	404	7.8	485	7.9	485	8.1	404
200	25	10.5	610	8.6	691	9.0	691	9.0	610
200	50	11.4	817	9.5	898	9.5	898	9.6	817
200	75	12.3	1023	10.3	1104	10.1	1104	10.2	1023
400	0	18.1	485	14.5	566	15.0	566	15.2	485
400	25	19.0	691	15.4	772	16.5	772	16.4	691
400	50	19.8	898	16.3	978	17.1	978	17.0	898
400	75	20.7	1104	17.1	1185	17.6	1185	17.6	1104

Appendix E: E14. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-soybean rotation; phosphorus incorporated with tillage, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.7	128	0.7	214	0.6	214	0.7	128
25	25	1.0	238	1.1	323	0.9	323	0.9	238
25	50	1.3	347	1.4	433	1.1	433	1.1	347
25	75	1.7	456	1.7	542	1.3	542	1.4	456
50	0	1.1	171	1.1	257	1.1	257	1.1	171
50	25	1.4	281	1.5	366	1.3	366	1.3	281
50	50	1.7	390	1.7	476	1.5	476	1.5	390
50	75	2.0	499	2.0	585	1.6	585	1.7	499
100	0	1.8	428	1.8	514	1.8	514	1.8	428
100	25	2.1	537	2.1	623	2.0	623	2.0	537
100	50	2.4	647	2.4	732	2.1	732	2.2	647
100	75	2.7	756	2.7	842	2.3	842	2.4	756
200	0	3.2	428	3.2	514	3.1	514	3.2	428
200	25	3.5	537	3.5	623	3.3	623	3.4	537
200	50	3.8	647	3.8	732	3.5	732	3.6	647
200	75	4.1	756	4.1	842	3.7	842	3.8	756
400	0	6.0	514	6.0	599	5.8	599	5.9	514
400	25	6.4	623	6.3	709	6.0	709	6.2	623
400	50	6.7	732	6.6	818	6.2	818	6.4	732
400	75	7.0	842	6.9	927	6.4	927	6.6	842

Appendix E: E15. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-winter wheat-soybean rotation; phosphorus incorporated with tillage, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.3	111	0.3	185	0.2	185	0.3	111
25	25	0.5	206	0.5	280	0.4	280	0.4	206
25	50	0.7	300	0.7	374	0.5	374	0.6	300
25	75	0.9	395	0.9	469	0.6	469	0.7	395
50	0	0.5	148	0.6	222	0.5	222	0.5	148
50	25	0.7	243	0.8	317	0.6	317	0.6	243
50	50	0.9	337	0.9	411	0.7	411	0.8	337
50	75	1.1	432	1.1	506	0.8	506	0.9	432
100	0	0.9	370	0.9	444	0.8	444	0.9	370
100	25	1.1	465	1.1	539	0.9	539	1.0	465
100	50	1.3	559	1.3	633	1.1	633	1.1	559
100	75	1.4	654	1.5	728	1.2	728	1.2	654
200	0	1.6	370	1.6	444	1.5	444	1.6	370
200	25	1.8	465	1.8	539	1.6	539	1.7	465
200	50	2.0	559	2.0	633	1.7	633	1.8	559
200	75	2.1	654	2.2	728	1.8	728	1.9	654
400	0	3.0	444	3.0	518	2.8	518	2.9	444
400	25	3.2	539	3.2	613	2.9	613	3.0	539
400	50	3.4	633	3.4	707	3.0	707	3.2	633
400	75	3.5	728	3.6	802	3.1	802	3.3	728

Appendix E: E16. Total phosphorus loss (Kg ha^{-1}) and P-index values in grain sorghum-soybean rotation; phosphorus incorporated with tillage, Franklin W-4

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.3	131	1.5	219	1.1	219	1.3	219	1.3	131
25	25	1.8	243	2.0	331	1.4	331	1.6	331	1.6	243
25	50	2.3	355	2.5	443	1.7	443	1.9	443	2.0	355
25	75	2.8	467	3.0	555	2.0	555	2.2	555	2.3	467
50	0	2.1	175	2.4	263	1.8	263	2.0	263	2.1	175
50	25	2.6	287	2.9	375	2.1	375	2.3	375	2.4	287
50	50	3.1	399	3.4	487	2.4	487	2.6	487	2.8	399
50	75	3.6	511	3.9	599	2.7	599	3.0	599	3.1	511
100	0	3.6	438	4.0	526	2.9	526	3.5	526	3.6	438
100	25	4.1	550	4.5	638	3.2	638	3.8	638	3.9	550
100	50	4.6	662	5.0	749	3.5	749	4.1	749	4.3	662
100	75	5.1	774	5.5	861	3.8	861	4.4	861	4.6	774
200	0	6.7	438	7.3	526	5.2	526	6.5	526	6.6	438
200	25	7.2	550	7.8	638	5.5	638	6.8	638	6.9	550
200	50	7.6	662	8.3	749	5.8	749	7.1	749	7.3	662
200	75	8.1	774	8.8	861	6.1	861	7.4	861	7.6	774
400	0	12.8	526	13.9	613	9.8	613	12.4	613	12.6	526
400	25	13.2	638	14.4	725	10.1	725	12.7	725	13.0	638
400	50	13.7	749	14.9	837	10.4	837	13.0	837	13.3	749
400	75	14.2	861	15.4	949	10.7	949	13.3	949	13.6	861

Appendix E: E17. Total phosphorus loss (Kg ha^{-1}) and P-index values in continuous corn rotation; phosphorus surface broadcast in a no-till system, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.4	98.6	2.0	164.3	1.4	164.3	1.4	98.6
25	25	2.8	266.5	2.3	332.2	2.2	332.2	2.2	266.5
25	50	4.1	434.4	3.2	500.1	3.1	500.1	3.1	434.4
25	100	7.1	770.2	5.3	836.0	4.9	836.0	4.9	770.2
25	200	13.7	1441.9	10.4	1507.6	8.7	1507.6	9.1	1441.9
50	0	1.8	131.4	2.4	197.2	1.8	197.2	1.7	131.4
50	25	3.2	299.4	2.7	365.1	2.7	365.1	2.6	299.4
50	50	4.5	467.3	3.6	533.0	3.5	533.0	3.5	467.3
50	100	7.5	803.1	5.7	868.8	5.4	868.8	5.4	803.1
50	200	14.2	1474.8	10.8	1540.5	9.2	1540.5	9.5	1474.8
100	0	2.5	328.6	3.2	394.3	2.6	394.3	2.5	328.6
100	25	3.9	496.5	3.4	562.2	3.5	562.2	3.4	496.5
100	50	5.3	664.4	4.3	730.1	4.4	730.1	4.3	664.4
100	100	8.4	1000.3	6.5	1066.0	6.3	1066.0	6.2	1000.3
100	200	15.1	1671.9	11.6	1737.6	10.1	1737.6	10.4	1671.9
200	0	4.0	328.6	4.8	394.3	4.2	394.3	4.0	328.6
200	25	5.4	496.5	4.8	562.2	5.3	562.2	5.0	496.5
200	50	6.9	664.4	5.8	730.1	6.2	730.1	6.0	664.4
200	100	10.0	1000.3	8.0	1066.0	8.1	1066.0	7.9	1000.3
200	200	16.8	1671.9	13.2	1737.6	12.0	1737.6	12.2	1671.9
400	0	7.0	394.3	7.9	460.0	7.4	460.0	7.1	394.3
400	25	8.5	562.2	7.6	628.0	8.8	628.0	8.2	562.2
400	50	10.0	730.1	8.6	795.9	9.8	795.9	9.3	730.1
400	100	13.2	1066.0	10.9	1131.7	11.8	1131.7	11.3	1066.0
400	200	20.1	1737.6	16.2	1803.4	15.8	1803.4	15.7	1737.6

Appendix E: E18. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-soybean rotation; phosphorus surface broadcast in a no-till system, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.0	99.7	1.0	166.2	1.0	166.2	1.0	100
25	25	1.9	184.6	1.7	251.1	1.5	251.1	1.5	185
25	50	2.8	269.6	2.5	336.1	2.1	336.1	2.1	270
25	100	4.6	439.4	3.9	505.9	3.1	505.9	3.2	439
25	200	8.3	779.1	7.2	845.6	5.0	845.6	5.4	779
50	0	1.8	133.0	1.8	199.4	1.8	199.4	1.8	133
50	25	2.6	217.9	2.5	284.4	2.2	284.4	2.3	218
50	50	3.5	302.8	3.2	369.3	2.7	369.3	2.8	303
50	100	5.2	472.7	4.6	539.2	3.6	539.2	3.8	473
50	200	9.0	812.4	7.9	878.9	5.6	878.9	6.0	812
100	0	2.7	332.4	2.6	398.9	2.6	398.9	2.6	332
100	25	3.4	417.3	3.3	483.8	3.0	483.8	3.1	417
100	50	4.3	502.3	3.9	568.7	3.5	568.7	3.6	502
100	100	6.0	672.1	5.4	738.6	4.4	738.6	4.6	672
100	200	9.8	1011.8	8.7	1078.3	6.4	1078.3	6.8	1012
200	0	4.3	332.4	4.3	398.9	4.3	398.9	4.3	332
200	25	5.0	417.3	4.8	483.8	4.6	483.8	4.6	417
200	50	5.9	502.3	5.5	568.7	5.1	568.7	5.1	502
200	100	7.6	672.1	7.0	738.6	6.0	738.6	6.2	672
200	200	11.4	1011.8	10.3	1078.3	8.0	1078.3	8.4	1012
400	0	7.7	398.9	7.7	465.4	7.7	465.4	7.7	399
400	25	8.2	483.8	7.9	550.3	7.8	550.3	7.8	484
400	50	9.0	568.7	8.6	635.2	8.3	635.2	8.3	569
400	100	10.8	738.6	10.1	805.1	9.2	805.1	9.3	739
400	200	14.7	1078.3	13.6	1144.8	11.2	1144.8	11.7	1078

Appendix E: E19. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-winter wheat-soybean rotation; phosphorus surface broadcast in a no-till system, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.5	99	1.4	168	0.5	165	1.4	168
25	25	1.1	183	2.5	254	0.8	249	2.1	254
25	50	1.7	267	3.7	340	1.2	333	2.7	340
25	100	2.9	435	6.2	512	1.9	501	4.0	512
25	200	5.4	772	11.8	856	3.1	838	6.7	856
50	0	1.1	132	1.1	198	2.2	202	2.3	202
50	25	1.7	216	1.6	282	3.4	288	2.8	288
50	50	2.2	300	2.2	366	4.5	374	3.3	374
50	100	3.4	468	3.3	534	7.0	546	4.3	546
50	200	5.9	805	5.9	871	12.7	890	6.8	890
100	0	1.6	329	2.2	135	3.4	337	3.4	404
100	25	2.2	414	2.9	221	4.6	423	4.6	490
100	50	2.7	498	3.6	307	5.8	509	5.8	576
100	100	3.9	666	5.1	479	8.3	681	8.3	748
100	200	6.4	1003	8.2	823	13.7	1025	14.0	1092
200	0	2.6	329	3.4	404	3.4	337	5.8	337
200	25	3.1	414	4.1	490	4.1	423	7.0	423
200	50	3.7	498	4.7	576	4.8	509	8.3	509
200	100	4.9	666	6.1	748	6.3	681	10.8	681
200	200	7.4	1003	8.7	1092	9.4	1025	16.2	1025
400	0	2.6	395	4.6	461	5.8	404	5.8	337
400	25	3.1	479	4.9	545	6.5	490	6.5	423
400	50	3.6	564	5.5	629	7.2	576	7.3	509
400	100	4.8	732	6.6	798	8.5	748	8.8	681
400	200	7.3	1069	9.3	1134	11.3	1092	11.9	1025

Appendix E: E20. Total phosphorus loss (Kg ha^{-1}) and P-index values in grain sorghum-soybean rotation; phosphorus surface broadcast in a no-till system, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.4	101	1.4	168	1.5	168	1.4	168	1.4	101
25	25	2.6	187	2.5	254	2.0	254	2.1	254	2.1	187
25	50	3.8	273	3.7	340	2.5	340	2.7	340	2.8	273
25	100	6.3	445	6.2	512	3.6	512	4.0	512	4.3	445
25	200	11.6	789	11.8	856	6.0	856	6.7	856	7.4	789
50	0	2.2	135	2.2	202	2.3	202	2.2	202	2.2	135
50	25	3.4	221	3.4	288	2.8	288	2.9	288	2.9	221
50	50	4.6	307	4.5	374	3.3	374	3.5	374	3.6	307
50	100	7.1	479	7.0	546	4.3	546	4.8	546	5.1	479
50	200	12.4	823	12.7	890	6.8	890	7.5	890	8.2	823
100	0	3.4	337	3.4	404	3.5	404	3.4	404	3.4	337
100	25	4.6	423	4.6	490	4.0	490	4.1	490	4.1	423
100	50	5.8	509	5.8	576	4.5	576	4.7	576	4.8	509
100	100	8.3	681	8.3	748	5.5	748	6.1	748	6.3	681
100	200	13.7	1025	14.0	1092	8.0	1092	8.7	1092	9.4	1025
200	0	5.8	337	5.8	404	5.8	404	5.8	404	5.8	337
200	25	7.0	423	7.0	490	6.4	490	6.5	490	6.5	423
200	50	8.3	509	8.2	576	6.9	576	7.2	576	7.3	509
200	100	10.8	681	10.8	748	8.0	748	8.5	748	8.8	681
200	200	16.2	1025	16.5	1092	10.4	1092	11.3	1092	11.9	1025
400	0	10.6	404	10.6	471	10.6	471	10.6	471	10.6	404
400	25	11.8	490	11.8	557	11.1	557	11.3	557	11.4	490
400	50	13.1	576	13.0	643	11.7	643	12.0	643	12.1	576
400	100	15.7	748	15.7	815	12.8	815	13.5	815	13.7	748
400	200	21.2	1092	21.5	1159	15.3	1159	16.4	1159	17.0	1092

Appendix E: E21. Total phosphorus loss (Kg ha^{-1}) and P-index values in continuous corn; phosphorus incorporation with tillage, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.3	108	1.4	180	1.2	108	1.3	108
25	25	2.0	292	1.8	364	1.6	292	1.7	292
25	50	2.7	476	2.3	548	2.0	476	2.1	476
25	100	4.1	844	3.3	916	2.7	844	3.0	844
25	200	7.1	1580	5.5	1652	4.1	1580	4.7	1580
50	0	2.0	144	1.9	216	1.9	144	1.9	144
50	25	2.7	328	2.4	400	2.3	328	2.4	328
50	50	3.4	512	2.9	584	2.7	512	2.8	512
50	100	4.8	880	3.9	952	3.4	880	3.7	880
50	200	7.8	1616	6.1	1688	4.8	1616	5.4	1616
100	0	3.3	360	3.0	432	3.2	360	3.2	360
100	25	4.0	544	3.6	616	3.6	544	3.7	544
100	50	4.7	728	4.1	800	4.0	728	4.2	728
100	100	6.2	1096	5.1	1168	4.7	1096	5.0	1096
100	200	9.2	1832	7.3	1904	6.1	1832	6.7	1832
200	0	6.0	360	5.3	432	5.8	360	5.9	360
200	25	6.7	544	5.8	616	6.4	544	6.4	544
200	50	7.4	728	6.4	800	6.7	728	6.9	728
200	100	8.9	1096	7.4	1168	7.5	1096	7.8	1096
200	200	12.0	1832	9.7	1904	8.9	1832	9.5	1832
400	0	11.3	432	9.8	504	11.0	432	11.1	432
400	25	12.1	616	10.4	688	11.8	616	11.9	616
400	50	12.8	800	11.0	872	12.2	800	12.4	800
400	100	14.4	1168	12.1	1240	13.0	1168	13.3	1168
400	200	17.5	1904	14.4	1976	14.5	1904	15.1	1904

Appendix E: E22. Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-soybean; phosphorus incorporation with tillage, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.9	112	1.0	187	0.9	112	0.9	112
25	25	1.3	208	1.3	283	1.1	208	1.2	208
25	50	1.8	303	1.7	378	1.4	303	1.5	303
25	100	2.6	494	2.4	569	1.8	494	2.0	494
25	200	4.1	877	3.7	951	2.6	877	2.9	877
50	0	1.7	150	1.7	224	1.6	150	1.7	150
50	25	2.0	245	2.0	320	1.8	245	1.9	245
50	50	2.4	341	2.3	416	2.0	341	2.1	341
50	100	3.1	532	2.9	607	2.4	532	2.5	532
50	200	4.7	914	4.3	989	3.1	914	3.4	914
100	0	2.8	374	2.7	449	2.7	374	2.7	374
100	25	3.1	470	3.0	544	2.8	470	2.9	470
100	50	3.4	565	3.3	640	3.0	565	3.1	565
100	100	4.2	756	3.9	831	3.4	756	3.5	756
100	200	5.7	1138	5.2	1213	4.1	1138	4.4	1138
200	0	4.9	374	4.7	449	4.7	374	4.8	374
200	25	5.1	470	4.8	544	4.8	470	4.9	470
200	50	5.5	565	5.1	640	5.0	565	5.1	565
200	100	6.2	756	5.8	831	5.4	756	5.6	756
200	200	7.8	1138	7.2	1213	6.2	1138	6.5	1138
400	0	9.1	449	8.6	524	8.9	449	9.0	449
400	25	9.2	544	8.6	619	8.8	544	8.9	544
400	50	9.5	640	8.9	715	9.0	640	9.2	640
400	100	10.3	831	9.6	906	9.4	831	9.6	831
400	200	11.9	1213	11.1	1288	10.2	1213	10.6	1213

Appendix E: E23.Total phosphorus loss (Kg ha^{-1}) and P-index values in corn-winter wheat-soybean rotation; phosphorus incorporated with tillage, Crawford site

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	0.4	103	1.4	190	0.4	103	1.3	114
25	25	0.7	191	1.9	287	0.5	191	1.5	211
25	50	1.0	279	2.4	384	0.7	279	1.8	308
25	100	1.5	455	3.4	578	1.0	455	2.3	502
25	200	2.5	806	5.7	967	1.4	806	3.3	891
50	0	1.0	138	1.0	206	2.2	228	2.2	228
50	25	1.2	225	1.3	294	2.7	325	2.4	325
50	50	1.4	313	1.5	382	3.2	422	2.7	422
50	100	1.9	489	2.0	558	4.2	616	3.1	616
50	200	2.8	841	3.0	910	6.5	1005	4.3	1005
100	0	1.6	344	2.1	152	3.7	380	3.7	456
100	25	1.8	432	2.4	249	4.2	477	4.2	553
100	50	2.1	520	2.7	346	4.7	574	4.7	650
100	100	2.5	696	3.3	540	5.7	768	5.7	844
100	200	3.5	1047	4.4	929	7.8	1157	8.0	1233
200	0	2.9	344	3.6	380	3.6	380	6.7	380
200	25	3.1	432	3.9	477	3.9	477	7.2	477
200	50	3.3	520	4.1	574	4.2	574	7.7	574
200	100	3.8	696	4.6	768	4.8	768	8.8	768
200	200	4.7	1047	5.7	1157	5.9	1157	10.9	1157
400	0	12.8	456	5.4	482	6.6	380	6.7	380
400	25	13.3	553	5.4	569	6.9	477	7.0	477
400	50	13.9	650	5.7	657	7.2	574	7.3	574
400	100	14.9	844	6.2	833	7.7	768	7.9	768
400	200	17.1	1233	7.2	1185	8.7	1157	8.8	1157

Appendix E: E24. Total phosphorus loss (Kg ha^{-1}) and P-index values in grain sorghum-soybean rotation with phosphorus surface broadcast and no-till system

Soil test phosphorus	Phosphorus application rates (Kg ha^{-1})	January		April		June		October		November	
		TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values	TP loss	PI values
25	0	1.3	114	1.4	190	1.4	190	1.3	114	1.3	114
25	25	1.8	211	1.9	287	1.7	287	1.5	211	1.6	211
25	50	2.3	308	2.4	384	1.9	384	1.8	308	1.9	308
25	100	3.3	502	3.4	578	2.4	578	2.3	502	2.5	502
25	200	5.4	891	5.7	967	3.5	967	3.3	891	3.6	891
50	0	2.1	152	2.2	228	2.2	228	2.1	152	2.1	152
50	25	2.6	249	2.7	325	2.4	325	2.3	249	2.4	249
50	50	3.1	346	3.2	422	2.7	422	2.6	346	2.7	346
50	100	4.1	540	4.2	616	3.1	616	3.1	540	3.3	540
50	200	6.2	929	6.5	1005	4.3	1005	4.1	929	4.4	929
100	0	3.7	380	3.7	456	3.5	456	3.6	380	3.6	380
100	25	4.2	477	4.2	553	3.8	553	3.9	477	3.9	477
100	50	4.7	574	4.7	650	4.0	650	4.1	574	4.2	574
100	100	5.7	768	5.7	844	4.5	844	4.6	768	4.8	768
100	200	7.8	1157	8.0	1233	5.6	1233	5.7	1157	5.9	1157
200	0	6.7	380	6.6	456	6.1	456	6.6	380	6.7	380
200	25	7.2	477	7.1	553	6.4	553	6.9	477	7.0	477
200	50	7.7	574	7.7	650	6.6	650	7.2	574	7.3	574
200	100	8.8	768	8.7	844	7.1	844	7.7	768	7.9	768
200	200	10.9	1157	11.1	1233	8.3	1233	8.7	1157	8.8	1157
400	0	12.8	456	12.5	532	11.4	532	12.7	456	12.8	456
400	25	13.3	553	13.1	629	11.6	629	13.0	553	13.1	553
400	50	13.9	650	13.6	726	11.9	726	13.2	650	13.4	650
400	100	14.9	844	14.7	920	12.4	920	13.8	844	14.1	844
400	200	17.1	1233	17.1	1309	13.6	1309	14.8	1233	14.6	1233

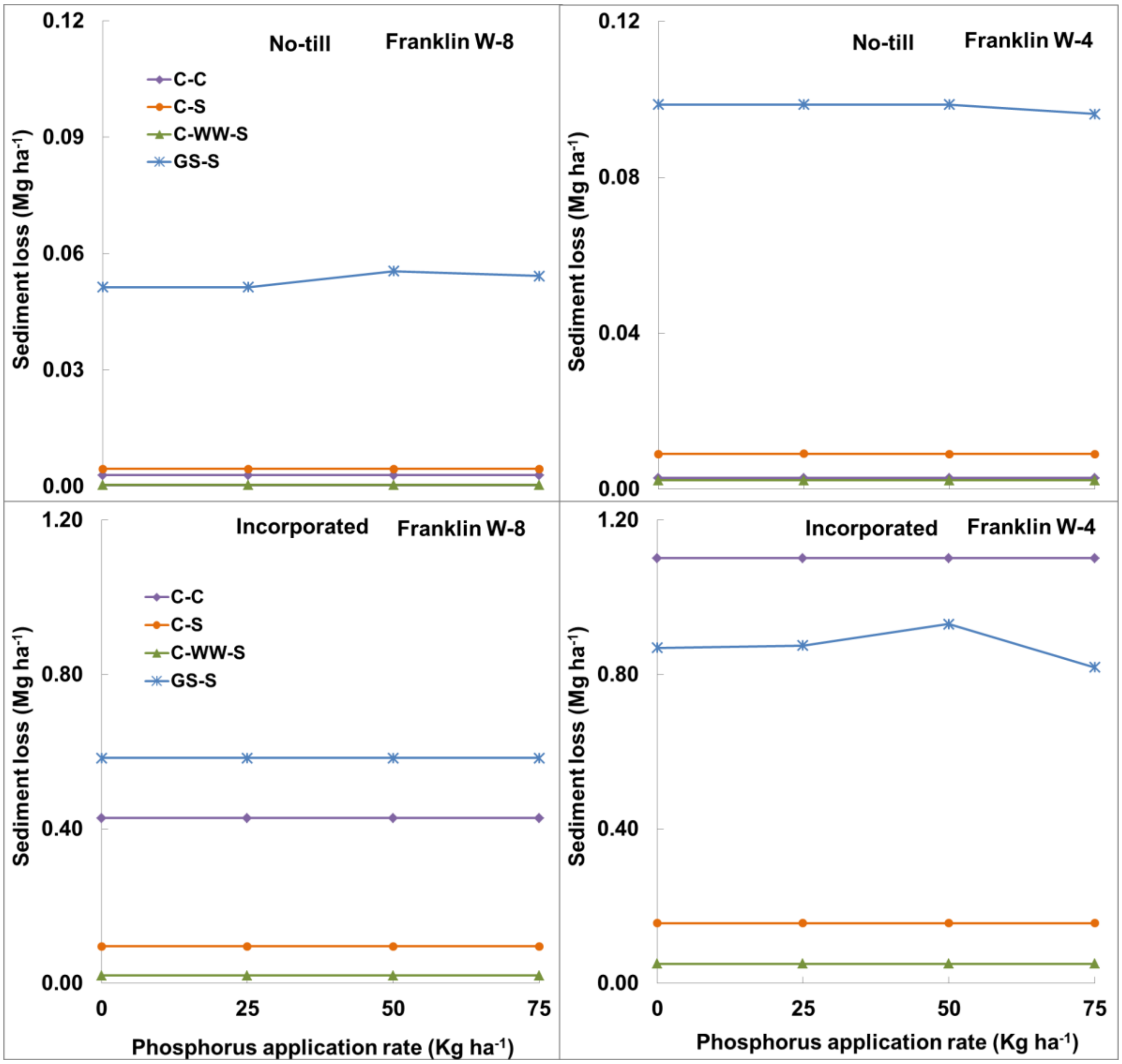


Figure E5. Average annual sediment loss by cropping system in Franklin runoff study site. C-C = Continuous corn; C-S = Corn-soybean; C-WW-S = Corn-winter wheat-soybean and GS-S = Grain sorghum-soybean cropping system

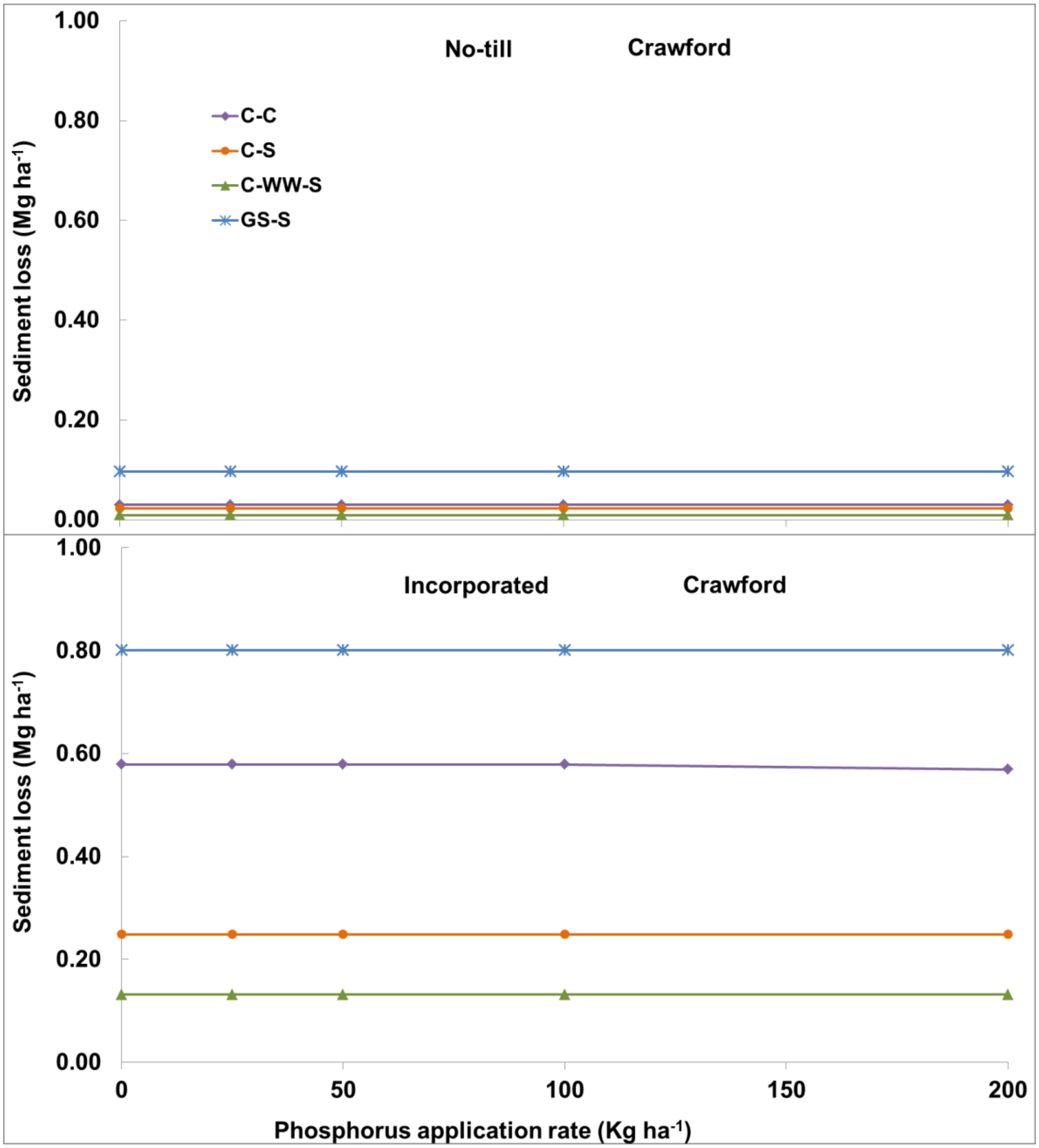


Figure E6. Average annual sediment loss by cropping system in each location, Crawford runoff study site. C-C = Continuous corn; C-S = Corn-soybean; C-WW-S = Corn-winter wheat-soybean and GS-S = Grain sorghum-soybean cropping system

APPENDIX F. Extra information on chapter 6

Section 1 - Procedure used for the batch experiment

- Weigh 1 g of soil into each of twelve (12 centrifuge tubes (Oakridge polycarbonate tubes).
- 0.01 M/L calcium chloride electrolyte solution. For this dissolve 1.4701 g of calcium chloride dehydrate ($CaCl_2.2H_2O$) in 1 L of DI water. Store in the refrigerator until use.
- Prepare 1 L of standard P concentrations (as outline below) in 0.01 M $CaCl_2$ solution.
- Add 25 ml of standard P solution (Appendix F: Table F1) to each tube.
- Place on end to end shaker at low speed for 24 hours.
- After 24 hours remove tubes from shaker, centrifuge at 10,000 RPM for 10 minutes and filter supernatant through a 0.45 µm filter.
- Save filtrate in 15 ml vials at 5°C.
- Analyze extracts on Lachate using 75.5 cm sample loop and standards from 0.025 to 2.0 ppm P. (Note- all the samples at concentrations greater than 2 ppm (7 to 12 in the Appendix F: Table1) will need to be diluted for analysis.

Standard P solutions:

1. 1000 ppm P stock standard solution was used in 0.01 M $CaCl_2$ to prepare the standards of 2 mg kg^{-1}, 1 mg kg^{-1}, 0.5 mg kg^{-1}, 0.2, 0.01 mg kg^{-1}, 0 mg kg^{-1}.

Section 2 -Procedure to analyze Ferrous Iron (Fe^{2+})

Chemicals and Stock solution preparation

0.015 M 1,10-o-phennanthroline regent

1. Add 150 mL of deionized water to the 250 ml volumetric flask (VF).
2. Add 0.75 g of 1,10-o-phenanthroline monohydrate to the flask.
3. Heat the solution carefully to 80 °C to dissolve the o-phenanthroline.
4. Once o-phenanthroline was dissolved, allow the solution to cool to room temperature.
5. Bring the final volume to 250 mL mark with deionized water (DI).

5M AOC

1. Add 250 ml of DI Water in 500 ml VF.
2. Add 192.5 g of AOC.
3. Bring to final volume with DI water.
4. **6M HCl**

1. Add 200 ml of DI water to 500 ml VF.
2. Carefully add 250 mL of concentrated HCl to the flask.
3. Slowly swirl to mix.
4. Allow solution to cool.

5. Bring to 500 mL final volume with DI water.

100 ppm iron (Prepare fresh daily)

1. Add 50 ml of DI Water in 100 ml VF.
2. Add 0.0702 g of Ferrous Ammonium Sulfate (FAS) and mix thoroughly.
3. Bring to final volume with DI water.

Prepare **Ferrous Iron (Fe^{2+})** standards by adding 100 mg Fe L^{-1} stock solution in 100 ml VF:

0.00 mg Fe L^{-1} = 0 mg Fe L^{-1}

0.30 mg Fe L^{-1} = 0.30 mg of 100 mg Fe L^{-1}

0.75 mg Fe L^{-1} = 0.75 mg of 100 mg Fe L^{-1}

1.50 mg Fe L^{-1}= 1.50 mg of 100 mg Fe L^{-1}

2.25 mg Fe L^{-1} = 2.25 mg of 100 mg Fe L^{-1} and

3.50 mg Fe L^{-1} = 3.50 mg of 100 mg Fe L^{-1}

Sample bottle preparation

- Seal the bottles with rubber stopper and aluminum seals.
- Vacuum the bottles for 5 minutes and deoxygenate with helium gas for 2-3 minutes (200psi).
- After deoxygenation, re-vacuum the bottles for another 5 minutes.

Standard curve development

- Add 1 mL of 1, 10-phennanthroline regent to the deoxygenated 30 ml amber color bottles using 3ml syringe.
- Add 6 ml of each Ferrous Iron (Fe^{2+}) standards using the 3ml syringe.
- Add 2ml of 5*M* Ammonium acetate with syringe and mix
- Add 1 ml of 6M HCl to keep the pH between 3-5. (1 ml of 6M HCl was determined by testing standards with 4 replications in which 1 ml of 6M HCl was added and pH was measured. The average pH of those 4 replications was 4.62.
- Measure the **Fe^{2+}** concentration using spectrophotometer.
- **Methods to analyze leachate samples:**
- Add 1 mL of 1, 10-phennanthroline regent to the 30 ml deoxygenated amber color bottles using 3 ml syringe.
- Connect the sample loop to the column directly to collect approximately 8 ml of sample.
- Transfer 6ml of the sample in a bottle containing 1 mL of 1,10-phennanthroline regent. Take the sample from the end that is connected to the column.
- Add 2ml of 5*M* Ammonium acetate with syringe and mix
- Add 1 ml of 6M HCl to keep the pH between 3-5.
- Using a spectrophotometer measure **Ferrous Iron (Fe^{2+})** Fe^{2+} concentration at λ= 510nm.

Section 3- MATLAB script used to estimate coefficient of hydrodynamic dispersion

```
% M-File script DispCoefEstimationRevised for determining dispersion
% coefficient D and retardation factor R by fitting Solution A1 of van
% Genuchten and Alves (1982) to data from a solute breakthrough experiment
% with a step inlet condition. This script calls the function A1Func.m to
% evaluate the analytical solution.
%
% In this script, Solution A1 of van Genuchten and Alves (1982) is fitted
% to measured breakthrough curve data. The script uploads the measured data
% from an Excel spreadsheet file. Times and relative solute concentrations
% for the breakthrough curve are placed in the first and second columns,
% respectively, of the spreadsheet file.
%
% This script was written by G.J. Kluitenberg on October 15, 2014.
% ***************************************************************************

% Clear MATLAB environment
clear all;
close all;
clc;

velocity = 'slow';
% velocity = 'medium';
% velocity = 'fast';

replicate = 'one';
% replicate = 'two';

% Read time and relative solute concentration data from Excel spreadsheet
% file ExampleBreakthroughData.xls. Times [h] are assigned to the vector
% XDATA and relative solution concentrations [-] are assigned to the
% vector YDATA.
switch velocity
    case 'slow'
        switch replicate
            case 'one'
                XDATA = xlsread('BhandariBromideBTCs',1,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',1,'b2..b70');
            case 'two'
                XDATA = xlsread('BhandariBromideBTCs',2,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',2,'b2..b70');
        end
    case 'medium'
        switch replicate
            case 'one'
                XDATA = xlsread('BhandariBromideBTCs',3,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',3,'b2..b70');
            case 'two'
                XDATA = xlsread('BhandariBromideBTCs',4,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',4,'b2..b70');
        end
    case 'fast'
        switch replicate
            case 'one'
```

```
                XDATA = xlsread('BhandariBromideBTCs',5,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',5,'b2..b70');
            case 'two'
                XDATA = xlsread('BhandariBromideBTCs',6,'a2..a70');
                YDATA = xlsread('BhandariBromideBTCs',6,'b2..b70');
        end
end

% Assign values for fixed constants
switch velocity
case 'slow'
    v = 0.208*(0.47/0.41);   % Average pore water velocity [cm/h]
case 'medium'
    v = 0.417*(0.47/0.41);   % Average pore water velocity [cm/h]
case 'fast'
    v = 1.25*(0.47/0.41);    % Average pore water velocity [cm/h]
end
z = 10;          % Depth at which concentration is evaluated [cm]

% Put fixed constants in column vector P for passing to A1func
P = [v; z];

% Initial estimates (i.e. guesses) for parameters to be estimated
lambda = 1;      % Dispersivity [cm]
D = lambda*v;    % Dispersion coefficient [cm^2/h]
R = 10;           % Retardation factor [-]

% Put initial parameter estimates in column vector XGUESS
XGUESS = [D; R];

% Vectors with upper and lower bounds for parameters to be estimated
UB = [100; 1.5];
LB = [0.001; 0.5];
% Use to adjust termination tolerances - Default values are 1.0e-6
OPTIONS = optimset('TolFun',1.0e-6,'TolX',1.0e-6);

% Perform curve-fitting. Estimated parameters are passed to vector X
[X,resnorm,residual,exitflag,output] = lsqcurvefit(@A1Func, XGUESS, XDATA,
YDATA, LB, UB, OPTIONS, P);

% Calculate fitted curves using optimized values of parameters
FITTEDYDATA = A1Func(X,XDATA,P);
% Plot results
hold on
plot(XDATA,YDATA,'bo');
plot(XDATA,FITTEDYDATA,'r');
xlabel('Time [h]');
ylabel('Relative Concentration [--]');
Dlabel = ['D = ' num2str(X(1), '%10.4f') ' cm^2/h'];
 h = text(55,0.5,Dlabel);
Rlabel  = ['R = ' num2str(X(2), '%10.4f')];
h = text(30,0.4,Rlabel);
```

Section 4- The backwards implicit method to solve the advection-dispersion equation

```
% M-File script Bhandari_Implicit that uses the backwards implicit method
% to solve the advection-dispersion equation with initial condition
% C(z,0)=0 and boundary conditions C(0,t)=C-sub-a and dC/dz=0.
%
% The value specified for Ld must be large enough that solute concentration
% front does not reach depth z = Ld. Of course, if the value for Ld is
% adjusted, the value for m must be adjusted accordingly.

% Clear MATLAB Environment
clear all;
%close all;
clc;

isotherm = 'Linear';
% isotherm = 'Langmuir';
% isotherm = 'Freundlich';

% inletconc = 'small';
inletconc = 'large';

velocity = 'slow';
% velocity = 'fast';

soil = 'control';

m = 200;
Ld = 100;         % Length of domain in z direction [cm]
L = 10;           % Column length [cm]
dz = Ld/m;        % Space increment [cm]
dt = 0.1;         % Time increment [d]

% Assign value for pore water velocity [cm/d]
switch velocity
case 'slow'
    v = 45;
case 'fast'
    v = 65;
end

% Physical properties
lambda =0.10;       % Dispersivity [cm]
rhob = 1.4e6;     % Bulk density [mg/L]
theta = 0.47;     % Volumetric water content [cm^3/cm^3]
D = lambda*v;     % Dispersion coefficient [cm^2/d]

% Constant for linear isotherm
 Kd = 2.4358e-6;        % Distribution coefficient [L/mg]--batch exp
% Kd = 0;

% Constants for Langmuir isotherm
switch soil
case 'control'
```

```
     Smax = 198.5e-6;  % Total sorption capacity [mg/mg]--batch exp
     k = 0.178;        % Distribution coeffient [L/mg]---batch exp

end

% Constants for Freundlich isotherm
switch soil
case 'control'
    Kf = 62.33e-6;     % Distribution coefficient [L/mg]^beta_bath exp
    beta = 0.271;      % Emperical fitting parameter [-]_batch exp
end

% Assign solute concentration at inlet [mg/L]
switch inletconc
case 'small'
    Ca = 30;
case 'large'
    Ca = 90;
end

% Assign initial values for solute concentration [mg/L]
switch isotherm
case 'Linear'
    C = zeros(m,1);
case 'Langmuir'
    C = zeros(m,1);
case 'Freundlich'
    C = 0.0001*ones(m,1);
end

% Create column vector of times used for plotting the breakthrough curve.
% The elements of "btctimes" must be multiples of dt.
switch velocity
case 'slow'
    tstep = 0.1;       % [d]
    endtime =8;  % [d]
    btctimes = (tstep:tstep:endtime)';
case 'fast'
    %tstep = 0.5;     % [d]
    tstep = 0.1;
    endtime = 5;   % [d]
    btctimes = (tstep:tstep:endtime)';
end

% Calculate index number for the node at the column exit. The value
% specified for L must be a multiple of dz.
btcnode = L/dz;

% Preallocate vector for saving results at the times in "btctimes"
btcresults = NaN(length(btctimes),1);

% Preallocate matrix for retardation factors at the times in "btctimes"
retardation = NaN(m,length(btctimes));
```

```
% Create square matrix A and column vector B with zero entries
A = zeros(m);
B = zeros(m,1);

z = dz*(1:m)'; % Column vector of depths
t = dt; % Set time for first pass through while loop
M = 1; % Initialize counter

% Begin stepping in time
while (t-endtime) <= sqrt(eps)

    switch isotherm
    case 'Linear'
    R = ones(m,1) + rhob*Kd/theta;
    case 'Langmuir'
    R = 1 + (rhob*k*Smax)./(theta*(1+k*C).^2);
    case 'Freundlich'
    R = 1 + (rhob*Kf*beta*C.^(beta-1))/theta;
    end

    % Calculate coefficients a-sub-i and b-sub-i
    a = dt*D./(dz^2*R);
    b = dt*v./(2*dz*R);

    A(1,1) = 1 + 2*a(1);
    A(1,2) = -(a(1)-b(1));
    B(1) = C(1) + (a(1)+b(1))*Ca;

    for i = 2:m-1
        A(i,i-1) = -(a(i)+b(i));
        A(i,i) = 1 + 2*a(i);
        A(i,i+1) = -(a(i)-b(i));
        B(i) = C(i);
    end

    A(m,m-1) = -2*a(m);
    A(m,m) = 1 + 2*a(m);
    B(m) = C(m);

    C = A\B;

    % Commands executed at times specified in the vector "btctimes"
    if any(abs(btctimes-t) <= sqrt(eps))
        % Write solute concentration at column exit to "btcresults"
        btcresults(M) = C(btcnode);
        % Write vector of retardation factors to "retardation"
        retardation(:,M) = R;
        % Increment counter
        M = M + 1;
    end

    % Commands used to calculate concentration profile when t=endtime
    if (endtime-t) <= sqrt(eps)
        % Write solute concentrations to "results"
        results = C;
```

```
        % Calculate exact concentration profile when t=endtime if the
        % sorption isotherm is linear
        if strcmp(isotherm,'Linear')
            exact = czt2(R(1),D,v,Ca,z,t);
        end
    end

    t = t + dt; % Increment time for next pass through while loop
end

% Use analytical solution to calculate approximation error if the sorption
% isotherm is linear
if strcmp(isotherm,'Linear')
    btcexact = czt2(R(1),D,v,Ca,L,btctimes);
    btcerror = btcresults - btcexact;
end

% Convert times in vector "btctimes" to pore volumes
btcporevolumes = v*btctimes/L;

% Calculate mesh-scale Peclet and Courant numbers for the case of a linear
% sorption isotherm.
if strcmp(isotherm,'Linear')
    Pe = v*dz/D;
    Cr = v*dt/(dz*R(1));
end

%Plot flux concentration versus time
figure(1)
hold on
plot(btctimes,btcresults,'bo');
if strcmp(isotherm,'Linear')
plot(btctimes,btcexact,'r');
end
xlabel('Time (d)');
ylabel('C (mg L^{-1})');

%Plot flux concentration versus pore volumes
figure(2)
hold on
plot(btcporevolumes,btcresults,'bo');
if strcmp(isotherm,'Linear')
    plot(btcporevolumes,btcexact,'r');
end
xlabel('Pore volume');
ylabel('Concentration (mg L^{-1})');

% Plot flux concentration versus depth
figure(3)
hold on
plot(results,z,'bo');
if strcmp(isotherm,'Linear')
plot(exact,z,'r');
end
set(gca,'YDir','reverse');
```

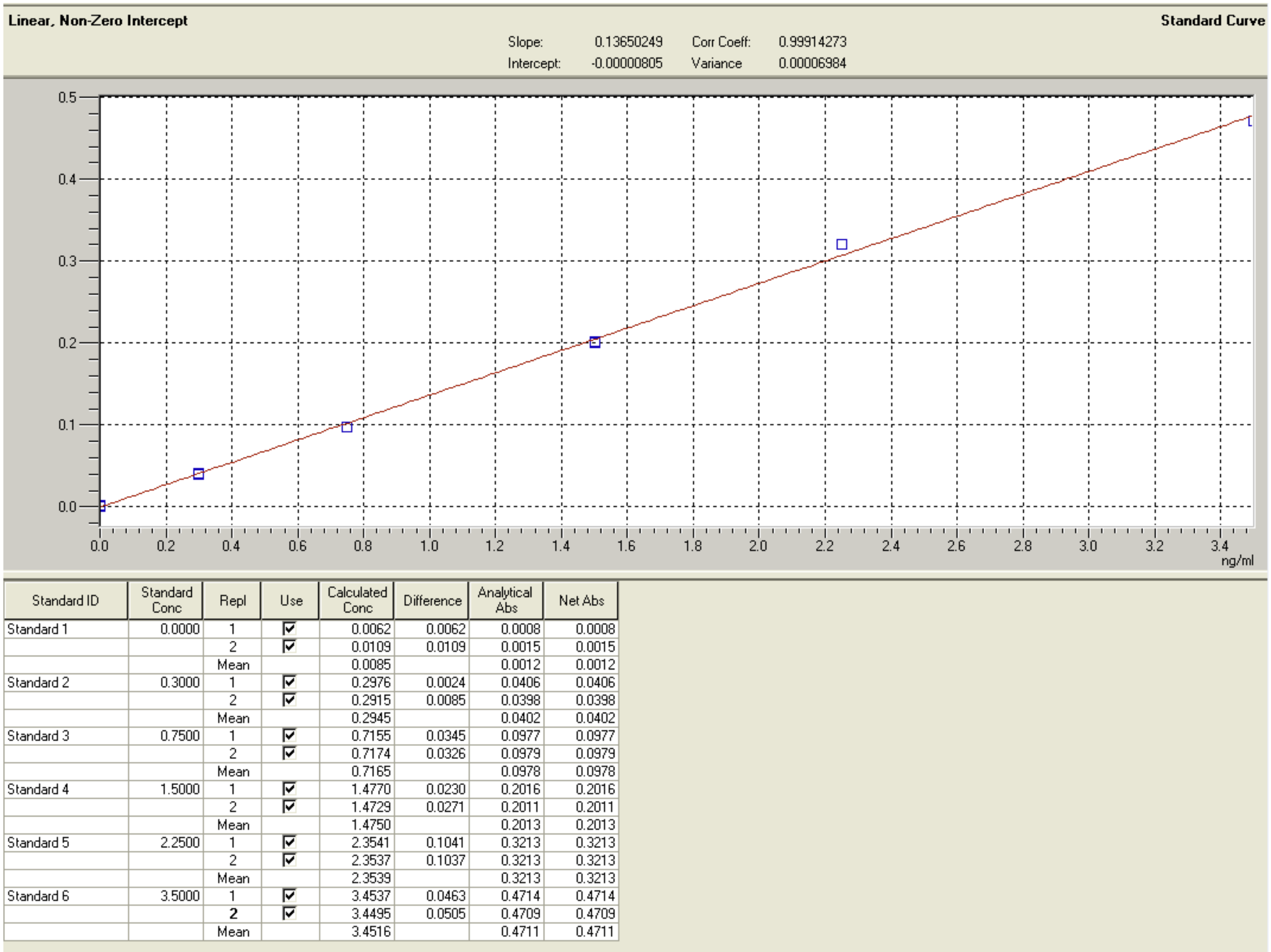
```
xlabel('C (mg L^{-1})');
ylabel('Depth (cm)');

% Create matrix for export results
output = [btcresults btctimes btcporevolumes];
xlswrite('FREUND_90mgP_FFR_test', output);
```

SECTION 5- ExtraTable and Figures

Appendix F: Table F1. Table format used to collect batch experiment data

Tube/Soil number	P added (mg/L)	Wt of soil (gram)	Solution added (ml)/ Wt (g)
Replication 1			
1	0 (check)		
2	0.001		
3	0.1		
4	0.2		
5	0.5		
6	2		
7	10		
8	20		
9	30		
10	40		
11	60		
12	100		
Replication 2			
1	0		
2	0.001		
3	0.1		
4	0.2		
5	0.5		
6	2		
7	10		
8	20		
9	30		
10	40		
11	60		
12	100		



Linear, Non-Zero Intercept

Standard Curve

Slope: 0.13650249 Corr Coeff: 0.99914273

Intercept: -0.00000805 Variance 0.00006984

Standard ID	Standard Conc	Repl	Use	Calculated Conc	Difference	Analytical Abs	Net Abs
Standard 1	0.0000	1	☑	0.0062	0.0062	0.0008	0.0008
		2	☑	0.0109	0.0109	0.0015	0.0015
		Mean		0.0085		0.0012	0.0012
Standard 2	0.3000	1	☑	0.2976	0.0024	0.0406	0.0406
		2	☑	0.2915	0.0085	0.0398	0.0398
		Mean		0.2945		0.0402	0.0402
Standard 3	0.7500	1	☑	0.7155	0.0345	0.0977	0.0977
		2	☑	0.7174	0.0326	0.0979	0.0979
		Mean		0.7165		0.0978	0.0978
Standard 4	1.5000	1	☑	1.4770	0.0230	0.2016	0.2016
		2	☑	1.4729	0.0271	0.2011	0.2011
		Mean		1.4750		0.2013	0.2013
Standard 5	2.2500	1	☑	2.3541	0.1041	0.3213	0.3213
		2	☑	2.3537	0.1037	0.3213	0.3213
		Mean		2.3539		0.3213	0.3213
Standard 6	3.5000	1	☑	3.4537	0.0463	0.4714	0.4714
		2	☑	3.4495	0.0505	0.4709	0.4709
		Mean		3.4516		0.4711	0.4711

Figure: F1. Standard curve developed for iron reduction test using colometric method in UV-spectrophotometer

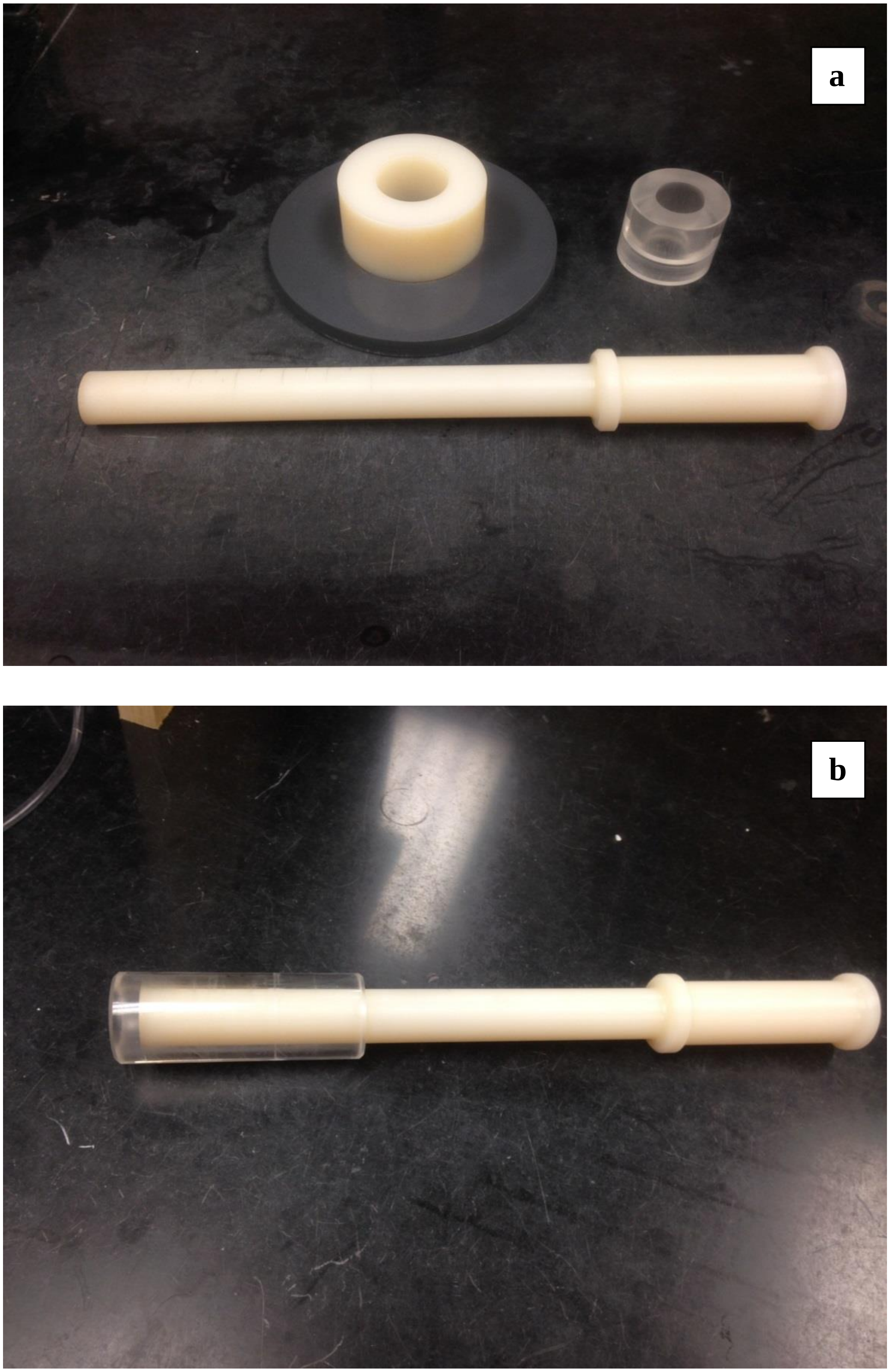


Figure F2. a) base, holder and a plunger (compacter) used to pack column b) demonstration of the compacter inserted inside the column

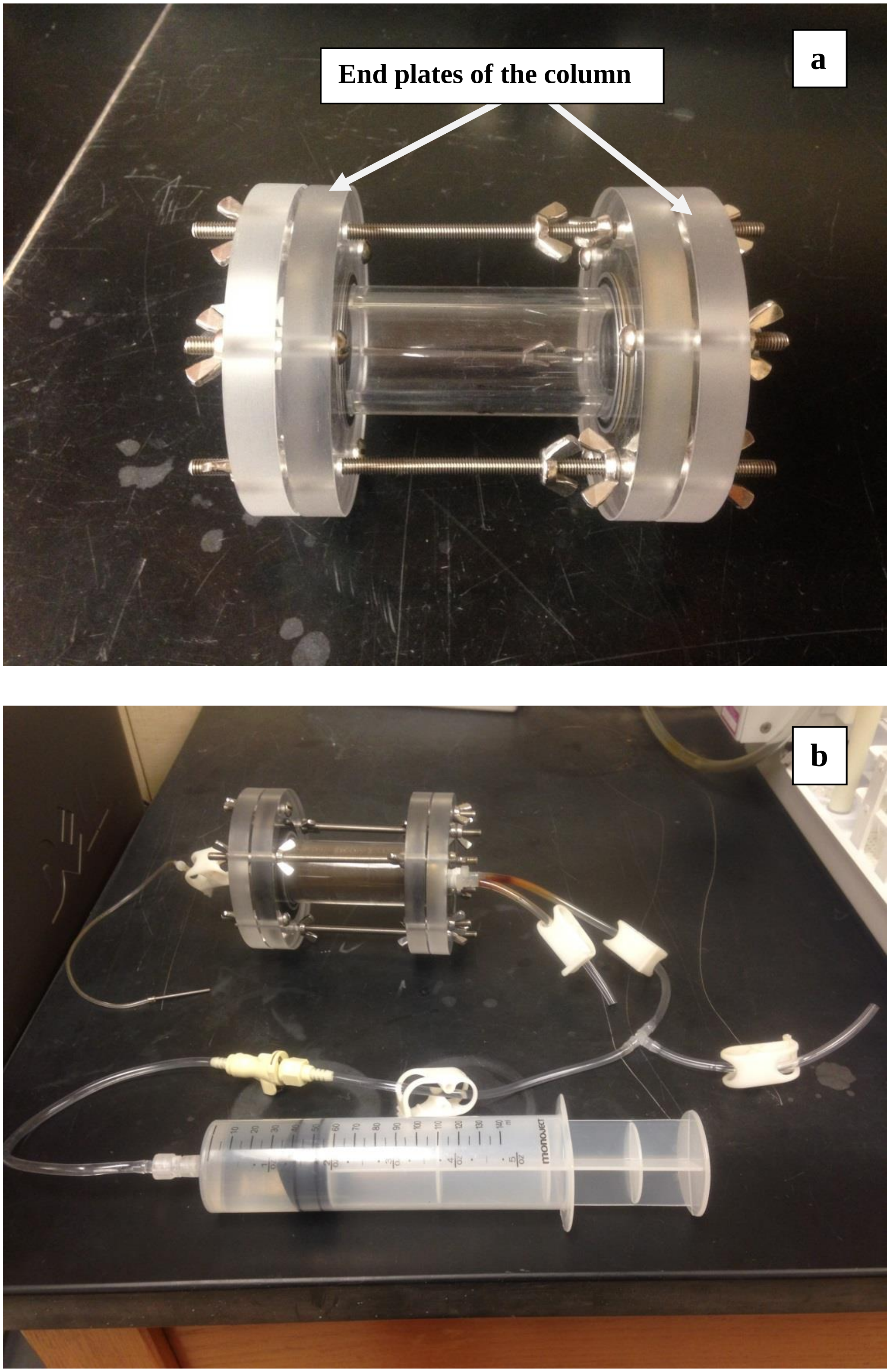
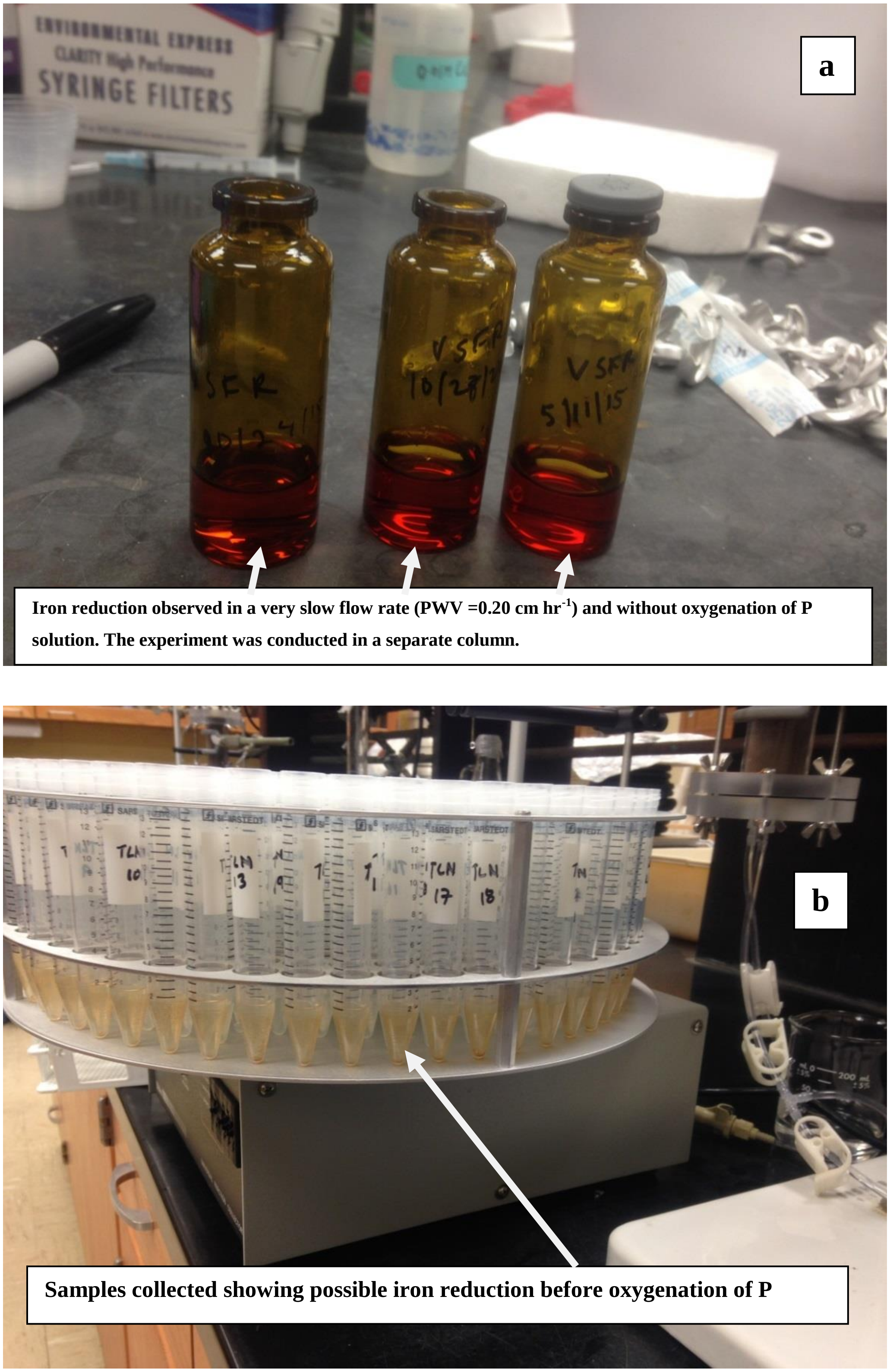


Figure F3. a) Column with end plates b) demonstration of the column, syringe, tubing and other apparatus used for the study

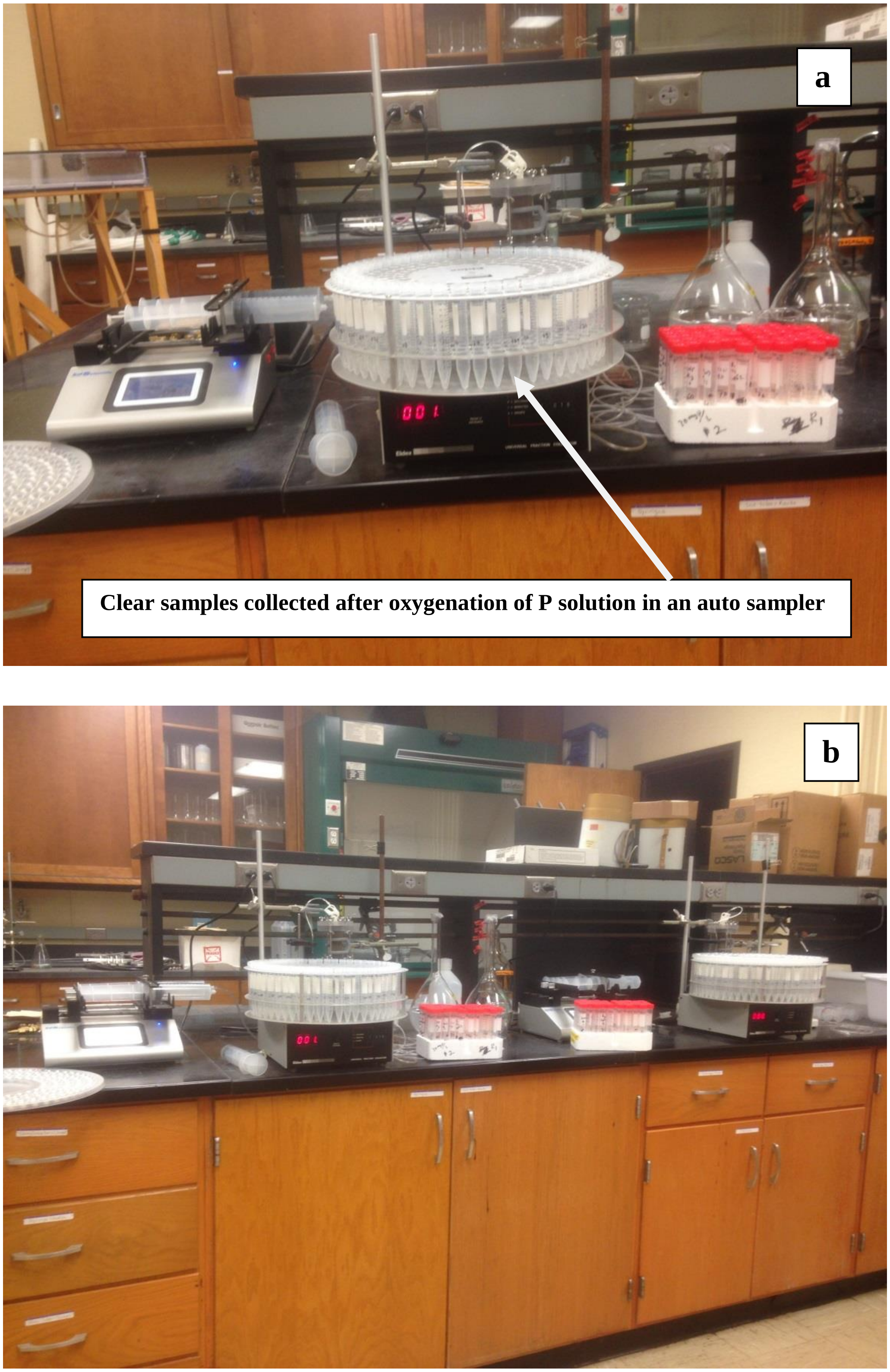
Figure F4. a) techniques showing deoxygenation (with helium gas), and re-vacuum of bottles b) Samples collected for reduced iron (Fe^{2+}) analysis



Iron reduction observed in a very slow flow rate (PWV =0.20 cm hr^{-1}) and without oxygenation of P solution. The experiment was conducted in a separate column.

Samples collected showing possible iron reduction before oxygenation of P

Figure F5. a) Reduced iron test with a very slow flow rate b) Samples collected in an auto sampler before oxygenation was started



Clear samples collected after oxygenation of P solution in an auto sampler

Figure F6. a) and b) lab settings with auto samplers collecting the leachate samples