# Coupling Precision Agriculture with Water Quality Credit Trading

Ann Sorensen, Research Director, American Farmland Trust

May 1, 2013 to August 31, 2015

69-3A75-12-204

Submitted November 25, 2015

Proposed Deliverables

- Standardized quantification methodology for calculating edge-of-field nutrient loss reductions from precision agriculture VRT and protocol for using the methodology to generate credits for water quality trading systems - ACHIEVED
- Regulatory review and support of methodology and protocols - NOT POSSIBLE
- Economic analysis of the cost and benefits of selling credits from precision agriculture into WQT programs - NOT POSSIBLE
- Donation of resulting nutrient credits from project participants - NOT POSSIBLE

Amended Deliverables

- Standardized quantification methodology for calculating edge-of-field nutrient loss from GPS guidance systems and protocol for using the methodology to generate credits for water quality trading systems - ACHIEVED
- Simulated test to confirm that enhanced nutrient management can produce both nutrient credits and carbon credits - ACHIEVED

## TABLE OF CONTENTS

**TABLE OF CONTENTS** (continued)

**Coupling Precision Agriculture with Water Quality Credit Trading**
**69-3A75-12-204**

## EXECUTIVE SUMMARY

This project addresses a USDA Natural Resources Conservation Service (NRCS) designated priority for Water Quality Trading (WQT) markets (also referred to in this report as Water Quality Credit Trading Markets (WQCT)): *Repeatable, science-based credit estimation methodologies that provide reasonable and practical levels of precision and efficacy to assess the reduction of nutrient loads by conservation practices*.

The stimulus for the project was a request from the Ohio River Basin Water Quality Trading Agricultural Stakeholder committee to develop a credit estimation methodology for Precision Agriculture. American Farmland Trust (AFT) is a collaborator in this on-going effort to establish a regional WQT market (supported by NRCS CIG grants in 2011, 2012 and 2015). The committee singled out precision agriculture variable rate technology (VRT) as an emerging technology that improves nutrient management and urged us to develop a quantification protocol for use in the emerging market. To participate in a WQT market, the best management practice (BMP) a farmer uses to generate credits must be new to the farm and implemented in response to the WQT opportunity. Getting out ahead of the adoption of a BMP means more farmers may qualify to sell the resulting credits.

Using improved nutrient management techniques to reduce nutrient run-off and generate WQT credits seems intuitive but is actually complex. Not all fields where VRT methods are adopted end up reducing nutrient run-off since nutrients must be in place before the crops need to use them, making them vulnerable to climatic events and subsequent run-off. To provide guidance on how to reduce nutrient run-off while maintaining the necessary nutrient resources for crop needs, USDA NRCS has developed the “4Rs” approach that combines the right application rate for crop needs, the right timing for applications, the right method of application and the right form/source of nutrients. Based on the assumption that use of these principles can reduce nutrient runoff, the project team structured an evaluation of VRT implementation practices.

The project set an overall goal of developing, testing and refining the first ever quantification protocol for crediting Precision Ag VRT practices in WQT programs. The project team proposed using data from universities and John Deere to compare crop uptake budgets with the amount of nutrients (phosphorus (P) and nitrogen (N)) applied and use modeling at the farm field level paired with edge-of-field monitors to account for the fate of excess nutrients. We planned to refine the resulting quantification protocol with data from participating farmers. Once we vetted the protocol with State permitting agencies in OH, IN and KY, participating farmers would then have the opportunity to donate any resulting nutrient credits to a credit reserve pool for the ORB WQT pilot trading program.

However, despite significant outreach over many months, the project team could not locate farmers who were: 1) using the type of Precision Ag VRT we needed; 2) had edge-

of-field monitors in place to help us improve the sensitivity of our model by monitoring impacts on water quality and 3) were keeping adequate records and willing to share years of data. This forced the project team to follow a different route to achieve our goal. We decided to rely on sophisticated computer modeling to develop the protocols and standards and expanded to include GPS guidance systems. The reliance on modeling increased the level of uncertainty and resulted in higher trade ratios. We amended our deliverables and extended the project by one year.

The project team overcame financial challenges regarding a portion of the proposed cash match. We originally envisioned recruiting two producers in Kentucky who had received state cost-share funds to implement precision agriculture to work with us (a projected $40,000 cash match for the project). However, we could not find producers currently receiving state funding who fit within the VRT profile, kept multiple years of the accurate data for the full list of parameters needed and were willing to share it with us. Although we failed to secure the cash match from Kentucky, we raised the additional cash needed to support the new direction taken by the technical team.

As a result of these early and mid-course corrections, the project team completed the first steps towards developing four credit estimation methods for edge-of-field P and N nonpoint source loading for WQT crediting purposes. To further develop and improve these methods, they will have to be tested using long-term farm operation records and environmental monitoring data including soil test, runoff, sediment and nutrient loading monitoring. We also considered the viability of crediting section boom control, a precision agriculture VRT method to reduce overlaps and skips during fertilizer applications. Section boom control VRT approaches can also use these credit estimation methods as appropriate.

The four equations and associated margins of safety are for:

1. VRT nutrient management for particulate phosphorus loading rates.
2. VRT nutrient management for particulate nitrogen loading rates.
3. VRT nutrient management with the use of nitrogen testing just before sidedress nitrogen applications for nitrates.
4. VRT nutrient management without soil testing before sidedress nitrogen applications for nitrates (may be applied conservatively to operations not using sidedress applications).

The following policy considerations can help WQT programs determine if these equations can be applied to a particular site:

- WQT credits should not be considered when the implementation of the VRT nutrient management approach results in a substantial yield loss.
- The credit estimation methods apply to zone map applications of VRT rather than on-the-go VRT systems.
- Particulate nutrient equations should not be applied to sites where the depth of soil erosion exceeds the soil profile depth of enriched nutrients to support crop production.

- N credit estimation should only be applied when N applications precede corn years and spring N soil samples are collected.
- Particulate P estimation methods are an adequate-conservative estimate for crediting TP when the particulate form dominates the total P edge-of-field loading. When a substantial fraction of soluble P is in the edge-of-field loading, the bioavailability ratio for agricultural row crop loading may change.
- The use of zone mapping VRT nutrient applications is preferred over the use of on-the-go VRT equipment when crediting for trading. On-the-go systems track a substantial amount of data regarding yield, soils, and application rates that must be reduced to account for available nutrients and soil erosion rates spatially. Currently without computerized record keeping for the field characteristics necessary to estimating credits, the on-the-go VRT data collation is considered too difficult for daily use in the field.

Other project findings include:

- A linear sensitivity analysis assessing results over a long-term management period confirmed the effectiveness of a 4R approach to nutrient management.
- The SWAT model results confirmed the validity of the CREAMS model algorithm used by the U.S. EPA STEPL/Region 5 models but the variability in P concentrations across actual fields calls into question the use of a default soil test nutrient value for P of 1 lb per ton of soil in these models.
- For the VRT methodology, the use of trade ratio to address the year-to-year variability that occurs appeared to be adequate. However, monthly time steps contain months that do not produce credits and therefore should not be used for contemporaneous credit generation settings.
- In a simulated test to stack nutrient and greenhouse gas credits, we found a 20 percent reduction in N application rates (30 lbs/acre) resulted in an acre loading reduction of only 0.4 lbs of TN per acre. N credit generation is bounded by two competing principles. On the one hand, a greater reduction in N application rate would have impacted yield and on the other hand, any less of an application reduction would have generated an edge-of-field loading that would be marginal given a trade ratio must also be applied.
- WQT programs will need an efficient credit aggregation method to accumulate substantial offsets required by most dischargers. One possibility is for fertilizer application service providers to aggregate credits on their clients' behalf.

## INTRODUCTION

### Overview of the Project

We developed the project in response to a request from the Ohio River Basin Water Quality Trading Agricultural Stakeholder committee to develop a credit estimation methodology for Precision Agriculture. American Farmland Trust (AFT), the lead for this CIG project, is a collaborator in this on-going effort to establish a regional WQT market (supported by NRCS CIG grants in 2011, 2012 and 2015). The ORB WQT Ag Stakeholder committee had singled out Precision Ag variable rate technology (VRT) as an emerging technology that improves nutrient management and urged us to develop a quantification protocol for use in the emerging market. Getting out ahead of BMP adoption means more farmers may qualify to sell the resulting credits. To participate in a WQT market, the BMP a farmer uses to generate credits must be new to the farm and implemented in response to the WQT opportunity.

Dr. Ann Sorensen, Research Director and Asst. V.P. of Programs for AFT led the project. Sorensen had directed AFT's research program since 1992 and had completed over 180 projects addressing AFT priorities. Jim Klang, Senior Project Engineer, Kieser & Associates, led the technical team. Klang had over 20 years of experience in water quality and watershed management. Prior to joining K&A, Mr. Klang was the lead Engineer at the MN Pollution Control Agency (MPCA) TMDL program. The project team included representatives from AFT, K&A, the Ohio Farm Bureau Federation, the Kentucky Division of Conservation, the Indiana State Department of Agriculture, Ohio Department of Natural Resources, John Deere, Trimble, University of Kentucky, Purdue University and The Ohio State University. We also had help and advice from two NRCS technical contacts (*See Appendix 1: #1. Project Team Members*)

The project set an overall goal of developing, testing and refining the first ever quantification protocol for crediting Precision Ag VRT practices in WQT programs. The target area for finding farmers using Precision Ag VRT and securing both data and testing sites included Ohio, Kentucky and Indiana, the states participating in the ORB WQT project. The objectives were to: 1) Use data from universities and John Deere to compare crop uptake budgets with the amount of nutrients (P and N) applied and using modeling at the farm field level and some edge-of-field monitors to account for the fate of excess nutrients; 2) Test and refine the resulting quantification protocol through one and a half growing seasons; 3) Vet the protocol with State permitting agencies in OH, IN and KY; 4) Pending their approval, provide participating farmers with the opportunity to donate any resulting nutrient credits to a credit reserve pool for the ORB WQT pilot trading program; and 5) Use the resulting protocol to help precision agriculture farmers document nutrient load reductions to qualify for emerging certification programs (e.g. Field to Market) and help inform NRCS conservation programs.

The proposed deliverables and products included: 1) Standardized quantification methodology for calculating edge-of-field nutrient loss reductions from precision agriculture VRT. Protocol for using the methodology to generate credits for water quality trading system; 2) Regulatory review and support of methodology and protocols;

3) Economic analysis of the cost and benefits of selling credits from precision agriculture into WQT programs; and 4) Donation of resulting nutrient credits from project participants.

The difficulty in finding collaborating farmers and farms ultimately forced the project team to re-envision the project and follow a different route to achieve our goal. We used sophisticated computer modeling to develop the protocols and standards and expanded to include GPS guidance systems. The reliance on modeling increased the level of uncertainty and resulted in higher trade ratios. The modeling also took much more time than originally envisioned so even though we extended the project period from two to three years, we still ran out of time to confirm the validity of the protocols with edge-of-field monitors, vet the protocols with the State Permitting agencies and incorporate these protocols and standards into WQT markets.

As a result of both the early and mid-course corrections we made, the project team was able to develop the first ever credit estimation methods for edge-of-field P and N nonpoint source loading for WQT crediting purposes. We also considered the viability of crediting section boom control, a precision agriculture VRT method to reduce overlaps and skips during fertilizer applications. Section boom control VRT approaches can also use these credit estimation methods as appropriate. In addition, using our calibrated model, we were able to show that a 20 percent reduction in N application rates could generate both nutrient and greenhouse gas credits.

The project requested $221,364 in USDA funding and committed to providing matching funds of $250,583, consisting of $110,682 in cash match and $139,900 in in-kind match. The project leveraged valuable in-kind support from the project team. They provided feedback to the technical team as they worked through the complexities of both Precision Ag systems and the challenges of modeling complex nutrient cycling throughout a growing season. John Deere provided access to their in-house data on GPS guidance systems and the associated reductions in fertilizer applications when overlaps are eliminated. The University of Kentucky facilitated access to a farm operation that could provide the data we needed to calibrate the model. However, since we only convened one in-person meeting, the in-kind matches originally pledged by the project steering committee fell short. Since modeling constituted the bulk of the project work, the technical team covered the remaining match requirement. Although we failed to secure the $40,000 cash match from Kentucky, AFT covered the cash match requirement with additional funds to support the new direction taken by the technical team.

## BACKGROUND

### The Problem

WQT programs need repeatable and science-based credit estimation methodologies that provide reasonable and practical levels of precision and efficacy to assess the reduction of nutrient loads by conservation practices. The ideal quantification method offers accuracy, consistently delivers the same results despite different users, reflects actual differences in the water quality indicators being measured (= sensitivity), is easy to understand and well-documented and is practical and economical to use (National Network on WQT 2015). For this reason, WQT has been generally limited to traditional conservation practices that have standardized practice methods established by USDA-NRCS and quantification protocols accepted by regulatory agencies for estimating edge-of-field losses of sediments and nutrients to determine trading credits.

The need to develop a science-based credit estimation methodology for Precision Ag was first identified by the Ohio River Basin Water Quality Trading Project. Several of the investigators to this proposed project (AFT, K&A, OFBF, OH Department of Natural Resources, KY Division of Conservation and IN State Department of Agriculture) are involved in developing an interstate WQT framework for the ORB. Upon implementation, this innovative ecosystem market application will be the world's largest WQT program, spanning at least eight states and making it possible for the 46 power plants and 2,000 wastewater utilities in the anticipated market area to purchase credits from producers in the basin. Pilot trades to test this interstate framework started in 2012.

The ORB producers and the ORB Agricultural Stakeholder Advisory Committee felt it was important to include new technologies and BMPs in this market as a way to enhance adoption and engage more producers in trading (Sorensen 2011). They pointed to Precision Ag as an emerging technology that improves nutrient management and indicated strong support for development of a quantification protocol for precision agriculture. They identified several compelling reasons to assess the potential for Precision Ag practices to generate WQT credits: Agriculture is a substantial contributor of nutrients to the ORB and downstream to the Gulf of Mexico; ORB producers who have already adopted traditional practices desire WQT programs to credit Precision Ag so they can continue advancing their environmental stewardship level; WQT opportunities are expanding in the ORB and future regulations on point sources are anticipated that will drive new opportunities to expand credit generation to agriculture; equipment costs for Precision Ag are high and returns on investments may reduce potential producer investment and deployment of these systems; and, WQT could be an economic incentive for adopting and deploying Precision Ag in the ORB and other areas of the country.

**The Novelty of the Approach**

To date, however, there are no tested or established quantification protocols for crediting Precision Ag practices in WQT programs. In particular, current WQT methods do not adequately capture the potential nutrient reductions provided by VRT. In part, this is because many crediting methodologies rely on averaged conditions across an entire field. Crediting units often include estimated reductions in sediment loading in tons/acre/year and nutrient reductions provided in pound/acre/year wherein the equations use whole field averages as inputs. Producers using VRT apply agronomic nutrients at rates that are determined by the crop nutrient needs at the specific location of application because differences in soils, moisture availability and past cropping practices are correlated with drops or increases in yield within a field. VRT can be either map-based where the field's crop yield history is the prescription for future applications, or sensor-based where real-time crop or field assessments control the input applications.

Since VRT responds to actual plant needs, it should minimize the amount of nutrients lost to the atmosphere, to run-off over field surfaces, or through drainage tiles to adjacent water bodies. Likewise, GPS guidance systems with section controls for booms allow for reduction of over application resulting from spreader overlapping during furrow passes when crossing grass waterways and turning around at end rows.

**Why the Focus on Precision Agriculture?**

In 2007, USDA NRCS published an agronomy technical note on Precision Ag recognizing that the primary driver for investing in precision agriculture equipment was the economic return on investment (USDA NRCS 2007). However, resource protection, while seldom the primary motivator, could be a secondary benefit. To achieve a positive impact on the environment, NRCS emphasized that the use of Precision Ag needed to be part of a system developed specifically to address a resource concern. Fine-tuning the environmental focus involved identifying the resource concern to be addressed, identifying the background data that is needed to address the resource concern, determining how to keep track of geospatial data, developing a plan for how Precision Ag will be used to address the resource concern, assembling the specialized equipment required to implement the plan and evaluating and revising the plan after each cropping season. To date, however, most of the existing Precision Ag systems are geared towards cost reductions and more efficient use of production inputs

The costs of equipment and need for additional management initially held back the adoption of Precision Ag systems. However, industry consolidation, the availability of USDA NRCS Environmental Quality Incentive Program (EQIP) cost-share funds and new technologies with ever-expanding potential could accelerate its adoption in the next few years. Typically, producers start by using yield monitors, go on to soil maps and finally invest in VRT to put yield and soil information together (Schimmelpfennig and Ebel 2011). The components of Precision Ag include spatial- or geo-referenced information on crop production fields (e.g., grid soil samples, detailed soil mapping, aerial photography, topographic maps, yield maps, soil texture maps, environmentally sensitive areas), recordkeeping systems, an analysis and decision-making process, specialized implementation equipment to precisely apply variable rates of crop inputs and measure yields to understand crop response (includes GPS guidance systems, variable rate-application equipment, yield monitors, electrical conductivity and moisture measuring devices), and provisions for evaluation and revisions after each cropping system.

Little empirical research has been conducted to document the actual changes in environmental impacts attributable to the implementation of Precision Ag. Intuitively, precision agriculture should reduce environmental loading by applying fertilizers and pesticides only where they are needed and when they are needed (Bongiovanni et al. 2004). According to USDA, Precision Ag can possibly reduce soil erosion, protect water quality, improve soil health and productivity and improve the wildlife and landscape (Bergtold 2007). Computer modeling of the carbon input:output ratio under different production strategies (both traditional farming and Precision Agriculture under no-till conditions) for a grain farmer in Kentucky concluded that all Precision Agriculture techniques produce a Pareto improvement over the base model (Brown et al. 2012). Automatic section control provided the greatest improvement with a mean net return 0.9 percent over the base. RTK provided the most significant enhancement in the carbon ration with an improvement of 2.42 percent over the base model. This was attributed to a 2 percent reduction in seed used (the carbon footprint of producing and selling each individual seed was calculated) and a 10 percent reduction in the use of tractor fuel.

Although reduced use of agrochemicals, more efficient use of nutrients, increased efficacy of managed inputs and increased protection of soils from degradation can all be viewed as potential benefits to the environment from Precision Ag, there can also be some negative impacts (Pierce and Nowak 2008). Precision Ag may make it possible for farmers to more aggressively treat site-specific potentials or problems and actually increase the use of chemical applications. For example, not all sites employing VRT realize yield increases or minimization of nutrient releases to the environment since there are a variety of spatial and temporal factors that can impact nutrient losses (Schepers 2008). The traffic pattern of the planting and tillage equipment can lead to soil compaction and a two to five-fold difference in water infiltration rates between rows. Also, the timing of nutrient application in relation to the timing and amount of precipitation is important. At least one study has documented differences between uniform rate application and variable rate N application (Harmel et al. 2004). During a two-year monitoring period with 22 storm sampling events, the overall median $NO_3$ + $NO_2$–N concentrations were significantly lower for the variable rate field in the second year of variable rate N application. The overall and event mean $NO_3$ + $NO_2$–N concentrations from the variable rate field tended to be higher, but median concentrations tended to be lower.

The potential exists for engaging farmers in WQT markets through their interest in Precision Agriculture. John Deere, one of this project's industry partners, estimates that precision technologies are being leveraged on slightly less than one third of the agricultural land across the eastern two-thirds of the U.S. Precision guidance systems and yield monitors are the most popular, with about 32 percent adopting (Diekmann and Batte 2010). In 2005-2006, VRT was used on 24 percent of the corn acres and 17 percent of the soybean acres in the country while GPS guidance systems were used on 13.2 percent of the corn acres and 18.4 percent of the soybean acres. While VRT use for fertilizer application remains modest, the use of GPS guidance systems has expanded rapidly in the intervening years. In the project's target area (Ohio, Indiana and Kentucky), the 2010 USDA Agricultural Resource Management Survey (ARMS) of corn acres found that VRT was being used for N application on 14 percent of acres in Indiana and 11 percent of acres in Ohio, VRT for P application on 15 percent of acres in Indiana and 27 percent of acres in Ohio and GPS guidance systems were used on 56 percent of acres in Indiana, 68 percent of acres in Kentucky and 59 percent of acres in Ohio.

The rate of adoption and the Precision Ag component adopted depends on the farm's size, its annual sales, and the type(s) of crop being grown. Adoption is seven times higher for the largest farm class than for the smallest class of commercial farmers. This could have significant implications for WQT programs because fewer contracts with larger farms covering more acreage and generating more nutrient credits may help reduce program costs. In addition, agricultural retailers play a key role in custom applications and the majority cover more than 50,000 acres annually for their customers, making it possible for them to act as aggregators for the resulting credits and further reducing market costs (Erickson and Widmar 2015).

## REVIEW OF METHODS

### Deciding on a modeling approach

The technical team needed to decide on a modeling approach that would approximate the complexity of nutrient cycles in the field. Based on extensive research, the project team endorsed the use of the SWAT model (*See Appendix 1*: #2. *SWAT Application for Developing a Credit Estimation Method for Precision Agriculture and Crediting Concept for Precision Ag*).

### Defining the Precision Agriculture VRT system

Creating a common vision for the many types of Precision Ag in existence is an essential component to the standardization of the WQT credit estimation method. Precision Ag can have many different applications under its domain. Basically, it is a set of related technologies that are designed to maximize the efficiency of crop inputs by making field operations more exact (Erickson and Widmar 2015). The end goal is higher crop productivity. On-the-go mapping, zone mapping, nitrogen VRT, phosphorus VRT, GPS guidance systems, sprayer controls, soil sensors, chlorophyll or greenness sensors, seed or pesticide Precision Ag -- all are often loosely defined as Precision Ag. For trading to provide a credit, the credit estimation method must create a standardized list of specifications that apply to that equation's assumptions. Knowledge about critical equipment, nutrient rates and application method, Precision Ag type and the site's physical and cropping characteristics are necessary to determine if the equation is appropriate for that setting. The team agreed to create a quality control process when soliciting future agricultural cooperators to minimize the number of contacts and time engaged with Precision Ag systems applying different methods

### Adding an additional crediting development track

Based on its literature review, the project team decided to pursue two crediting development tracks instead of just one. One of the tracks focused on Precision Agriculture VRT as described in the original proposal. We were hopeful that we could identify conditions where VRT provides a reduction in nutrient loading but were concerned that VRT might not be consistent enough to generate WQT credits. The Team felt that GPS/RTK was more promising so we added an additional track focusing on Geographic Positioning Systems (GPS) guidance systems that reduce overlaps on fertilizer application.

John Deere agreed to provide their in-house data on GPS and associated reductions in fertilizer applications when overlaps are eliminated. GPS controlled systems reduce overlap applications from two operating situations. The first is when operator error occurs. When the end row turns take place, sometimes a furrow overlap occurs and that row receives two applications. This type of operator error would also include uncontrolled duplicate applications at the end rows themselves if the operator does not quickly shut off and restart the spreader. A second overlap reduction occurs when the application equipment width creates a double application in portions of the end rows on irregular fields. A wide boom will have one section enter into an end row or grassed area well ahead of the rest of the boom sections. The second situation, section boom control, is the type of GPS guidance system John Deere brought to the project. The GPS guidance system shuts off application on the boom by sections as the coverage enters into areas with previous applications.

This method has to the potential to provide records associated with the estimates to support trading. While using this type of BMP to generate nutrient credits for trading may not pay for the equipment on one operation, use by agricultural retailers who apply nutrients for many farmers could aggregate the nutrient reductions from all of their client's operations.

**Securing producer data**

In the original proposal, the project team thought we could identify and secure the participation of up to 30 producers who farmed in the Ohio River Basin in Kentucky, Indiana and Ohio. In Kentucky, we also planned to recruit at least two producers who were receiving KY cost-share funds to implement precision agriculture (representing a $40,000 cash match from the State for the project). Our priority was to secure farms with edge-of-field water quality monitors. The team planned to use the field-scale water quality model setup it developed and calibrate it to provide results for sites with 2013 applications of conventional and precision agriculture nutrient management. The team would then evaluate and compare the edge-of-field monitoring results, field-scale water quality model results and the results derived from using the WQT credit estimator. The team planned to use the reactions and recommendations from producers and their technical service providers during the testing period to improve the WQT credit estimator and possibly re-test it during the spring of 2014 for early season applications. However, the difficulty in finding farmers who fit our needs and were willing to share their data ended up to be an insurmountable barrier.

The team secured a field site in Kentucky almost immediately and we used this site to calibrate the SWAT model. To find other sources for data and field sites, we developed a site selection evaluation form. Team members, including our USDA NRCS technical contacts, suggested potential sources for data and field sites. We talked with the Indiana State Department of Agriculture (part of Indiana on-farm network), Manchester College (part of IN Upper Eel Watershed Mississippi River Basin Initiative), Indiana University (part of IN Upper East Fork-White River MRBI), the Iowa Soybean on-farm network, the IPM Institute (leading the Lake Erie basin dissolved P reduction projects), the Conservation Technology Information Center (part of the Indian Creek MRBI project), the University of Illinois (part of the Upper Salt Fork MRBI project), USDA Agricultural Research Service (ARS) in Ohio (Upper Big Walnut Creek), USDA ARS in Iowa and USDA ARS in Missouri. The Iowa Soybean On-Farm Network offered to share agronomic data with us but they were outside of our target area. They had found that the type of fertilizer and its placement were more important than the rate and that temperature and precipitation heavily influence uptake. Confounding their results was the fact that VRT was not standardized nor well-defined. The USDA ARS laboratory in Columbia, MO had a long-term site using Precision Ag with edge-of-field water quality monitoring in place and we hoped to be able to use their data. However, they planned to publish a paper based on the data and did not want to release it prematurely.

**Addressing the need for data confidentiality**

In anticipation of finding farmers who were: 1) using the type of Precision Agriculture VRT we needed; 2) had edge-of-field monitors in place to help us improve the sensitivity of our model by monitoring impacts on water quality and 3) who were also keeping adequate records and were willing to share years of data with us, the project team considered a confidential information protocol and developed a Farm Data Release Form (*See Appendix 1: #3. Draft Farm Data Release Form*). Assuring data confidentiality can be a large stumbling block for many projects. Ultimately, we found only two farmers who fit the project's specifications, had rich datasets detailing their operational approach and yield where they were using VRT and were willing to share their data. However, other USDA CIG projects may benefit from considering and using a similar confidential information protocol to put farmers at ease when they agree to share data.

**Adjusting for the limited availability of surface runoff monitoring data**

The project couldn't find surface runoff monitoring data from sources/studies where the provider was actually willing to provide sufficient data for model set up and calibration. As a result, the team decided to base the SWAT model calibration on agronomic relationships between nutrients and yield. While the SWAT model has an agronomic component, the model estimation capability for yield estimates is not as robust as that found in other agronomic models that do not provide water quality estimation. Our chosen approach increased the uncertainty surrounding water quality and quantity predictions and meant we would have to increase the margin-of-safety-ratio in the trade. However, since the SWAT model was originally created for use in unmonitored watersheds, we felt this approach was sufficient to provide reduction efficiency estimates. The resulting crediting protocol would include a higher trade ratio and could be later be tested by taking water quality samples. The technical team planned to use the default SWAT model setup in a sensitivity analysis in order to provide insight into year-to-year variability as weather patterns are shifted (artificially). They were able to model planting and harvest events under different weather cycles.

**Adding a credit stacking analysis**

While we were developing our VRT protocol for WQT, the ORB WQT project proposed to test the concept of credit stacking by enrolling producers who were using enhanced nutrient management on corn and applying both the EPRI-MSU Nitrous Oxide Greenhouse Gas Emissions Offset Methodology and an edge-of-field calculator for nutrient load reductions. To better understand if the ORB WQT credit stacking scenario would work, we used our calibrated field level SWAT model to evaluate two approaches to reducing N application rates.

The first approach assessed the potential ancillary water quality benefits associated with uniform N application rates throughout the field. The second approach evaluated the effects of Precision Agriculture VRT. One benefit of the SWAT model approach is that the evaluation can set up conditions where water quality benefits can be generated and compare those settings to assess the possibility of a yield loss. Calibrating the model at the field scale based on agronomic yields, the assessment process can be guided by the potential for yield impacts from rate reductions. In this way, when a farmer switches to N application rates that comply with the greenhouse gas protocol, the model allows for an additional evaluation of both improved water quality and the potential for crop yield reductions.

In addition, not every VRT method being applied in agriculture today will reduce the total N application in a given field. Some VRT approaches substantially increase the total N application rate due to increased applications on prime production areas that are not offset by decreased rates on marginally producing areas. This can result in a breakeven field application rate or an increase in overall N applications with no discernible increase in yield. Using multiple SWAT runs, we could evaluate the farm operation and physical conditions that exist when benefits do or do not occur. The analysis ultimately concluded that it was technically viable to generate WQT credits when using the same nutrient management techniques required under the MSU-EPRI GHG protocol (*See Appendix 2: # 4. Final Draft Report: Viability and Potential for Stacking Greenhouse Gas (GHG) and Water Quality Credit Trading (WQCT) Credits*)

**Project Delays**

The project's primary source of delay was our inability to find cooperating farmers using the type of Precision Ag VRT we needed with sufficient data needed to calibrate the SWAT model. The lack of cooperators who fit all of our needs also meant that the project would not realize all of its objectives. We extended the project by one year thinking this might allow us time to locate producers to adequately test the protocols in the field as originally envisioned in the project but were still unable to find cooperators. The second source of delay was caused by the lack of available data in regards to water quality modeling set up and calibration. To overcome the lack of edge-of-field water quality monitoring data, the technical team developed a SWAT modeling set up and calibration approach that is based on the agronomy algorithms in SWAT but the amount of information needed to set up and calibrate the model was significant and calibration was very time-consuming.

**Schedule of Events**

Although we had originally envisioned several in-person meetings for the committee and regular conference calls, we ended up holding one in-person meeting at the start of the project and then convened calls at critical decision points. The project team met early on to agree to modeling approaches, help identify data sources and potential field sites and identify concerns and barriers. We scheduled subsequent calls whenever the technical team needed feedback. The technical team also benefited from the help and advice of the project's two NRCS technical contacts.

**November-December 2012:**
The team convened two calls to discuss the types of data we would need to develop a credit estimation tool for WQT. The technical team provided information on WQT for the partners who were new to trading programs as well as information on data needs (*See Appendix 1: #4. AFT CIG: Developing a Water Quality Credit Trading Credit Estimation Method for Precision Agriculture: Draft Project Flow Path for Discussion).*

The technical team then reassessed its projected methods based on feedback from the November calls and asked team members to fill out a form to provide data for an initial site selection evaluation that provided the following information:

- A brief description of the proposed field - Including location, size, crop rotation and equipment passes
- Baseline - A brief description of prior practices on the same field for the years before the VRT study (necessary to calculate before and after comparisons)
- Yield monitoring data - Duration of data collection (in years), description of collection methods (judgment regarding accuracy of maps), as well as data format
- Soil data availability - Soil nutrient content (N, P levels and measuring/extraction methods used)
- Presence of other BMPs - Other practices that are in place that might interfere with the accuracy of the evaluation process
- VRT application - Description of VRT method, range of application rates, how often the application rate changes (for example if the rate varies every ¼ or ½ acres), frequency and amount of application, type of application, equipment used
    - Presence of locally operated weather stations - Parameters measured and frequency of measurement
    - Water chemistry and water quantity monitoring stations - Description of each station, including drainage area (single field, multiple fields, or small watershed), parameters, location and period of record

**January - June 2013**
The project convened an in-person meeting in Chicago, Illinois but poor weather forced several people to cancel at the last minute. We discussed our model choices, the pros and cons of establishing two crediting protocol tracks (VRT and GPS Guidance systems and how to define them) and how to collect enough data and field testing sites. The project then convened a catch-up call for the remaining team members. Using this information, the technical team began to map out an approach, explore the limitations of the SWAT model and calibrate the model with data from the Kentucky farm. While the delays in finding the appropriate farm-level data slowed down the work on VRT, the team worked with John Deere and data from a GPS controlled section boom shut off operation to develop a methodology for GPS guidance systems. Although not originally in the scope of the project, the rapid expansion of acreage under GPS guidance systems indicated that this might be a promising BMP for water quality trading markets to include if a methodology could be developed before adoption expands even more.

**July 2013 - June 2014**
The project team reacted to a spreadsheet created by the technical team that showed some of the VRT equipment approaches and what and how SWAT tracks the crop's nutrient mass balance. The team discussed the data needs to run protocols and whether farmers would have the data. They also discussed the possibilities of using models to point out what the risk potentials are for farmers.  In a second call, the team discussed a memo from the technical team that summarized the Precision Ag projects crediting approach and set appropriate project expectations regarding which Precision Ag types to study and the limitations in accuracy that would be faced when applying it to sites with sizable differences in site characteristics.

For its VRT work, the team confirmed the viability of using a second producer site in Illinois.  The farm fit our needs and the producer was willing to work in tandem with his consultant to share data from his farm.   The technical team met with the producer and secured permission to work with his service providers to confirm the availability of necessary agronomy records.  This farm was using VRT for both P and N and allowed us to evaluate the fate of N up to a point - this farm also lacked edge-of-field monitors.  The technical team took the committee's feedback under advisement and then began the time consuming work of using the nine years of data from the Illinois farm to calibrate and fine-tune the SWAT model.

**July 2014 - June 2015**
During this period, the technical team finalized data reduction and statistical analysis of the Illinois farm field.  The site evaluation included the SWAT model setup, calibration and several scenarios.  When the output results for the large number of model runs was combined the edge-of-field nitrate analysis, statistical significance was increased substantially.

The project team reviewed and made suggestions for the Precision Ag presentation to be given at the Soil and Water Conservation Society Meeting May 21, 2015. After presenting the project's progress at the SWCS meeting, the technical team then completed a greenhouse gas and water quality credit trading stacking feasibility scenario and developed preliminary zone mapping VRT credit estimation method for particulate nutrients.

The project team also discussed the development of the crediting protocols: Crediting protocol for GPS guidance systems (GPS guidance system practice standard); VRT practice standard - phosphorus and nitrogen; and stacking credits (using MSU-EPRI GHG protocol (based on N fertilizer rate) to calculate greenhouse gas (GHG) credits and linking that to possible nutrient reductions at edge-of-field that could be converted to water quality credits).   (*See Appendix 1:*  #5.  *AFT Presentation for May 21, 2015 team meeting: Water Quality Trading Credit Method Development for Variable Rate Technology*).  After the meeting, the team was sent the draft report on stacking credits to review.

**What worked, what didn't work and why**

The concept of crediting protocols and standards for specific Precision Ag components was a good one but we quickly found that VRT is not standardized or well-defined. Also, the formulas used to determine what fertilizer application will be applied and what this rate is based on varies between agronomists and was not shared with the team. This limited the team to an analysis based on what was applied without being able to consider the agronomist's assumptions when adjusting the application rates. In addition, crop consultants stress that while they make recommendations, only the producer knows what was actually applied. This disconnect contributes to the issues discussed regarding finding producers with adequate records. With GPS guidance systems, these kinds of complications are not as much of a problem since the equipment generates records at the time of application.

The challenge we could not overcome was our inability to locate the precise combination of farm, Precision Ag system, data and water quality monitoring we needed. The project spent months and months trying to locate farmers who were: 1) using the type of Precision Agriculture VRT we needed; 2) had edge-of-field monitors in place to help us improve the sensitivity of our model by monitoring impacts on water quality and 3) were keeping adequate records and willing to share years of data with us. Although we found many operators who were using VRT, the specific methodologies they were using added too many complications to developing the crediting tool (e.g. using on-the-go versus zone mapping; unique changes in their script for nutrient management adjustments).

To overcome the lack of edge-of-field water quality monitoring data, the technical team developed a SWAT modeling set up and calibration approach that is based on the agronomy algorithms in SWAT but the amount of information needed to set up and calibrate the model was significant and calibration was very time-consuming. Even though we extended the project period from two to three years, we still ran out of time to confirm the validity of the protocols with edge-of-field monitors, vet the protocols with the State Permitting agencies and incorporate these protocols and standards into WQT markets. Our reliance on modeling increased the level of uncertainty and resulted in higher trade ratios.

## DISCUSSION OF QUALITY ASSURANCE

### Project Site Descriptions

Two study sites were provided for this project based on availability of field operation record, including VRT implementation, and the landowners' willingness to provide data and cooperate with the project team. Both sites have the corn-soybean rotation typical of the Midwest.

The first site was a 124-acre field located in north central Kentucky. This field has been in no-till for over a decade. The field was not artificially drained. The majority of the soil in the field had a slope between 2~10 percent. Nicholson silt loam and Lowell silt loam were the two dominant soil series.

The second site in Illinois was a 159-acre field located in north central Illinois. Except for a 10-12 inch deep chisel plowing before each corn planting, the field did not have any other tillage operations. The field was tile-drained in depressions with a tile depth around 4 feet. Nearly all of the soils in the field had a slope less than 2 percent. Ashkum silty clay loam and Elliott silty clay loam formed the majority of the soil series in the field.

**Sampling Design and Procedures & Custody Procedures**
The project did not utilize water quality monitoring data sets.

**Calibration**
Because neither of the two studied fields was monitored for flow or water quality, model calibration was done only for the crop yield by modifying the crop growth factors of RUE (radiation-use efficiency of the plant) and/or GSI (maximum leaf conductance, related to plant transpiration rate). Duration of the model simulations for calibration was determined by the available farm operation data provided by the landowner.

The model set up for yield calibration for the Kentucky site was the five-year crop rotation started in 2007 and ended in 2011: soybean-corn-soybeans-corn-soybeans. Model output from the first year of simulation (2007) was not used in the calibration so that model parameters, especially those related to nutrient and water balances in the soil, could be stabilized. The landowner provided the yield information.

Due to the importance of soil loss in determining nutrient loading from agricultural fields and the role of sediment loss as an indication of surface runoff from the field, adjustments of sediment yield from the fields were conducted in addition to crop yield calibration for the Kentucky site. This sediment yield adjustments were based on: 1) common literature values for SWAT parameters related to surface runoff: CN2-initial SCS runoff curve number for moisture condition II (Waidler et al. 2009; Almendinger and Ulrich 2012; Arabi et al. 2008); OV_N-Manning's "n" for overland flow (Almendinger and Ulrich, 2012; Arabi et al. 2008); and sediment yield (USLE_C-Universal Soil Loss Equation C factor (Arabi et al. 2008; Kieser &Associates 2005) in the Midwest; and 2) best professional judgment by Dr. Mueller on a likely magnitude of sediment yield from the study field.

The model setup for yield calibration for the Illinois site was the nine-year crop rotation started in 2005 and ended in 2013: soybean-corn-soybeans-corn-soybeans-corn-soybeans-corn-soybeans. Model output from the first year of simulation (2005) was not used in the calibration to stabilize the initial model nutrient and water balances. Because no single source of data could provide site specific or complete yield information for this study site, the final yield values used for calibration were a composite of: 1) data provided by the landowner and the landowner's assistant, 2) grain delivery reports, 3) un-calibrated harvest maps, and 4) county averages from crop yield surveys reported by USDA-National Agricultural Statistics Service (NASS).

For the Illinois site, default SWAT parameter values were sufficient to produce model sediment yield at a reasonable average rate for no-till operations on flat slopes. No additional adjustments of sediment yield from the Illinois field were conducted.

**Quality Control Procedures**

Data provided by landowners for this study were checked for their general consistency based on the knowledge of the technical team on local agricultural operations. When available, multiple sources of crop yield data were cross-checked and apparent inconsistencies were resolved by consulting with the landowners, their service providers, and USDA county survey data. The final crop yield data used for SWAT model calibration reflected actual weather conditions over the calibration period and best professional judgment of the technical team.

For SWAT model setup, the most updated and detailed soil data were downloaded from the USDA's soil map depository on its website. For the Kentucky study site, NOAA meteorological data were supplemented with the 5-minute statewide station network and the Kentucky MESONET data for precipitation, temperature, humidity, and wind. HRUs (unique combinations of soil, slope, and soil nutrient level) were generated for SWAT using the "all possible combinations," resulting in 1500 HRUs for the Kentucky study site and over 800 HRUs for the Illinois site. These HRUs ensured model simulations captured effects of small differences in soil, slope and soil nutrient level on nutrient loading.

For SWAT model crop yield calibration, simulated annual values were calibrated within 10 percent of the reported values. The average crop yield over the entire calibration period was calibrated within 5 percent of the reported value.

**Data Reduction, Analysis, Review, and Reporting**

SWAT simulations generated copious amount of data for each HRU. The data files were imported into Microsoft Access and Excel programs. Visual Basic Application scripts were written in these programs to extract required data and speed up the processing of these data. The processed data were then used to calibrate the models, demonstrate nutrient loading characteristics, and develop load quantification methods. Results were presented in this report (and the appendices) in illustrative tables.

For the multiple linear regression (MLR) analyses conducted for nutrient loading in this study, the independent variables were selected first through the examination of potential influencing parameters such as soil erosion, fertilizer application rate, and plant nutrient uptake. Then the Pearson's correlation coefficient (r) table was calculated (in Excel) for all potential independent variables. Variables with a high r value (close to 1) were selected first for the MLR analysis. In the MLR analysis, first, the resulting correlation coefficient ($R^2$) was examined. Any MLR analysis with an $R^2$ value smaller than 0.5 was rejected. Second, the t-statistic of each of the independent variable was examined. If the p value for the t-statistic of an independent variable was greater than 0.05, that independent variable was also removed from the equation. Another variable was then selected based on its r value and underlying connection with nutrient loading. This variable was added to the equation and the regression analysis was repeated until the $R^2$ value was greater than 0.5 and p values for the t-statistics of all independent variables were all smaller than 0.05.

To establish the margin of safety of a MLR derived nutrient loading quantification method, the regression standard errors of the MLR equations were used to include 95 percent of all SWAT simulated value. Assuming that nitrate loading from a field eventually reverts to a long-term average, the ratio of 2 times standard error over the long term average would include approximately 95 percent of all simulated values under various climatic and soil nutrient conditions. This ratio was used as the basis for the margin of safety. For example, if the ratio was at 60 percent, we would consider a margin of safety of 100 percent. When this margin of safety was applied in a WQT setting, a trading ratio of 2:1 would be recommended for the edge-of-field credit.

For the application of EPA Region 5/STEPL model for particulate nutrient loading calculation, the margin of safety was developed in a similar fashion. Instead of a linear regression, descriptive statistics for comparing the Region 5/STEPL model and SWAT output were calculated to evaluate adopting the Region 5/STEPL model in this study. As a result, the standard deviation of the differences between Region 5/STEPL model results and SWAT simulated loading values were used. In a normal distribution, approximately 95 percent of observations fall within ± 2 times standard deviation. Therefore, the following calculation: *(Average Difference ± 2 × Standard Deviation of Differences) / SWAT Average* would give the percent of time that 95 percent of the long term average estimated by the Region 5/STEPL model would fall within 2 standard deviations of the SWAT estimated long term average load. Further, because load under-estimation could presumably provide a conservative estimate of load reduction in a WQCT setting, a margin of safety would be required to cover only the higher end of the distribution. Consequently, only the results of + 2 times the Standard Deviation of Differences were included in the margin of safety consideration.

## FINDINGS

### Primary Findings

The project team developed four credit estimation methods for edge-of-field P and N nonpoint source loading for WQT crediting purposes (*See Appendix 2: Technical Reports: #1. Soil and Water Assessment Tool Application for Developing a Credit Estimation Method for Precision Agriculture; and #2.Water Quality Credit Trading: Credit Estimation Method Development*). In addition, we considered the viability of crediting section boom control, a precision agriculture VRT method to reduce overlaps and skips during fertilizer applications (*See Appendix 2: Technical Reports: #3. VRT with Auto-steer Systems and Section Boom Control*.) Section boom control VRT approaches can also use these credit estimation methods as appropriate. The four equations, recommended eligibility policies and associated margins of safety recommended are explained by the methods below.

***Total Phosphorus and Particulate Phosphorus Credit Estimation Method***
Crediting of total phosphorus when implementing VRT nutrient management can be completed by using the STEPL/Region 5 modeling approach for particulate phosphorus when this fraction dominates the total composition of phosphorus runoff.

Recommended VRT eligibility policies to consider:

- A site's nutrient management planning includes consideration of the historic crop yield and associated macro- and micro-nutrients needs for that yield. In addition to the nutrient assessment, consideration of the soil pH and its influence on the amount of nutrient that is available is important. These management considerations are critical to limiting the nutrient losses to the environment due nutrient deficiency from one or more nutrients creating lower yields and therefore, over applications of other nutrients.
- This credit estimation method is not recommended on fields with high soil erosion rates (e.g., greater than 6 tons/acre/year) and variability of soil phosphorus concentrations according to depth. When high concentrations of soil phosphorus are at the surface (i.e., top 2 to 10 cm) and lower concentrations occur below the surface, the credit estimation method can over predict the reduction in phosphorus edge-of-field loading. This may occur when using no-till management practices and surface application of fertilizer without incorporation.
- Applying particulate phosphorus estimation method to predict total phosphorus is an adequate approach when soluble phosphorus is a minor fraction of total phosphorus. The estimation method applies a conservative estimate for crediting TP.
- More evaluation is recommended before applying the particulate phosphorus estimation method to credit TP when the soluble fraction is sizeable. Consideration of differences in the bioavailability of particulate and soluble phosphorus forms is recommended before assuming the PP estimation method provides a conservative estimate of TP. Runoff containing a substantial fraction of soluble phosphorus, which is very bioavailable, may not realize the estimated TP reduction of bioavailable fractions.

The particulate phosphorus estimation equation is:

$$P_p = 3{,}164 \times P_{soil} \times S^{0.8}$$

Where,

$P_p$: Particulate P (lb/ac);
$P_{soil}$: soil P test results (soil total P content); and
S: sediment loss from the field (t/ac; as predicted by RUSLE or RUSLE2 soil erosion modeling).

The recommended margin of safety for the edge-of-field estimation is 75 percent.

***Particulate Nitrogen (organically bound fraction) Credit Estimation Method***

Crediting of organically bound nitrogen when implementing VRT nutrient management can be completed by using the STEPL/Region 5 modeling approach for particulate nitrogen when this fraction dominates the total composition of nitrogen in runoff.

Recommended VRT eligibility policies to consider:

- A site's nutrient management planning includes consideration of the historic crop yield and associated macro- and micro-nutrients needs for that yield. In addition to the nutrient assessment, consideration of the soil pH and its influence on the amount of nutrient that is available is important. These management considerations are critical to limiting the nutrient losses to the environment due nutrient deficiency from one or more nutrients creating lower yields and therefore, over applications of other nutrients.

The particulate nitrogen estimation equation is:

$$N_p = 3{,}164 \times N_{soil} \times S^{0.8}$$

Where,

$N_p$: Particulate N (lb/ac);
$N_{soil}$: soil P content (Total (Kjeldahl) Nitrogen - ammonium-nitrogen); and
S: sediment loss from the field (t/ac; as predicted by RUSLE or RUSLE2 soil erosion modeling).

The recommended margin of safety for the edge-of-field estimation is 175 percent.

***Nitrate Nitrogen Credit Estimation Method (With Pre-sidedress Soil Testing)***

Crediting of nitrate nitrogen for VRT nutrient management with the use of nitrogen testing just before sidedress applications requires slightly less margin of safety estimation based on pre-plant soil test results (~5 percent). This is because the method used to develop the equation for corn years is influenced heavily by the potential for nitrates to be flushed out of the system by spring storm events. However, the process applied below rounds up margins of safety to the nearest 25 percent and therefore any differences within the 25 percent range are absorbed.

Recommended VRT eligibility policies to consider:

- A site's nutrient management planning includes consideration of the historic crop yield and associated macro- and micro-nutrients needs for that yield. In addition to the nutrient assessment, consideration of the soil pH and its influence on the amount of nutrient that is available is important. These management considerations are critical to limiting the nutrient losses to the environment due nutrient deficiency from one or more nutrients creating lower yields and therefore, over applications of other nutrients.

- Nitrate credit estimation should only be applied when nitrogen applications precede corn years and spring nitrogen soil samples are collected. Spring testing is a critical component of determining the nitrate lost to the environment.

The nitrate nitrogen estimation equation is:

$$Nitrate\ load = 5.389 + 1.624\ RO_{3month} + 0.221\ N_{applied} + -0.164\ SNO_{3,SD}$$

Where:

*Nitrate load*: load of nitrate from the field (lb/ac);
$RO_{3month}$: the three month surface runoff volume from one month before the planting to two months after (inches; can be determined by averaging local long-term metrological records);
$N_{applied}$: N applied from fertilizers (lb/ac); and
$SNO_{3,SD}$: soil nitrate level two weeks before nitrogen side-dress (lb/ac).

The recommended margin of safety for the edge-of-field estimation is 100 percent.

***Nitrate Nitrogen Credit Estimation Method (Without Pre-sidedress Soil Testing)***
Crediting of nitrate nitrogen for VRT nutrient management with the use of nitrogen testing just before sidedress applications requires slightly more margin of safety estimation based on pre-plant soil test results (~5 percent). This is because the method used to develop the equation for corn years is influenced by the potential for nitrates to be flushed out of the system by spring storm events. However, the process applied below rounds up margins of safety to the nearest 25 percent and therefore any differences within the 25 percent range is absorbed.

Recommended VRT eligibility policies to consider:

- A site's nutrient management planning includes consideration of the historic crop yield and associated macro- and micro-nutrients needs for that yield. In addition to the nutrient assessment, consideration of the soil pH and its influence on the amount of nutrient that is available is important. These management considerations are critical to limiting the nutrient losses to the environment due nutrient deficiency from one or more nutrients creating lower yields and therefore, over applications of other nutrients.
- Nitrate credit estimation should only be applied when nitrogen applications precede corn years and spring nitrogen soil samples are collected. Spring testing is a critical component of determining the nitrate lost to the environment.

The nitrate nitrogen estimation equation is:

$$Nitrate\ load = 8.606 + 2.098\ RO_{3\mathrm{month}} + 0.093\ N_{applied} - 0.165\ SNO_{3,preplant}$$

Where:

*Nitrate load*: load of nitrate from the field (lb/ac);

$RO_{3month}$: the three month surface runoff volume from one month before the planting to two months after (inches; can be determined by averaging local long-term metrological records);
$N_{applied}$: N applied from fertilizers (lb/ac); and
$SNO_{3,preplant}$: soil nitrate level before planting (lb/ac).

The recommended margin of safety for the edge-of-field estimation is 100 percent.

**Supplementary Findings**

The following Supplementary findings and considerations can help WQT programs determine if these equations can be applied to a particular site:

- On-the-go VRT systems are far more complicated to assess because of the ever-changing rates, yields and soils. It is more manageable and therefore more conservative to provide a credit estimation method for zone map applications of VRT. The use of zone map application recommendations allow the credit estimation methods to be applied on a reasonable scale for input requirements such as soil erosion estimates.
- A linear sensitivity analysis assessing results over a long-term management period confirmed the effectiveness of using the 4R approach to nutrient management.
- Regional verification/adjustment of the credit estimation methods could be completed using local edge-of-field water quality monitoring results across a substantial period of record (e.g., 7 to 10 years).
- The SWAT model results confirmed the validity of the CREAMS model algorithm used by the U.S. EPA STEPL/Region 5 models but the variability in P concentrations across actual fields calls into question the use of a default soil test nutrient value for P of 1 lb per ton of soil in these models.
- For the VRT methodology, the use of a trade ratio to address the year-to-year variability that occurs appeared to be adequate. However, monthly time steps contain months that do not produce credits and therefore should not be used for contemporaneous credit generation settings.
- In a simulated test to stack nutrient and greenhouse gas credits, we found a 20 percent reduction in N application rates (30 lbs/acre) resulted in an acre loading reduction of only 0.4 lbs of TN per acre. N credit generation is bounded by two competing principles. On the one hand, a greater reduction in N application rate would have impacted yield and on the other hand, any less of an application reduction would have generated an edge-of-field loading that would be rather marginal given a trade ratio must also be applied.
- WQT programs will need an efficient credit aggregation method to accumulate substantial offsets required by most dischargers. One possibility is for fertilizer application service providers to aggregate credits on their clients' behalf.

## CONCLUSIONS AND RECOMMENDATIONS

Our initial studies show that VRT does have the potential to generate credits for WQT programs. We have completed the first steps towards developing credit estimation methods for quantifying these credits. To further develop and improve these methods, they will have to be tested using long-term farm operation records and environmental monitoring data including soil test, runoff, sediment and nutrient loading monitoring. Since the project did not have access to several decades of farm records, our long term simulation of VRT relied on applying recent VRT field operations to past climatic records. Ideally, for a true long-term simulation of soil nutrients and their loading from the field, soil nutrient levels simulated by the models could be extracted periodically and compared to desired values for crop production and environment needs. VRT fertilizer application rates would then be adjusted to achieve these values by working with experienced agronomists or crop technicians. Such an approach would be able to provide results that could enable us to truly track the effect of the VRT and thus provide a more realistic basis for load quantification tools development.

We recommend the following next steps:

- Test findings on sites with edge-of-field water quality and quantity measurements.
- Further develop the credit estimation method for nutrient management by comparing findings from this study with similar evaluations from fields with different physical settings and/or agricultural operations (for example, in the current study, only commercial fertilizer was used, and no manure applications were considered).
- Develop a life-cycle economic analysis. An economic analysis is intended to inform decision makers regarding long-term average costs and the related break point where generating credits provides a reasonable profit to compensate for the occasional and nominal yield loses incurred due to nitrogen rate reductions.
- Develop field nutrient measurement protocols for determining TP and TN concentrations in soils; and
- Solicit peer review of findings.

Other important recommendations based on this project include:

- USDA should stress the need for better data keeping by farms and consider offering incentives for sharing farm data with CIG projects (while guaranteeing farmers that this data will be kept confidential) (e.g. offer higher priority for cost-share funding if willing to share data). Having access to farm level data is a critical choke point for many projects.
- All projects using farm data should have signed confidentiality agreements with their producers.

## REFERENCES CITED


Almendinger, J. E. and J. Ulrich. 2012. Applying a SWAT model of the Sunrise River watershed, eastern Minnesota, to predict water-quality impacts from land-use changes, report pursuant to the project: "Sunrise River Watershed SWAT Modeling Phase 5," funded by the Minnesota Pollution Control Agency under contract No. B47177.

Arabi, M., J. R. Frankenberger, B. A. Engel, and J. G. Arnold. 2008. Representation of Agricultural Conservation Practices with SWAT, Hydrological Processes 22(16): 3042-3055, DOI: 10.1002/hyp.6890

Bergtold, Jason. 2007. "The Conservation Decision: Economics of Conservation and Precision Agriculture", USDA Agriculture Outlook Forum 2007, March 1, 2007.

Bongiovanni, R.and Lowenberg-Deboer, J. 2004. "Precision Agriculture and Sustainability", *Precision Agriculture,* 5(2004): 359–387.

Brown, R. M., J. Schieffer and J. Shockley. 2012. The Impact of Precision Agriculture Techniques on Kentucky Grain Farmers' Carbon Footprint. Selected paper prepared for the Southern Agricultural Economics Association Annual Meeting, Birmingham, AL February 4-7, 2012. 17 pp.

Diekmann, F. and M. T. Batte. 2010. 2010 Ohio Farming Practices Survey: Adoption and Use of Precision Farming Technology in Ohio. AEDE-RP-0129-10. August 2010. 21 pp.

Erickson, B. and D. A. Widmar. 2015. 2015 Precision Agricultural Service Dealership Survey Results. Department of Agricultural Economics and Department of Agronomy, Purdue University. 37 pp. August 2015.

Harmel, R. D., A. L. Kenimer, S. W. Searcy and H.A. Torbert. 2004. Runoff Water Quality Impact of Variable Rate Sidedress Nitrogen application. Precision Agriculture 5(3): pp. 247-261(15).

Kieser & Associates, LLC. 2005. SWAT Modeling of the St Joseph River Watershed, Michigan and Indiana. Prepared for the Friends of the St Joseph River (June 2005).

National Network on Water Quality Trading. 2015. Building a Water Quality Trading Program: Options and Considerations. Version 1.0. June 2015: Point-Nonpoint Trades. 224 pp. Available at: http://www.wri.org/nn-wqt

Pierce, F. J. and P. Nowak. 2008 "Precision agriculture," in AccessScience, ©McGraw-Hill Companies, 2008, http://www.accessscience.com

Schepers, J. S. 2008. Landbauforschung- vT1 Agriculture and Forestry Research 3 2008(58):153.160.

Schimmelpfennig, D. and R. Ebel. 2011. On the Doorstep of the Information Age:EIB-80, U.S. Department of Research, Economic Research Service. August 2011. 31 pp.

Sorensen, A. 2011. Barriers and Solutions for Farmer Participation in the Ohio River Basin Water Quality Trading Program. Technical Update 1023642. EPRI, Palo Alto, CA. September 2011. 32 pp.

USDA NRCS. 2007. Precision Agriculture: NRCS Support for Emerging Technologies. Agronomy Technical Note No. 1. East National Technology Support Center, Soil Quality National Technology Development Team. June 2007. 11 pp.

Waidler, D., M. White, E. Steglich, S. Wang, J. Williams, C. A. Jones, and R. Srinivasan. 2009. Conservation Practice Modeling Guide for SWAT & APEX, Texas A&M University. Available at http://oaktrust.library.tamu.edu/handle/1969.1/94928?show=full; last accessed on October 9, 2015.

## APPENDICES

### APPENDIX 1: Project Materials

1. The Project Team

2. SWAT Application for Developing a Credit Estimation Method for Precision Agriculture

3. Draft Farm Data Release Form

4. AFT CIG: Developing a Water Quality Credit Trading Credit Estimation Method for Precision Agriculture: Draft Project Flow Path for Discussion

5. AFT Presentation for May 21, 2015 team meeting: Water Quality Trading Credit Method Development for Variable Rate Technology.

### APPENDIX 2: Technical Reports

1. Soil and Water Assessment Tool Application for Developing a Credit Estimation Method for Precision Agriculture

2. Water Quality Credit Trading: Credit Estimation Method Development

4. VRT with Auto-steer Systems and Section Boom Control

4. Final Draft Report: May 2015. Viability and Potential for Stacking Greenhouse Gas (GHG) and Water Quality Credit Trading (WQCT) Credits

# APPENDIX 1

## Item #1.  PROJECT TEAM MEMBERS

**The Project Team**

The project design team included representatives from American Farmland Trust, Kieser and Associates, the Ohio Farm Bureau Federation, the Kentucky Division of Conservation, the Indiana State Department of Agriculture, Ohio Department of Natural Resources, John Deere, Trimble, University of Kentucky, Purdue University and The Ohio State University. We also had help and advice from two NRCS technical contacts.

*Ann Sorensen, Research Director, American Farmland Trust: Project Leader*: Sorensen had headed up AFT's research program since 1992 and had completed over 180 projects addressing AFT priorities. Prior to that, she worked 7 years for the American Farm Bureau Federation covering environmental issues, 2 years as an IPM specialist at the Texas Department of Agriculture and 9 years doing academic research on integrated pest management and social insect behavior at the University of Georgia and Texas A & M University. Her education included a B.A. in Science from University of California at Santa Cruz and a Ph.D. in Entomology from the University of California at Berkeley. She had over 70 refereed research publications and was serving on EPA's Farm, Ranch and Rural Communities Federal Advisory Committee.

*Steve Coleman, Director, Kentucky Division of Conservation: Project Co-Lead:* Steve Coleman agreed to serve as the project co-leader for this proposed effort. He started working at the Division of Conservation as a soil scientist in 1975 and became head of its soil survey program in 1979 and its director in 1994. Coleman coordinated Kentucky's Nonpoint Source Pollution program and had been Chairman of the Kentucky Agriculture Water Quality Authority since 1994. He had a B.S. in Forestry from the University of Kentucky.

*Mark Kieser, Senior Scientist, Kieser & Associates: Crediting Protocol Development and Refinement*: Kieser had over 26 years of environmental consulting experience in addition to three years of academic research on water resource issues. Mr. Kieser had also played a prominent role in water quality trading program and policy development since 1995. Kieser was involved in trading efforts being conducted in 14 states. Since 2001, Mr. Kieser had been serving as the Acting Chair of the Environmental Trading Network. The Network is a non-profit clearinghouse for water quality trading program information. His education included a B.S. in Biological Sciences from Wittenberg University and M.S. in Biological Sciences from Michigan Technological University.

*Jim Klang, Senior Project Engineer, Kieser & Associates, Crediting Protocol Development and Refinement:* Klang had over 20 years experience in water quality and watershed management. Prior to joining K&A, Mr. Klang was the lead Engineer at the MN Pollution Control Agency (MPCA) TMDL program. He was the technical lead for the MN River Summer Low Flow DO TMDL and co-authored the Low Dissolved Oxygen TMDL Protocol at the MPCA. He also had extensive experience in water quality trading through involvement in the Rahr Malting Company and Southern MN Sugar Beet Cooperative NPDES permit, and the MN River Basin General Phosphorus Watershed

Permit. His education included a B.S. in Civil Engineering from Colorado State University.

_Jimmy Daukas, V.P. for Programs, American Farmland Trust: Farmer Outreach and Engagement_: Daukas had been with AFT since 1997 managing national policy campaigns as well as senior project management, communications and development responsibilities. He was leading AFT's efforts to engage agriculture in developing new policy solutions, creating ecosystem service markets and conducting on-farm demonstrations to maximize the participation of farmers and ranchers in reducing greenhouse gases and expanding the adoption of conservation practices that improve water quality. Before joining AFT, he was the director of marketing and acting vice president of marketing and communications for Earth Force. His education included a B.A. in Economics from Middlebury College and an M.B.A. and M.P.M. (Public Management) from the University of Maryland.

_Larry Antosch, Senior Director, Program Innovation and Environmental Policy, Ohio Farm Bureau Federation: Farmer Outreach and Engagement:_ Before joining Ohio Farm Bureau in 1999, Antosch was an environmental specialist for the Ohio Environmental Protection Agency for 13 years. At Ohio Farm Bureau, Larry specialized in water quality and quantity issues, most recently focusing on problems with phosphorus run-off from agriculture. His education included a B.S. in environmental sciences from the University of Wisconsin-Green Bay, a M.S. in environmental sciences at the University of Texas at Dallas and a Ph.D. in water resources at Iowa State University.

_Jerod Chew, Director, Indiana State Department of Agriculture, Division of Soil: Conservation_: Chew had directed the Indiana State Department of Agriculture's Division of Soil Conservation since 2008. He had more than 10 years of experience in working in conservation. Chew was overseeing the Department's environmental stewardship initiatives and conservation programs, including direct on-farm technical and financial assistance for conservation practices implementation, supporting Indiana's 92 Soil and Water Conservation Districts and conservation promotion. Chew had a B.S. degree in Life Sciences from Indiana State University.

_John Kessler, P.E., Deputy Chief, Ohio Department of Natural Resources, Division of Soil & Water Resources_: Kessler had held positions with the Ohio EPA and Ohio DNR over the last 19 years in the water quality protection and conservation program areas and within regulatory and voluntary programs. He held B.S. and M.S. degrees in engineering.

_Chris van der Loo, Market Manager, Water Management Segment of Trimble Agriculture:_ Van der Loo's role at Trimble focused on providing high-performance solutions for diverse global agriculture markets dealing with irrigation and drainage challenges. Mr. van der Loo was a qualified land surveyor and had worked for 11 years at Trimble's land surveying and agriculture divisions. He had extensive experience in applying GNSS and optical technologies to improve productivity and profitability for many industries across the globe in both emerging and high end markets.

*Pauley Bradley, Nutrient Application Product Manager, John Deere Company*: Bradley was a Crop Systems Specialist with John Deere Company. His responsibilities included delivering training to John Deere dealership employees and Deere customers, maintaining a relationship with University research and extension personnel, and partnering with other agricultural entities to better serve Deere's customer base.

*Mike Baise, Midwest Director, American Farmland Trust:* Baise had joined AFT in 2012 as the Midwest Region Director. He had worked for 12 years in program and management positions at the Illinois Department of Agriculture and 15 years at the Indiana Farm Bureau as an advocate for agricultural and natural resource issues. He held a master's degree in agricultural economics from the University of Illinois and a master's in public affairs from Indiana University.

*Brian Brandt, Director, Agricultural Conservation Innovations Center, American Farmland Trust:* Since joining AFT in 1999, Brandt had played an integral role in the effort to develop innovative risk management tools that help farmers increase adoption of Best Management Practices. He spearheaded development of the Nutrient BMP Insurance policy and proposal, both of which were approved by USDA's Risk Management Agency. Working with partners in Minnesota, he was leading efforts to develop the Conservation Marketplace, the first multiple credit ecosystem services market in the nation. He also played a key role in the Ohio River Basin Water Quality Credit Trading project by organizing participation of agriculture stakeholders and producers in the program.

*Tom Mueller, University of Kentucky, Plant and Soil Sciences:* Tom Mueller taught and did research in the areas of precision conservation, Google Earth and Google Maps for land use assessment, soil sensors, map quality and carbon mapping at the University of Kentucky. He had also studied the value of soil electrical conductivity and topographical information for VRT and erosion indices derived from terrain attributes. His education included BS and MS from Purdue University and PhD from Michigan State University.

*Bruce Erickson, Ph.D., Agronomic Education Manager, American Society of Agronomy, Department of Agronomy, Purdue University*: Erickson was using his experience in education and agribusiness to provide solutions for crop producers, their advisers, and the industries that depend on them. His areas of expertise included corn and soybean production, remote sensing and its application in precision agricultural practices, instructional design, and competency-based education and assessment. Erickson had started as an agronomist with Pioneer Hi-Bred in Iowa and was an adjunct assistant professor at Purdue University and Agronomic Education Manager for the American Society of Agronomy. He had a B.S. degree in agronomy from Iowa State University, a master's degree in crop production and physiology from Iowa State University and a Ph.D. in agronomy from Purdue University

*Scott Shearer,Ph.D., Chair, Food, Agricultural and Biological Engineering, College of Engineering, The Ohio State University*: Shearer had had a research/teaching appointment at the University of Kentucky since 1986 and left that role in July 2011 to become Chair of Food, Agricultural and Biological Engineering at Ohio State University. He specialized in the development and analysis of control systems for agricultural field machinery, with an emphasis in sensor development, fluid power circuit design and product testing and evaluation. He had over 60 refereed journal publications and two patents and held a PhD in Agricultural Engineering from The Ohio State University.

We also had help and advice from two NRCS technical contacts: David Buland and Lyn Kirschner.

**Team Changes During the Project Period**

The make-up of the team changed during the project.

- K&A brought in their project engineer, Andrew Feng Feng, to help with model calibration.
- Four members either changed jobs or retired: Chad Amos replaced John Kessler. Kim Richardson replaced Steve Coleman. Tara Wessler-Henry replaced Jerrod Chew. T. J. Schulte replaced Chris van der Loo for Trimble.
- One member shifted jobs but stayed on the committee: Tom Mueller left University of Kentucky and joined John Deere.
- Two members left the committee: Scott Shearer and Bruce Erickson shifted jobs and left the committee.

Although we had originally envisioned several in-person meetings for the committee and regular conference calls, we ended up holding one in-person meeting at the start of the project and then convened calls at critical decision points.

# APPENDIX 1

## Item #2. SWAT APPLICATION FOR DEVELOPING A CREDIT ESTIMATION METHOD FOR PRECISION AG

**To:** Ann Sorensen, AFT

**Date:** August 16, 2013

**From:** Jim Klang
Joanna Allerhand
Kieser & Associates, LLC

**cc:** Project files

**RE:** **SWAT Application for Developing a Credit Estimation Method for Precision Agriculture**

This memorandum describes the proposed approach for developing a relatively simple nutrient credit estimation tool for water quality credit trading (WQCT) credits associated with precision agriculture technologies. In order to appropriately represent the complexity of nutrient cycles, the project team selected the Soil and Water Assessment Tool (SWAT) model to inform the development of a credit estimation tool. This model was considered the most applicable existing tool for quantifying nutrient load reductions achieved through implementation of precision agriculture. However, because SWAT was not designed for this purpose, the model is limited in its ability to represent certain scenarios of interest. Despite these limitations, SWAT is considered one of the best watershed models for incorporating agronomy considerations.

SWAT provides an agronomically based nutrient budget combined with a sophisticated simulation of hydrological transport processes. The model often is used to predict sediment, nutrient, and agricultural chemical loading to surface waters and can account for substantial heterogeneity within the watershed of interest.[1] For example, it can incorporate variable soils and land conditions. To accomplish this, SWAT relies on location-specific input data (i.e., weather, vegetation, topography) to model physical processes.

In order for precision agriculture technology to be eligible for credit generation, there must be a demonstrated and repeatable method for calculating nutrient reductions. SWAT was selected based on its ability to estimate nonpoint source runoff to surface waters and its widespread acceptance among watershed practitioners as a leading model for agricultural applications. However, SWAT was designed to be a watershed model, not an agronomy model. As such, the tool has limited capabilities for simulating the agronomy attributes of a crop. These limitations somewhat restrict the specific

[1] Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams (2011) Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute Technical Report No. 406. Available online at: http://twri.tamu.edu/reports/2011/tr406.pdf

technologies that can be included in the assessment. For instance, SWAT does not generate estimates based on variations in seeds planted. However, the model is considered the best watershed model for assessing precision agriculture given its inclusive approach for balancing both water quality estimations and agronomy considerations.

The project is focused on assessing the following technologies for credit generation: variable rate technology (VRT) nutrient applicators and global position system (GPS) guidance systems. Both VRT and GPS guidance system practices provide a range of control resolution. VRT systems that are map-based generate a coarser resolution than sensor-based options. Likewise, GPS guidance systems that control specific tractor implements provide a finer resolution than options controlling the overall tractor system. Data associated with VRT practices are being requested and evaluated to assess how this technology might align with project goals.

For GPS guidance systems, crediting will be determined by comparing nutrient releases when fertilizer overlap is minimized. Examples of GPS guidance systems include mechanisms to prevent overlap of fertilizer applications, such as section boom controls. These controls operate by turning off a portion of the spray nozzles across the boom for the section of boom above crops that have already received fertilizer or land planted into grass, such as a waterway or field border. Preventing spray overlap reduces nutrient applications and potentially reduces runoff. This practice also saves the producer money by reducing inputs. A producer might desire to implement a guidance system for multiple field operations (e.g., pesticide application, seed application). When this is the case, WQCT credits potentially can be more cost-effective.

GPS yield monitors provide information on the variability of yield data within the field. This variability is necessary for estimating plant nutrient uptake. To benefit from the agronomy attributes represented in SWAT, producers who provide data for model calibration must have GPS combine yield monitor records for previous years. This data, combined with nutrient application information, can be used to establish a nutrient mass balance at a finer resolution than a whole-field average. The nutrient mass balance for a given field must include information regarding the inputs and crop use in order to determine the nutrient losses to surface waters.

The SWAT model will be used to assess the quantity of nutrients released to water resources associated with the specific precision agriculture technologies. This estimate will be generated by calculating a nutrient mass balance over the year of interest. Table 1 lists the mass balance elements and indicates whether each element is a model input or output.

Table 1. Mass balance elements associated with SWAT.

| Mass Balance Element | SWAT Input / Output |
|---|---|
| **Soil storage at the start of the season** | Data input |
| **Previous year's residue** | Estimated by SWAT |
| **Nutrient applications** | Data input |
| Commercial fertilizer | Data input |
| Manure | Data input |
| **Atmospheric deposition** | Estimated by SWAT |
| **Legumes fixation** | Estimated by SWAT |
| **Harvested materials** | Estimated by SWAT |
| **Leaching to groundwater** | Estimated by SWAT |
| **Shallow aquifer recharge of streams** | Estimated by SWAT |
| **Surface runoff** | Estimated by SWAT |
| **Atmospheric emissions (nitrogen)** | Estimated by SWAT * |
| **Soil storage at the end of the season** | Estimated by SWAT |
| *** Note: Nitrate is given a half life estimate for bacterial uptake, chemical changes due to redox reactions and other processes** | |

The following figures illustrate how SWAT represents the nutrient mass balance approach with in the field. Figure 1 illustrates the nitrogen mass balance and Figure 2 illustrates the phosphorus mass balance. The model tracks nitrogen and phosphorus separately given differences in mobility between the two nutrients. Nitrogen is more easily able to change valance states and therefore tends to be more mobile. Nitrogen also is affected by whether soil conditions are anaerobic or aerobic. In anaerobic conditions, nitrogen undergoes denitrification, whereby oxygen molecules are stripped from oxidized forms of nitrogen and the resulting gaseous nitrogen is released to the atmosphere. Under aerobic conditions, nitrification occurs and ammonium ($NH_4^+$) is oxidized to nitrite ($NO_2^-$) and nitrate ($NO_3^-$). Saturated soils can become anaerobic, which alters the nitrogen conversion process and the rates at which nitrogen is volatilized or denitrified.

Figure 1 depicts the nitrogen mass balance and the different forms of nitrogen created or lost as the nitrogen cycle is driven by chemical and biological processes within the soil. Precipitation rates and timing are important external controls that impact the potential for water to leech and alter oxygen availability within the soil. The groundwater depth also will affect the oxygen availability, which influences what form of nitrogen will exist in the soil. The complicated processes associated with the nitrogen cycle are tracked by SWAT. However, not all WQCT field representatives will be able to apply SWAT. This project intends to analyze the SWAT model across multiple conditions to develop an estimation tool that emulates the SWAT results for nitrogen release but is easier to use than the full SWAT model.

Figure 2 illustrates the phosphorus mass balance and the various forms of phosphorus associated with the phosphorus cycle.  At the far left of the figure, the circles represent phosphorus cycling between soluble and particulate forms.  Particulate-bound forms are the fractions that adhere to soils and are used by soil and crop biological processes.  As soil phosphorus concentrations increase, the capacity of the soil to hold phosphorus in a stable form begins to be exceeded and soluble concentrations increase.

Based on the considerations discussed, it is important for the team to recognize the types of precision Ag technologies being assessed by SWAT and therefore used to development a WQCT crediting estimation tool.  This discussion will have important implications regarding project expectations.  While multiple types of precision Ag technologies exist, only a few techniques are being evaluated for this project, based on available data and the ability of SWAT to model the practice.  During the second half of the project, participating farmers evaluating the credit estimation tool will only be able to apply the tool if their operation aligns with the methods applied at the study farm.  An additional consideration is the tool applicability in different geographical settings.  While the development approach can work across multiple states, the credit equation results are expected to vary by region.  The accuracy of the results would be strongly influenced by site characteristics, such as soil characteristics and weather conditions.  As such, the range of locations where the tool is applicable for crediting can be expected to be limited in the early development stages.

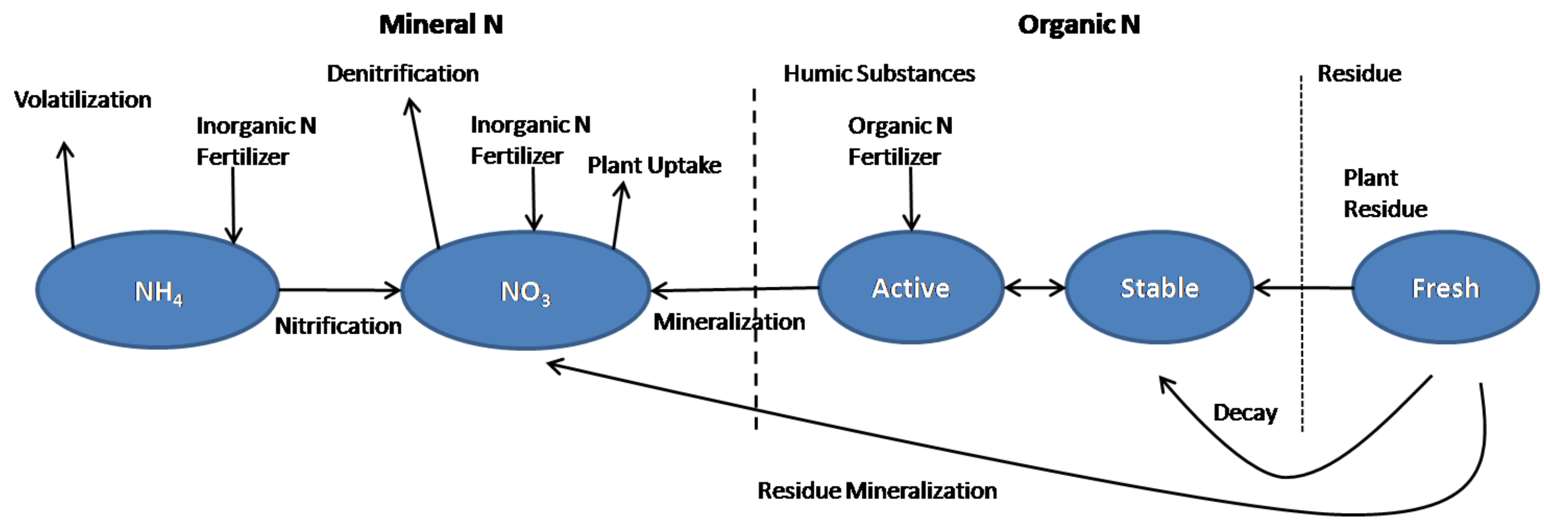



**Figure 1. SWAT nitrogen mass balance approach (Neitsch, 2009)**

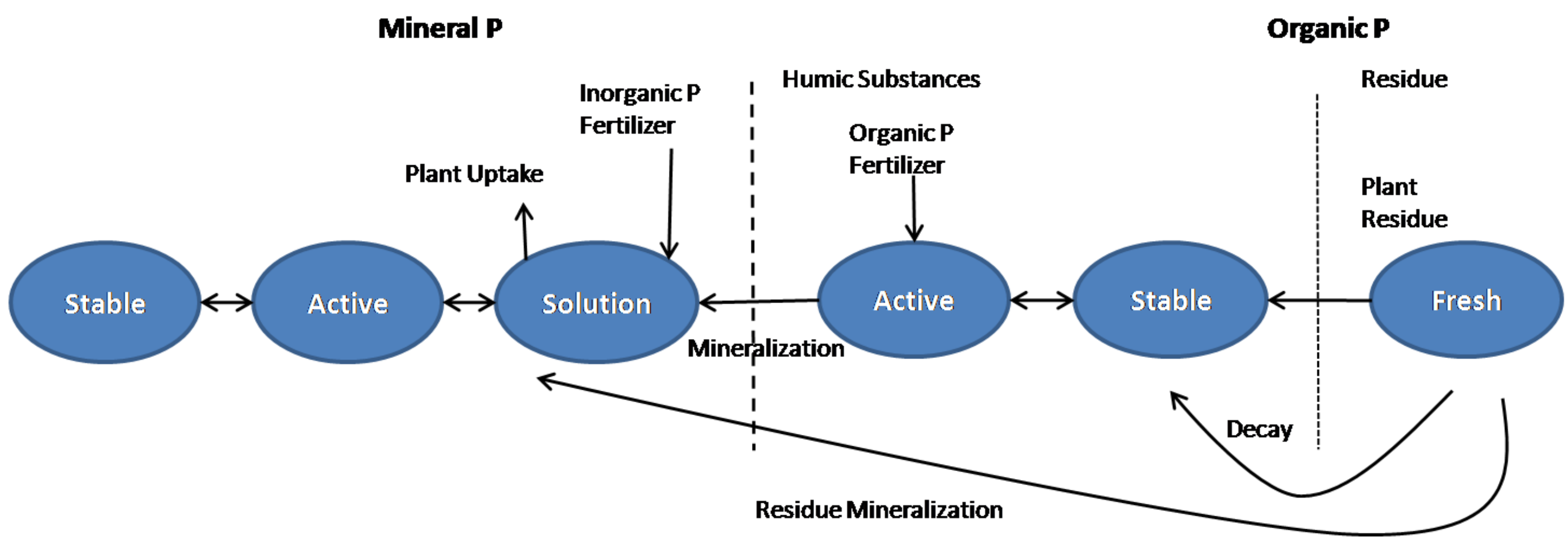



**Figure 2. SWAT phosphorus mass balance approach (Neitsch, 2009)**

# APPENDIX 1

## Item #3. DRAFT FARM DATA RELEASE FORM

DRAFT: April 4, 2013 - Farm Data Release Form - American Farmland Trust

This farm agrees to participate in a USDA NRCS Conservation Innovation Grant led by American Farmland Trust to develop, test and refine the first-ever credit estimators for crediting precision agriculture variable rate technologies (VRT) and GPS guidance systems in Water Quality Credit Trading programs. The project will use data from farms to compare crop uptake budgets with the amount of nutrients (P and N) applied and use modeling at the farm-field level and sites with edge-of-field monitors to account for the fate of excess nutrients. The resulting quantification protocols will be tested and refined with farmers over two growing seasons.

<u>How the data will be used</u>: Data collected on farms will be used to calibrate the model, estimate nutrient releases to adjacent water bodies and develop crediting protocols.

<u>Storage of data</u>: Data will be stored inn digital and hard copy formats by Kieser & Associates in Kalamazoo, Michigan, the technical lead on the project. When the project ends, hard copy materials will be shredded and digital copies erased.

<u>Project reports</u>: The project will provide model best-fit summaries, output results and a final report summarizing the nutrient related finding correlated to field practices, nutrient application rates and yields to USDA NRCS. The names of collaborating farmers will be shared with USDA NRCS (as required by Conservation Innovation Grants) but we will not share their operation-specific information. This information will not be released to the public.

<u>How farm and operational data will be shared with the public</u>:

- We will not use or release personal information including name, name of farm, address, phone number and field location (latitude and longitude).
- Reports will include summary formats regarding location including spatial descriptions limited to county and state and watershed information limited to 8-digit HUC size. Aerial field photos will not be provided if a field's irregular shape can be used to identify the location. The use of a photo will require the owner/operator's explicit written permission.
- Operation-specific information will be discussed to the extent relevant to the project objectives and outcomes including yield, nutrient application rates, nutrient application methods, precision agriculture equipment description tillage operations and estimated nutrient releases with and without precision agriculture.

I agree to share data from my farm operation with the understanding that personal identification and farm operation information will be kept confidential as outlined above.

Name of owner/operator: ________________________________
Date: ___________________
Name of AFT Staff: __________________________________________
Date: ___________________

## APPENDIX 1

## Item #4. AFT CIG: DEVELOPING A WATER QUALITY CREDIT TRADING CREDIT ESTIMATION METHOD FOR PRECISION AGRICULTURE: DRAFT PROJECT FLOW PATH FOR DISCUSSION

# American Farmland Trust
# Conservation Innovation Grant

## Developing a Water Quality Credit Trading Credit Estimation Method for Precision Agriculture

## Draft Project Flow Path for Discussion

This project has the potential to provide access to water quality credit trading (WQCT) funding to agricultural producers interested in using precision agriculture tools for nutrient applications. This funding could assist producers by making available both the equipment and knowledge necessary for transitioning to nutrient applications using variable rate technology (VRT). However, in order to determine if this technology is eligible for WQCT requires demonstrating the ability to estimate the resulting real and consistent nutrient reductions. The project flow path will include the following:

Development Team tasks include:

1. Field-scale model selection
2. Data gathering from precision agriculture and traditional production field-scale studies
3. Model setup and calibration
4. Model sensitivity analysis
5. Model scenario development
6. Development of the credit estimation tool based on the assessment results
7. Generation of a report describing identified information gaps, methods to address introduced uncertainty, and future initiatives that would improve the methodologies

Working with EQIP-eligible producers and their technical service providers, the Team would:

8. Set up demonstration events and producer implementation sites to further test and vet the credit estimation method for functionality, ease of use, and perceptions regarding accuracy of results
9. Gather feedback from producers and technical service providers for reporting and evaluation assessments to be used for project dissemination and adjusting the credit estimation tools

These nine steps over-simplify the scope of work involved for the purposes of providing a brief overview. A more detailed discussion is presented using an illustrated project flow path and accompanying narrative. Two attachments to this memo provide additional information, including background on WQCT credits (Attachment A – U.S. EPA trading policy) and descriptions of potential data requests (Attachment B).

Step 1. Gather information regarding appropriate field-scale models and select the project model

- Models must be able to estimate water quantity and quality attributes
- Models must respond to differences in agricultural operations and agronomic factors

Step 2. Based on required model inputs, gather input parameter information using the following hierarchy:

- Use field study monitoring results
- Use typical regional values and appropriate peer reviewed literature
- Use professional judgment supplied and vetted by the collaborator team

Step 3a. Conduct model setup, calibration, and validation for an initial site

- Begin field modeling on the best candidate field
- Complete the model setup and calibration
- Report to the collaboration team regarding the model performance, identified gaps, and resulting limitations
- Evaluate the resource needs associated with setting up and calibrating a field model

Step 4. Complete a model sensitivity analysis to determine the input parameters that generate the largest model response

Step 3b. Select the remaining field studies for model setup, calibration, and validation

- Select additional fields based on their ability to represent a broad range of site characteristics; considerations include:
  - Emphasis on input parameters highlighted in the sensitivity analysis
  - Availability of site data
  - Soil classification
  - Nutrient rates
  - Latitude
  - Crop rotation/yield
- Setup and calibrate the selected field models

Step 5. Beginning with the first field study model, create reduction scenarios based on varying input parameters to determine a range of results driven by slight alterations to site characteristics

- Record differences in results during wet, moderate, and dry years for each scenario
- Structure the scenario in order to alter controllable attributes, such as application timing and rate
- Use nutrient reduction results to evaluate whether too much variability exists for WQCT to be cost effective
- Use results to inform the team regarding practice standard development considerations

Step 6. Evaluate modeling equations and scenario results to determine a practical method for providing a field estimate of nutrient reductions

- Draft a VRT practice standard for WQCT
- Develop regression equations for each controllable attribute using scenario results
- Consider different methods for combining attribute results
- Recommend a credit estimation method
- Test application of results against validation dataset from scenario runs
- Vet the method with the collaborator team

Step 7. Report to team the following:

- Identified information gaps that could improve the process
- Recommended methods for improving the process
- Draft practice standard
- Draft credit estimation tools

Step 8. Identify EQIP eligible producers and develop:

- Demonstration sites
- WQCT VRT practice standard training materials

Step 9. Work with EQIP eligible producers and technical service providers to demonstrate and vet the WQCT tools

- Determine functionality
    - Determine potential producer acceptance of practice standard
    - Determine field availability of credit estimation inputs
- Determine ease of use
    - Consider time involved for implementation and crediting
    - Evaluate requirements/reluctance regarding collecting more information needed for crediting
- Gather user perceptions regarding:
    - Accuracy of predictions
    - Potential participation in WQCT programs
    - General concerns
- Return to steps 5, 6, and 7 to implement needed revisions as grant resources allow

## Background

The objective of the American Farmland Trust lead Conservation Innovation Grant (AFT-CIG) project is to develop a Water Quality Credit Trading (WQCT) credit estimation method for precision agriculture practices. WQCT programs need repeatable and science-based credit estimation methodologies to assess the reduction of nutrient loads associated with conservation practices. These methods also must provide reasonable and practical levels of precision and efficacy. For this reason, WQCT generally has been limited to traditional conservation practices that have standardized procedures established by USDA-NRCS. In addition, the typical WQCT practices have quantification protocols for estimating edge-of-field losses of sediments and nutrients to determine trading credits that are accepted by regulatory agencies.

Precision Agriculture is characterized as a Best Management Practice (BMP) that provides many beneficial attributes, ranging from cost savings to environmental protection. The United States Global Positioning website (GPS.gov[1]) states:

> "GPS-based applications in precision farming are being used for farm planning, field mapping, soil sampling, tractor guidance, crop scouting, variable rate applications, and yield mapping. Today, more precise application of pesticides, herbicides, and fertilizers, and better control of the dispersion of those chemicals are possible through precision agriculture, thus reducing expenses, producing a higher yield, and creating a more environmentally friendly farm."

[1] GPS.gov. Offical U.S. Government information about Global Positioning System (GPS) and related topics website. Accessed October 30, 2012 at: http://www.gps.gov/applications/agriculture/

While the environmental benefits alluded to in this quote seem intuitive to some, quantification of the environmental benefits of variable rate technology (VRT) is a difficult task. Studies to quantify nutrient loading reductions to surface waters from VRT have produced mixed results[2]. It has proven difficult to find monitoring studies that fully support the claim that a nutrient nonpoint source load reduction consistently occurs from implementation of precision agriculture-based nutrient applications.

## Who Participates in Trading?

WQCT is a permit process that provides a wastewater treatment plant (WWTP) an affordable alternative compliance option when a new restrictive nitrogen or phosphorus effluent limit is required. WQCT guidance establishes that standard methods must be used to estimate credit values from agricultural nonpoint source pollutant reductions. These credits then can be purchased by the WWTP in lieu of expensive facility upgrades. *[While nutrients are vital to the agricultural industry and promote healthy fisheries in moderate quantities; too much nutrient loading causes eutrophication in waterbodies. Hence the term "pollutant" is sometimes applied to nutrient loads.]*

This flexible compliance program for the WWTP can benefit farmers by providing a funding mechanism for Best Management Practices sought by the farmer. Other benefits can include flexibility in funding contracts regarding the number of acres or length of time specified for BMP implementation. For instance the whole farm can be under contract for high residue use instead of a cap of a few hundred acres, which is commonly the case for EQIP program funding.

It is important to clarify that WQCT is a voluntary process. The choice to participate in trading is voluntary for both the buyer (WWTP) and seller. Either entity can choose not to participate. When an entity does choose to participate, a legally binding agreement is developed between the buyer and seller of the credits. This agreement involves similar stipulations to those found in an agreement for a cost share program. As such, the producer liability stems from the contract itself, not the NPDES permit enforcement liability. The WWTP buyer cannot pass on the permit enforcement liability to third parties. When engaging in trades, the WWTP representatives must ensure that trading can attain their NPDES permit compliance goals. As such, the WWTP buyers can structure the agreements in order to reduce the potential for the credit generation contract to become deficient. Example contract provisions to reduce risk include:

- Providing annual payment schedules instead of full payments up front
- Granting rights of access to inspect the Best Management Practice(s) during construction and establishment, as well as proper operation and maintenance
- Including punitive damage clauses if the contract deficiency is the result of improper operation or lack of maintenance

[2] Harmel, R. D., A. L. Kenimer, S. W. Searcy and H.A. Torbert. 2004. Runoff Water Quality Impact of Variable Rate Sidedress Nitrogen application. Precision Agriculture 5(3): pp. 247-261(15).

## Why the Interest in Precision Agriculture for WQCT?

VRT has been raised in a positive light at several farmer focus groups and is viewed as a BMP that could benefit the producers who have implemented many conservation practices. In the context of trading, the presence of several existing practices can put producers at a relative disadvantage. WQCT has many framework provisions to provide assurances that offsite reductions create real and equivalent nutrient loading reductions when compared to upgrading the WWTP. These include baseline requirements that ensure the agricultural BMPs generating reductions are not already required by rule or ordinance and/or already in place. If either of these pre-existing conditions are present, then implementing the BMPs would provide no additional load reduction and the WWTP discharge to the water resource would not be recognized as a legitimate offset. This requirement is often referred to as implementing "additional" BMPs for credit generation or using "additionality" requirements.

Additionality also imposes some cost restrictions on the agricultural producer. When considering nonpoint source nutrient loading, it is generally true that producers who have already adopted many BMPs that reduce nutrients can expect less nutrient reductions from subsequent BMPs. This could place producers that are further along in implementing their conservation plans at a disadvantage compared to producers who have not implemented a substantial number of BMPs. In addition, early conservation practice adopters might not desire the remaining BMPs on the list of options. Producers consider other operation goals such as yield, production acreage, and the time and equipment necessary to add an additional BMP.

## Application of Water Quality Credit Trading Principles to VRT

WQCT uses certain attributes of a commodity market to allow cost-effective offsets to be used for compliance instead of paying for a costly upgrade for WWTP. However, a trading program deviates from a "free market" in several ways. The most notable is the level of regulatory control overseeing the NPDES permit process. A second difference is the current limited level of buyer demand. This might change in the future when states fully develop nutrient criteria for rivers and streams. In addition, efforts to solve estuary issues like the Chesapeake Bay and Gulf of Mexico hypoxia problems also could generate credit demand. However, historically, WQCT has been successfully applied to assist water quality attainment issues in smaller watersheds.

The Clean Water Act (CWA) granted the authority for US EPA to create and run the National Pollutant Discharge Elimination System (NPDES) permit program. A portion of Part 40 in the Code of Federal Regulations (40 CFR) provides more detail regarding operations of the NPDES permit process (e.g., 40 CFR 122, 123, 124, and 130). WQCT does not specifically appear in either the CWA or 40 CFR. Instead, the US EPA developed a WQT policy in 2003, which is included as Attachment A. The fundamental message is that trading must be:

- Real: represent actual reductions based on monitoring or estimates that are based on accepted science and use standard methods

- Equivalent:  differences in source loading from among trading entities are accounted for to provide reductions that are  equal to or greater than reductions that would occur under conventional measures
- Enforceable:  regulatory provisions in the NPDES permit outline the expectations the WWTP is required to meet (i.e., credit reduction amount across a given period, monitoring and reporting requirements.  As previously stated, NPDES permit liability cannot be passed on to the agricultural producer.)
- Cost effective:  as a voluntary program, trading would not be considered viable when it does not provide a substantial cost savings

Trading programs also must meet other EPA policy provisions, including regulations designed to protect any progress made toward achieving water quality objectives and protecting the environment.  Based on these provisions, trade transactions should be conducted in a manner that complies with the following:

- Prevention of “local hot” spots (not causing or contributing to water quality violations)
- Prevention of treatment facility backsliding (once a level of treatment is attained, the plant must always operate at or better than that level)
- Nondegradation (Treatment applications are required where the receiving water is below narrative or numeric criteria and additional treatment is required to keep the water at this level)

### *Real*

Simply stated the credit estimation method must use science-based and standardized methods to provide assurances that the stated reduction actually occurs.  The method must estimate credited reductions in a way that is conservative, accurate, and addresses any introduced uncertainty surrounding the calculation method.

For this project, the tasks include gathering field data, developing a credit estimation method, and testing the process.  The goal is to provide WQCT programs with a repeatable and science-based estimation method that, when correctly applied, provides an estimate of nutrient load reductions that is conservatively accurate (real).  The method can underestimate the reductions to address uncertainties, but doing so comes at a cost.  Underestimation assures the transaction process will result in at least the exchanged values of reduction.  But when conservative valuation is excessive, the trading program’s cost-saving value is diminished.  A worst-case scenario would be when many conservative assumptions are compounded and trading becomes no longer viable.  For example, multiple conservative assumptions would reduce the cost savings associated with trading to a point when the WWTP operators would rather upgrade their facility despite the presence of any remaining cost savings because they control more of the treatment process and better understand their risks.

The AFT-CIG project will mainly focus on this aspect of WQCT – the need for a credible, quantifiable credit estimation method for VRT.  There is a potential this project will be unable to develop a practice standard that has regional or national application. If this is the case, the project will identify the gaps and recommend next steps.

### *Equivalent*

The credited reduction must be **equivalent** to conventional reductions that would be achieved by the on-site reductions at the WWTP in the absence of trading. In order to justify this equivalence, the credit estimation process considers the reductions in nutrient loading leaving the edge of the field, in addition to several discount factors. The trade ratio requires the buyer to purchase more credits than discharged. The list of trade ratio components that are addressed can include:

- The differences in nutrient attenuation that occurs between the field and the water resource of concern, or between the WWTP discharge location and the water of concern
- The difference in bioavailability between the nutrient forms in farm-field runoff and those discharged in WWTP effluent
- Policy goals established for the protection or improvement of waterbodies and other conservation initiatives (e.g., incorporation of a net benefit factor, which includes an additional requirement to purchase more credits than discharged so a percentage can be retired for the good of the environment)

These trade ratio components are considered when creating the WQCT program framework and often result in a 2 : 1 or more multiplier. That is to say, for every credit needed, two must be purchased.

The AFT-CIG project scope does not include addressing these provisions. Instead, equivalence is only supported by providing a list of nitrogen and phosphorus forms that reach the surface waters.

### *Enforceable*

WQCT often only monitors the physical presence of the BMP-based credit generation. It is not affordable to conduct water quality monitoring at each site for many reasons. These reasons include the number of contracts necessary to offset a WWTP load, difficulties in collecting and sampling nonpoint source runoff, the fact that a credit generation site might only be contributing a very small percentage of the nutrient loading at a watershed scale. As such, many programs partner with other monitoring efforts in the region and add a strong BMP inspection program to provide assurance that implementation and operation are adequate.

The AFT-CIG project will support this aspect by developing an example practice standard. The standard will be only for the types of VRT nutrient application methods that the credit estimation process can substantiate. For instance, the practice standard will be developed considering the application rates that can be supported by data. In this case, the standard and contract would limit the rate the producer can apply using VRT to the environmental protection level and not the economically optimum nitrogen rates for production-based goals. The production rate allows a producer to apply rates that provide an added “insurance” in the event a bumper crop season occurs. Buyers participating in a WQCT program using this type of practice standard may have to augment the credit payments to include the opportunity cost associated with this level of reduced application rates.

The practice standard and related contract provisions would address the enforceable requirements of trading. Based on the developed standard and adequate record keeping, the producer requirements would be made clear. If these standards are not followed, the contract would be found deficient.

### *Cost Effective*

WQCT feasibility studies funded by US EPA include evaluations that compare WWTP nutrient treatment costs with BMP implementation costs using a $/pound unit cost. The AFT-CIG process scope does not include this type of analysis. The team will consider placing a brief description of the steps necessary to conduct a life cycle cost analysis in the recommended next steps section of the report. Published literature will be used to establish a range of costs associated with the modeled nutrient reductions.

## Proposed Project Outline

In order to offer VRT as an eligible practice for credit generation in a WQCT program, an acceptable standard method is needed for practice implementation and credit estimation. The development of the method must provide a practice standard that specifies the VRT process that is eligible for WQCT. In addition, a credit estimation method must be provided that produces a real, conservative estimate using the best available science.

The following project outline follows the NRCS AFT-CIG award. However, the outline contains more detail than presented in the proposal and/or contracts. As such, there is some flexibility available to the team if the alterations improve the project and the time, staff, and financial resources are available to implement the changes.

### Task One: Data collection, field model setup, and crediting tool development

1. Field-scale water quality and agronomic model selection. The data collection efforts will be based on the final selection of the appropriate model to assess VRT technologies at the field scale. The model must be able to provide water quality evaluations, as well as respond to differences in farm operation and plant growth/nutrient uptake.

Different VRT studies have provided mixed environmental protection results in the past. However, even study sites where nutrient nonpoint source loadings have increased in the past can provide key insight to aid in developing a water quality nutrient reduction practice standard.

The nutrient cycle allows for long-term or temporary storage of applied nutrients via plant uptake and soil sequestration. In addition, nutrients can be released to the environment in surface runoff, shallow and deep aquifer infiltration, as well as into the atmosphere directly as gas or in particulate-attached forms from wind erosion.

To develop a practice standard, the key data that should be collected at each field site would include:

- Location (latitude and longitude)
- Metrological data (best if collected at the field and daily averages at a minimum)
- VRT type and procedures (e.g., application rates, methods, and incorporation timing)
- Crop rotations
- Crop implement passes and typical dates for entire crop rotation
- Soil types (maps)
- Soil nutrient content
- Yield results (e.g., yield monitor results from previous years and the year VRT is applied)
- Any other nutrient information gathered, such as corn stalk nitrogen test results
- Nonpoint source runoff quantity and water quality monitoring results for sediment, nitrogen, and phosphorus (as available)

The proposed approach is to select a water quality model at a field scale that provides the modeler with the ability to adjust inputs related to the key data sets listed above.

Currently, the Kieser & Associates, LLC (K&A) staff are considering using the Soil and Water Assessment Tool (SWAT). This model can be calibrated at a field scale and allows diversity in farm applications such as implement passes, nutrient application rates, and timing. In addition, the model can accommodate multiple crop types and yields based on crop growth. The model also can include multiple years of meteorological data and is GIS based.

*Do the committee members prefer other models or recommend consideration of different analysis tools?*

2. Data collection to support the water quality assessment. The list of attached variables input in SWAT is provided in Attachment B as an example of the type of information that will be gathered.

Should any local field data not be available, regional data sets will be selected to fill as many gaps as possible. Examples of possible regional data sets include:

- NRCS Web Soil Survey
- Nearby meteorological station records
- Stream water quality monitoring records

If any remaining data are desired for proper calibration of the field model, the committee and design team will be consulted to identify the relevant regional peer reviewed literature and provide an opportunity to offer their own professional opinions.

It will be important to review as much relevant data and indicators as possible to minimize the introduced uncertainty associated with the practice standard and credit estimation method. Therefore, support for a thorough data gathering process is requested by all cooperators on the team.

3. Calibration and validation of the field scale model. After the first field is selected, the model will be set up and calibrated. Then step 4, the sensitivity analysis will be runt to determine the salient characteristics of the modeling approach with regards to VRT. Based on the sensitivity analysis and information regarding the necessary resources to establish a working model a set number of calibration sites will be selected (e.g., three fields). The number will be determined based on the desire to collect a wide variety of data regarding crops, climate, and soils. The field-scale models for the selected fields will be set up using the best available data for soils, meteorological inputs, crop rotations and yields, implement practices, and nutrient application rates and methods. Calibration will be performed using field-scale monitoring results when available. If actual monitoring is not available for a site, the design team and committee will be asked to review and comment on the model results. (Should this be the case, once the collaborators are satisfied with the general range of results from the model and credit estimation process, a margin of safety will be determined to address the larger amount of uncertainty introduced by not having local monitoring data.)

4. Sensitivity Analysis of the field scale model. A detailed sensitivity analysis will be performed using the model setup that is accepted by the collaborators. This analysis simply alters one model parameter at a time to determine which parameters have the greatest impact on the nutrient reduction results. The sensitivity analysis will be performed in a methodical manner that records:

- The coefficient value used in the model setup
- The expected range of variability
- The range of variability tested (e.g., adjustment of the model setup coefficient by plus or minus 100 percent and 50 percent of the range of variability expected)
- The change in results for each adjustment

In this way, the project team can focus on those parameters that either reduce the nutrient reduction efficiencies the most or introduce the most uncertainty in the predicted reduction values.

5. Create multiple scenarios to evaluate the reduction performance of the VRT nutrient application method under the most critical conditions. For example, nitrogen loss occurs during precipitation events after nutrient applications[3]. Therefore, considering critical timing of

[3] H. Torbert et al. 1993. Short-term excess water impact on corn yield and nitrogen recovery. J. Prod. Agric. 6:337-344

precipitation events after nutrient applications for both the base case and VRT methods will be an important component of the credit estimation method. For instance, after a scenario that considers a long-term precipitation record and set nutrient application dates, the nutrient releases can be assessed for which combinations of sequenced precipitation events and applications events are the most critical. A conservative WQCT credit estimation process could then be based on the performance during the most critical sequences or a lower quartile event.

An incomplete forecast of other sensitive attributes that affect nutrient releases to surface waters include:

- Soil nutrient concentrations
- Application rates
- Incorporation methods
- Crop yield/plant uptake
- Soil classifications and hydrologic group
- Presence of subsurface drainage

The sensitivity analysis and multiple scenario generation efforts will combine to provide a robust model output data set that will be used to evaluate the potential for crediting the VRT practices. In addition, the data set will provide information necessary to determine the introduced uncertainty due to changes in climatic events, soil types, and differences in crop uptake and yield.

It will not be possible to represent all the slight changes that affect credit valuation under the scope of this contract (e.g., testing all soil classifications or variability in density of subsurface drainage). However, the credit estimation methodology report will detail recommendations regarding how to adjust the method for settings outside the boundaries tested.

6. The selected field model algorithms and scenario results will be assessed to develop salient credit value prediction equations. A credit estimation process must be conservatively accurate (that is to say estimate at or below the actual value), easy to use by field personnel and provide repeatable results no matter who operates the system. As such, the credit estimation method must balance the desire for accuracy against the capabilities of local field personnel. Approaches that are too sophisticated will not be functional in the field. Limited data sets and/or lack of modeling capability by the user may render tools that provide the highest accuracy useless. As such, data from these approaches can be mined to determine surrogate prediction tools that provide conservative estimates. These surrogates methods include converting the sophisticated assessment tool results into regression equations, nomagraphs and simplified metrics based on the most salient algorithms found in the original assessment tools.

7. Next steps: The credit estimation methodology and scenario results will be assessed for information gaps that can be overcome in the future (gaps analysis), methods to address

introduced uncertainty by using adequate margin of safety or implicit conservative assumptions and recommended future initiatives.

Task Two: Farmer Participation, implementation, and demonstration

8. Support the establishment of field demonstration sites and EQIP eligible producer implementation sites. The credit estimation methods will be field tested working with producers and their technical service providers to assess the functionality of the crediting process, ease of use, and perceptions regarding accuracy of the results.
9. Feedback from producers and technical service providers will be captured to assess the need for appropriate adjustments to the crediting methodology and practice standards.

Many of the identified nine steps will have iterative loops, and input from the collaborator team will be essential to the success of the project.

# Attachment A: Final Water Quality Trading Policy

**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**

**Office of Water**
**Water Quality Trading Policy**
**January 13, 2003**

**I. Background and Purpose of the Policy**

The Clean Water Act (CWA)[1] was enacted in 1972 to restore and maintain the chemical, physical, and biological integrity of the nation's waters. It established a national policy that called for the discharge of pollutants to be eliminated and established interim goals for protecting fish, wildlife and recreational uses. The CWA also established a national policy for development and implementation of programs so the goals of the Act could be met through controls of point and nonpoint sources of pollution. Congress recognized and preserved the primary responsibilities and rights of the States to prevent, reduce and eliminate pollution.

The application of technology and water quality based requirements through the National Pollutant Discharge Elimination System (NPDES) permit program has achieved and remains critical to success in controlling point source pollution and restoring the nation's waters. Despite these accomplishments approximately 40% of the rivers, 45% of the streams and 50% of the lakes that have been assessed still do not support their designated uses[2]. Sources of pollution such as urban storm water, agricultural runoff and atmospheric deposition continue to threaten our nation's waters. Nutrient and sediment loading from agriculture and storm water are significant contributors to water quality problems such as hypoxia in the Gulf of Mexico and decreased fish populations in Chesapeake Bay. Population growth and development place increasing demands on the environment making it more difficult to achieve and maintain water quality standards.

Finding solutions to these complex water quality problems requires innovative approaches that are aligned with core water programs. Water quality trading is an approach that offers greater efficiency in achieving water quality goals on a watershed basis. It allows one source to meet its regulatory obligations by using pollutant reductions created by another source that has lower pollution control costs. Trading capitalizes on economies of scale and the control cost differentials among and between sources.

The United States Environmental Protection Agency (EPA) believes that market-based approaches such as water quality trading provide greater flexibility and have potential to achieve water quality and environmental benefits greater than would otherwise be achieved under more traditional regulatory approaches. Market-based programs can achieve water quality goals at a substantial economic savings. EPA estimates that in 1997 annual private point source control costs were about $14 billion and public point source costs were about $34 billion[3]. The National Cost to Implement Total Maximum Daily Loads (TMDLs) Draft Report estimates that flexible approaches to improving water quality could save $900 million dollars annually compared to the least flexible approach (EPA, August 2001). Nitrogen trading among publicly owned treatment works in Connecticut that discharge into Long Island Sound is expected to achieve the required reductions under a TMDL while saving over $200 million dollars in control costs. Market-based approaches can also create economic incentives for innovation, emerging technology, voluntary pollution reductions and greater efficiency in improving the quality of the nation's waters.

The purpose of this policy is to encourage states, interstate agencies and tribes to develop and implement water quality trading programs for nutrients, sediments and other pollutants where opportunities exist to achieve water quality improvements at reduced costs. More specifically, the policy is intended to encourage voluntary trading programs that facilitate implementation of TMDLs, reduce the costs of compliance with CWA regulations, establish incentives for voluntary reductions and promote watershed-based initiatives. A number of states are in various stages of developing trading programs. This policy provides guidance for states, interstate agencies and tribes to assist them in developing and implementing such programs.

This policy addresses issues left open by and limitations encountered implementing projects and programs under EPA's January 1996 Effluent Trading In Watersheds Policy and May 1996 Draft Framework for Watershed-Based Trading ("Draft Framework"). This policy should be given precedence over any inconsistencies with the Draft Framework.

This policy draws upon lessons from a number of recent pilot trading projects and state experiences in developing water quality trading programs. These initiatives demonstrate how trading can occur under the CWA and existing federal regulations. They illustrate the importance of voluntary watershed-based partnerships, inter-agency cooperation and public participation in implementation of trading programs. They show that flexible market-based approaches can facilitate states and tribes finding solutions to complex and diverse water quality and socioeconomic issues. These efforts have also highlighted the importance of keeping transaction and administrative costs manageable while retaining accountability. The lessons learned from these efforts have informed the development of this policy.

This policy describes various requirements of the CWA and implementing regulations that are relevant to water quality trading, including: requirements to obtain permits (Sections 402 and 404), antibacksliding provisions (Section 303(d)(4) and Section 402(o)), the development of water quality standards including antidegradation policy (Section 303(c)), federal NPDES permit regulations (40 CFR Parts 122, 123 and 124), TMDLs (Section 303d(1)) and water quality management plans (40 CFR Part 130). These CWA provisions and regulations contain legally binding requirements. This policy does not substitute for those provisions or requirements. In addition, this policy identifies general elements and provisions that EPA believes are important for creating credible water quality trading programs.

When EPA makes a decision with regard to any particular permit, TMDL, water quality standards or water quality management plan that includes provisions for trading to occur, it will make each decision on a case-by-case basis guided by the applicable requirements of the CWA and implementing regulations and the specific facts and circumstances involved.

**II. Trading Objectives**

EPA supports implementation of water quality trading by states, interstate agencies and tribes where trading:

A. Achieves early reductions and progress towards water quality standards pending development of TMDLs for impaired waters.
B. Reduces the cost of implementing TMDLs through greater efficiency and flexible approaches.
C. Establishes economic incentives for voluntary pollutant reductions from point and nonpoint sources within a watershed.
D. Reduces the cost of compliance with water quality-based requirements.
E. Offsets new or increased discharges resulting from growth in order to maintain levels of water quality that support all designated uses.
F. Achieves greater environmental benefits than those under existing regulatory programs. EPA supports the creation of water quality trading credits in ways that achieve ancillary environmental benefits beyond the required reductions in specific pollutant loads, such as the creation and restoration of wetlands, floodplains and wildlife and/or waterfowl habitat.
G. Secures long-term improvements in water quality through the purchase and retirement of credits by any entity.
H. Combines ecological services to achieve multiple environmental and economic benefits, such as wetland restoration or the implementation of management practices that improve water quality and habitat.

**III. Water Quality Trading Policy Statement**

A. CWA Requirements. Water quality trading and other market-based programs must be consistent with the CWA.

B. Trading Areas. All water quality trading should occur within a watershed or a defined area for which a TMDL has been approved. Establishing defined trading areas that coincide with a watershed or TMDL boundary results in trades that affect the same water body or stream segment and helps ensure that water quality standards are maintained or achieved throughout the trading area and contiguous waters.
C. Pollutants and Parameters Traded. EPA supports trading that involves nutrients (e.g., total phosphorus and total nitrogen) or sediment loads. In addition, EPA recognizes that trading of pollutants other than nutrients and sediments has the potential to improve water quality and achieve ancillary environmental benefits if trades and trading programs are properly designed. EPA believes that such trades may pose a higher level of risk and should receive a higher level of scrutiny to ensure that they are consistent with water

quality standards. EPA may support trades that involve pollutants other than nutrients and sediments on a case-by-case basis where prior approval is provided through an NPDES permit, a TMDL or in the context of a watershed plan or pilot trading project that is supported by a state, tribe or EPA.

EPA also supports cross-pollutant trading for oxygen-related pollutants where adequate information exists to establish and correlate impacts on water quality. Reducing upstream nutrient levels to offset a downstream biochemical oxygen demand or to improve a depressed in-stream dissolved oxygen level are examples of cross-pollutant trading.

EPA does not currently support trading of pollutants considered by EPA to be persistent bioaccumulative toxics (PBTs). EPA would consider a limited number of pilot projects over the next two to three years to obtain more information regarding trading of PBTs. EPA believes pilot projects may be appropriate where the predominant loads do not come from point sources, trading achieves a substantial reduction of the PBT traded and where trading does not cause an exceedance of an aquatic life or human health criterion. Based on the findings of these pilot projects, EPA will consider making revisions to its policy.

Where state or tribal water quality standards allow for mixing zones, EPA does not support any trading activity that would exceed an acute aquatic life criteria within a mixing zone or a chronic aquatic life or human health criteria at the edge of a mixing zone using design flows specified in the water quality standards.

D. Baselines for Water Quality Trading. As explained below, the baselines for generating pollution reduction credits should be derived from and consistent with water quality standards. The term pollution reduction credits ("credits"), as used in this policy, means pollutant reductions greater than those required by a regulatory requirement or established under a TMDL.

For example, where a TMDL has been approved or established by EPA, the applicable point source waste load allocation or nonpoint source load allocation would establish the baselines for generating credits. For trades that occur where water quality fully supports designated uses, or in impaired waters prior to a TMDL being established, the baseline for point sources should be established by the applicable water quality based effluent limitation, a quantified performance requirement or a management practice derived from water quality standards. In these scenarios the baseline for nonpoint sources should be the level of pollutant load associated with existing land uses and management practices that comply with applicable state, local or tribal regulations.

E. When Trading May Occur.

1. Trading to Maintain Water Quality Standards. Trading may be used to maintain high water quality in waters where water quality standards are attained, such as by compensating for new or increased discharges of pollutants.

2. Pre-TMDL Trading In Impaired Waters. EPA supports pre-TMDL trading in impaired waters to achieve progress towards or the attainment of water quality standards. EPA believes this may be accomplished by individual trades that achieve a net reduction of the pollutant traded or by watershed-scale trading programs that reduce loadings to a specified cap supported by baseline information on pollutant sources and loadings.

EPA also supports pre-TMDL trading that achieves a direct environmental benefit relevant to the conditions or causes of impairment to achieve progress towards restoring designated uses where reducing pollutant loads alone is not sufficient or as cost-effective.

If pre-TMDL trading does not result in the attainment of applicable water quality standards, EPA expects a TMDL to be developed. After a TMDL has been approved or established by EPA, the reductions made to generate credits for pre-TMDL trading may no longer be adequate to generate credits under the TMDL. This will depend on the remaining level of reduction needed to achieve water quality standards and, where applicable, the allocation of point and nonpoint source pollutant loads established by the TMDL.

3. TMDL Trading. Trades and trading programs in impaired waters for which a TMDL has been approved or established by EPA should be consistent with the assumptions and requirements upon which the TMDL is established. EPA encourages the inclusion of specific trading provisions in the TMDL itself, in NPDES permits, in watershed plans and the continuing planning process.
EPA does not support any trading activity that would delay implementation of a TMDL approved or established by EPA or that would cause the combined point source and nonpoint source loadings to exceed the cap established by a TMDL.

4. Technology-Based Trading. EPA does not support trading to comply with existing technology-based effluent limitations except as expressly authorized by federal regulations. Existing technology-based effluent guidelines for the iron and steel industry allow intraplant trading of conventional, nonconventional and toxic pollutants between outfalls under certain circumstances (40 CFR 420.03).

EPA will consider including provisions for trading in the development of new and revised technology-based effluent guidelines and other regulations to achieve technology-based requirements, reduce implementation costs and increase environmental benefits.

5. Pretreatment Trading. EPA supports a municipality or regional sewerage authority developing and implementing trading programs among industrial users that are consistent with the pretreatment regulatory requirements at 40 CFR Part 403 and the municipality's or authority's NPDES permit.

6. Intra-Plant Trading. EPA supports intra-plant trading that involves the generation and use of credits between multiple outfalls that discharge to the same receiving water from a single facility that has been issued an NPDES permit.

F. Alignment With The CWA. Provisions for water quality trading should be aligned with and incorporated into core water quality programs. EPA believes this may be done by including provisions for trading in water quality management plans, the continuing planning process, watershed plans, water quality standards, including antidegradation policy and, by incorporating provisions for trading into TMDLs and NPDES permits.

When developing water quality trades and trading programs, states and tribes should, at a minimum, take into account the following provisions of the CWA and implementing regulations:

1. Requirements to Obtain Permits. Sources and activities that are required to obtain a federal permit pursuant to Sections 402 or 404 of the CWA must do so to participate in a trade or trading program.

2. Incorporating Provisions For Trading Into Permits. In some cases, specific trades may be identified in NPDES permits, including requirements related to the control of nonpoint sources where appropriate. EPA also supports several flexible approaches for incorporating provisions for trading into NPDES permits: i) general conditions in a permit that authorize trading and describe appropriate conditions and restrictions for trading to occur, ii) the use of variable permit limits that may be adjusted up or down based on the quantity of credits generated or used; and/or, iii) the use of alternate permit limits or conditions that establish restrictions on the amount of a point source's pollution reduction obligation that may be achieved by the use of credits if trading occurs. EPA also encourages the use of watershed general permits, where appropriate, to establish pollutant-specific limitations for a group of sources in the same or similar categories to achieve net pollutant reductions or water quality goals through trading. Watershed permits issued to point sources should include facility specific effluent limitations or other conditions that would apply in the event the pollutant cap established by the watershed permit is exceeded.

3. Public Notice, Comment and Opportunity For Hearing. Notice, comment and opportunity for hearing must be provided for all NPDES permits (40 CFR 124). NPDES permits and fact sheets should describe how baselines and conditions or limits for trading have been established and how they are consistent with water quality standards. EPA does not expect that an NPDES permit would need to be modified to incorporate an individual trade if that permit contains authorization and provisions for trading to occur and the public was given notice and an opportunity to comment and/or attend a public hearing at the time the permit was issued.

4. Consistency With Standard Methods. Where methods and procedures (e.g., sampling protocols, monitoring frequencies) are specified by federal regulations or in NPDES permits, they should continue to be used where applicable for measuring compliance for point sources that engage in trading. EPA believes this is necessary to provide clear and consistent standards for measuring compliance and to ensure that appropriate enforcement action can be taken.

5. Protecting Designated Uses. EPA does not support any use of credits or trading activity that would cause an impairment of existing or designated uses, adversely affect water quality at an intake for drinking water supply or that would exceed a cap established under a TMDL.

6. Antibacksliding. EPA believes that the antibacksliding provisions of Section 303(d)(4) of the CWA will generally be satisfied where a point source increases its discharge through the use of credits in accordance with alternate or variable water quality based effluent limitations contained in an NPDES permit, in a manner consistent with provisions for trading under a TMDL, or consistent with the provisions for pre-TMDL trading included in a watershed plan.

These antibacksliding provisions will also generally be satisfied where a point source generates pollution reduction credits by reducing its discharge below a water quality based effluent limitation (WQBEL) that implements a TMDL or is otherwise established to meet water quality standards and it later decides to discontinue generating credits, provided that the total pollutant load to the receiving water is not increased, or is otherwise consistent with state or tribal antidegradation policy.

7. Antidegradation. Trading should be consistent with applicable water quality standards, including a state's and tribe's antidegradation policy established to maintain and protect existing instream water uses and the level of water quality necessary to support them, as well as high quality waters and outstanding national resource waters (40 CFR 131.12). EPA recommends that state or tribal antidegradation policies include provisions for trading to occur without requiring antidegradation review for high quality waters. EPA does not believe that trades and trading programs will result in "lower water quality" as that term is used in 40 CFR 131.12(a)(2), or that antidegradation review would be required under EPA's regulations when the trades or trading programs achieve a no net increase of the pollutant traded and do not result in any impairment of designated uses.

G. Common Elements of Credible Trading Programs. EPA believes that, in addition to including provisions to be consistent with the CWA, trading programs should include the following general elements to be credible and successful:

1. Legal Authority and Mechanisms. Clear legal authority and mechanisms are necessary for trading to occur. EPA believes the CWA provides authority for EPA, states and tribes to develop a variety of programs and activities to control pollution, including trading programs. The CWA and federal regulations provide authority to incorporate provisions for trading into NPDES permits issued to point sources and for trading under TMDLs that include provisions for trading to occur.

In addition, states and tribes should use specific legal mechanisms to facilitate trading. Provisions for trading may be established through various mechanisms, including: legislation, rule making, incorporating provisions for trading into NPDES permits and establishing provisions for trading in TMDLs or watershed plans. These provisions may incorporate or be supplemented by private contracts between sources or third-party contracts where the third party provides an indemnification or enforcement function.

2. Units of Trade. Clearly defined units of trade are necessary for trading to occur. Pollutant specific credits are examples of tradable units for water quality trading. These may be expressed in rates or mass per unit time as appropriate to be consistent with the time periods that are used to determine compliance with NPDES permit limitations or other regulatory requirements.

3. Creation and Duration of Credits. Credits should be generated before or during the same period they are used to comply with a monthly, seasonal or annual limitation or requirement specified in an NPDES permit. Credits may be generated as long as the pollution controls or management practices are functioning as expected.

4. Quantifying Credits and Addressing Uncertainty. Standardized protocols are necessary to quantify pollutant loads, load reductions, and credits. States and tribes should develop procedures to account for the generation and use of credits in NPDES permits and discharge monitoring reports in order to track the generation and use of credits between sources and assess compliance.

Where trading involves nonpoint sources, states and tribes should adopt methods to account for the greater uncertainty in estimates of nonpoint source loads and reductions. Greater uncertainty in nonpoint source estimates is due to several factors including but not limited to variability in precipitation, variable performance of land management practices, time lag between implementation of some practices and full performance, and the effect of soils, cover and slope on pollutant load delivery to receiving waters.

EPA supports a number of approaches to compensate for nonpoint source uncertainty. These include monitoring to verify load reductions, the use of greater than 1:1 trading ratios between nonpoint and point sources, using demonstrated performance values or conservative assumptions in estimating the effectiveness of nonpoint source management practices, using site- or trade-specific discount factors, and retiring a percentage of nonpoint source reductions for each transaction or a predetermined number of credits. Where appropriate, states and tribes may elect to establish a reserve pool of credits that would be available to compensate for unanticipated shortfalls in the quantity of credits that are actually generated.

The site-specific procedures and protocols used in water quality trading programs that involve agriculture and forestry operations should be developed by states and tribes in consultation with United States Department of Agriculture (USDA) agencies. Those procedures should estimate nutrient or sediment load delivery to the stream segment, water body or watershed where trading occurs. Numerous methods and procedures to determine nutrient and sediment load reductions associated with conservation practices on agricultural and forest land have been developed or used by the USDA agencies, including the Natural Resources Conservation Service, Forest Service, Agricultural

Research Service and the Cooperative State, Research, Education and Extension Service. Some of these methods may be applied to water quality trading.

As an example, the Revised Universal Soil Loss Equation (RUSLE) may be used in some locations to estimate the sediment yield at the end of a slope in agricultural settings. The sediment yield at the end of a slope coupled with an appropriate method to estimate sediment delivery to the receiving waters can provide a reasonable estimate of sediment load and load reductions. Representative soil sampling to determine the phosphorus content of soils can be used with this approach to estimate non-soluble sediment-bound phosphorus loads and load reductions. Different methods are appropriate to estimate soluble phosphorus and nitrogen loads and load reductions.

EPA and the USDA are working with other agencies to evaluate existing methods and to develop improved methods and procedures for estimating loads from agricultural and forestry lands. More precise estimations will be possible as technologies improve and new technologies are developed.

For storm water runoff other than agriculture, EPA recommends monitoring or modeling to estimate pollutant loads and load reductions. EPA believes this may be based on local hydrology and actual data or pollutant loading factors that relate land use patterns, percent imperviousness or percent disturbed land and controls or management practices in a watershed to per acre or per unit pollutant loads, where other methods are not specified in a permit or regulation.

5. Compliance and Enforcement Provisions. Mechanisms for determining and ensuring compliance are essential for all trades and trading programs. These may include a combination of record keeping, monitoring, reporting and inspections. Compliance audits should be conducted frequently enough to ensure that a high level of compliance is maintained across the program. States and tribes should establish clear enforceable mechanisms consistent with NPDES regulations that ensure legal accountability for the generation of credits that are traded. In the event of default by another source generating credits, an NPDES permittee using those credits is responsible for complying with the effluent limitations that would apply if the trade had not occurred. EPA also recommends that states and tribes consider providing periodic accounting and reconciliation periods and establishing appropriate enforcement provisions for failure to generate the quantity of credits that are traded.

EPA recommends that states and tribes consider the role of compliance history in determining source eligibility to participate in trading.

EPA recommends that states and tribes consider including provisions to address situations where nonpoint source controls and management practices that are implemented to generate credits fail due to extreme weather conditions or other circumstances that are beyond the control of the source.

6. Public Participation And Access To Information. EPA supports public participation at the earliest stages and throughout the development of water quality trading programs to strengthen program effectiveness and credibility.

Easy and timely public access to information is necessary for markets to function efficiently and for the public to monitor trading activity. EPA encourages states and tribes to make electronically available to the public information on the sources that trade, the quantity of credits generated and used on a watershed basis, market prices where available, and delineations of watershed and trading boundaries. This information is necessary to identify potential trading opportunities, allow easy aggregation of credits, reduce transaction costs and establish public credibility.

7. Program Evaluations. Periodic assessments of environmental and economic effectiveness should be conducted and program revisions made as needed. Environmental evaluations should include ambient monitoring to ensure impairments of designated uses (including existing uses) do not occur and to document water quality conditions. Studies should be performed to quantify nonpoint source load reductions, validate nonpoint source pollutant removal efficiencies and determine whether the anticipated water quality objectives have been achieved. Economic evaluations should include the number and type of trades, the price paid for pollutant reduction credits, transaction costs, the costs incurred to administer the program, and where possible any net cost savings resulting from trading.

The results of program evaluations should be made available to the public. An opportunity for comment should also be provided on changes to the program as necessary to ensure that water quality objectives and economic efficiencies are achieved, and that trading does not result in an impairment of designated uses (including existing uses).

H. EPA's Oversight Role. States and tribes are encouraged to consult with EPA throughout development of trading programs to facilitate alignment with the CWA. EPA has various oversight responsibilities under the CWA, including approval or establishment of TMDLs, approval of revisions to state or tribal water quality standards, review of NPDES permits and provisions for reviewing and making recommendations regarding revisions to a state's or tribe's water quality management plans through the continuing planning process. In general, EPA does not believe that the development and implementation by states and tribes of trading programs consistent with the provisions of this policy necessarily warrant a higher level of scrutiny under these oversight authorities than is appropriate for activities not involving trading. However, where questions or concerns arise, EPA will use its oversight authorities to ensure that trades and trading programs are fully consistent with the CWA and its implementing regulations.

[1] Federal Water Pollution Control Act (Public Law 92-500, as amended), 33 U.S.C. Sec. 1251, et. seq.

[2] About 33 percent of the nation's waters have been assessed by States and tribes pursuant to Section 305(b) of the Clean Water Act (National Water Quality Inventory: 2000 Report, EPA). The proportion of non-assessed water that do not meet designated uses is likely lower since assessments tend to be focused in known problem areas.

[3]A Retrospective Assessment of the Costs of the Clean Water Act: 1972 - 1997 (EPA October, 2000).

# Attachment B

## Requested data

The following list of data needs is based on the required inputs for the SWAT model. The data requested of the team might not be available at each site. It is not expected that every site will be collecting water quality data or have the depth of agronomic research testing described here. As such, a combination of actual data, regional data sets and, team professional judgment will be used to inform the set up and calibration process for the field-scale model.

## Site Description

- Latitude/longitude
- Elevation
- Crop rotation
- Implement type, number of passes, and schedules
- Fraction of the field that drains into potholes
- Presence of subsurface tiling
    - Depth to tile
- Best Management Practices located upstream of water quality monitoring stations
- Presence of irrigation activities

## Meteorological Data

Site-specific meteorological data sets should be gathered for each study site as data availability allows.

- Temperature -daily averages or hourly measured temperatures, plus daily records that indicate:
    - Maximum
    - Minimum
- Solar Radiation ($MJ/m^2$)
- Precipitation
    - Rainfall
    - Snowfall
        - Depth
        - Water content
- Daily average wind speed
- Daily average relative humidity

## Evapotranspiration Data

If site-specific estimates are available please provide for background purposes and SWAT calibration:

- Identify for soil moisture depletion:
    - Water vapor
    - Rainfall interception from vegetation cover
    - ...
- Regional evapotranspiration measurements
    - Results
    - Short description of collection methods

## Soil/Plant Growth Characteristics

Please provide the site-specific information as available (the project team can estimate these characteristics from national data sources if necessary). However, some of the soil properties derived from other sources (e.g., from the NRCS Web Soil Survey) will tend to increase the variability in results, thus increasing the introduced uncertainty of the models.

- Depth to impervious layer
- Soil classification
- Hydrologic Soil Group
- Information on size and length of macropores (e.g., regarding field observations of, or tendency for the soil horizon to develop macropores and the level at which they are disturbed by field implements)
- Root density to depth relationships
- Canopy closure dates
- Canopy cover extent
- Phosphorus availability index
- Crop information - the following are examples of inputs needed for an adequate determination of crop uptake:
    - Maximum root depth
    - Maximum canopy height
    - Plant nitrogen and phosphorus uptake rates at emergence, 50 percent of maturity, and maturity
    - Plant biomass removed during harvesting
    - Normal fractions of nitrogen and phosphorus in yield
    - SWAT model setups for any specific crops for which this modeling or other calculations have been performed; this assistance would be very beneficial to the project outcome
- Universal Soil Loss Equation estimates for
    - C factor guidance on percent of residue, duration, and decay rates

## Nutrient Applications

Please provide all fertilizer applications and related soil information.  In addition, a description of the VRT process applied will be important.

- Number of applications
- Amount applied at each event
- Incorporation description (equipment, schedule and resulting depth)
- Fraction of mineral N and P in fertilizer (NO3 and NH4)
- Fraction of organic N and P in fertilizer
- Fraction of mineral N applied as ammonia
- Fertilizer tests for nutrient content associated with the inert fraction
- Whether or not the field has a history of manure applications (livestock generating the manure, rates, timing, and incorporation methods)
- Soil nutrient test methods and results

# APPENDIX 1

## Item #5. AFT PRESENTATION FOR MAY 21, 2015 TEAM MEETING: WATER QUALITY TRADING CREDIT METHOD DEVELOPMENT FOR VARIABLE RATE TECHNOLOGY

# Water Quality Trading Credit Method Development for Variable Rate Technology



MODELING RESULTS FOR EDGE-OF-FIELD LOADING CHANGES USING DIFFERENT FERTILIZER APPLICATION RATES ON A FARM FIELD IN ILLINOIS

# USDA-NRCS CIG



*This material is based upon work supported by the Natural Resources Conservation Service, U.S. Department of Agriculture, under number 69-3A75-12-177. Any opinions, findings, conclusions, or recommendations expressed in the this presentation are those of the authors and do not necessarily reflect the views of the U.S. Department of Agriculture.*

# Project Partners



- American Farmland Trust
- Indiana State Department of Agriculture
- John Deere
- Kentucky Division of Conservation
- Ohio Department of Natural Resources
- Ohio Farm Bureau
- Ohio State University
- Purdue University
- Trimble
- USDA Natural Resources Conservation Service
- University of Kentucky

# Agenda



- Re-introductions
- Project progress
- Illinois farm site
- WQCT credit generation potential using the MSU-EPRI GHG protocol
- Variability WQCT credits; characteristics
- Crediting methodology limitations
- Preliminary recommendations
- Next steps

# Project Progress



**VARIABLE RATE TECHNOLOGY; WATER QUALITY CREDIT TRADING ESTIMATION METHOD DEVELOPMENT**

# Project Progress



- Acquired 9-years of field data from a progressive operation in Illinois (e.g., yield, rates, timing as available)
- Calibrated a SWAT model based on nutrient application rates, weather and yield for the site (no water quality data available)
- Completed a greenhouse gas and water quality credit trading stacking feasibility scenario
- Developed preliminary zone mapping VRT credit estimation method for particulate nutrients

# Illinois Farm Site



**VARIABLE RATE TECHNOLOGY; WATER QUALITY CREDIT TRADING ESTIMATION METHOD DEVELOPMENT**

# Illinois Field Characteristics



- 159 acres
- Flat slopes (<= 2%)
- Soils are dominated by loam complexes
- Corn - Soybean crop rotation
- Approximately 166 bu/ac corn and 49 bu/ac beans
- Mulch-till operation; 9+ years running
- Practicing VRT pre 2009
- VRT applications based on the zone map approach

# Illinois Field Application Rate Scenarios



- Corn VRT Nitrogen application rates range from 200 to 230 lbs/ac
- Corn VRT Phosphorus application rates range from 39 to 69 lbs/ac $P_2O_5$
- National Agricultural Statistics Service statewide average nutrient application rates:
  - Corn nitrogen: 157 lbs/ac
  - Corn $P_2O_5$: 84 lbs/ac

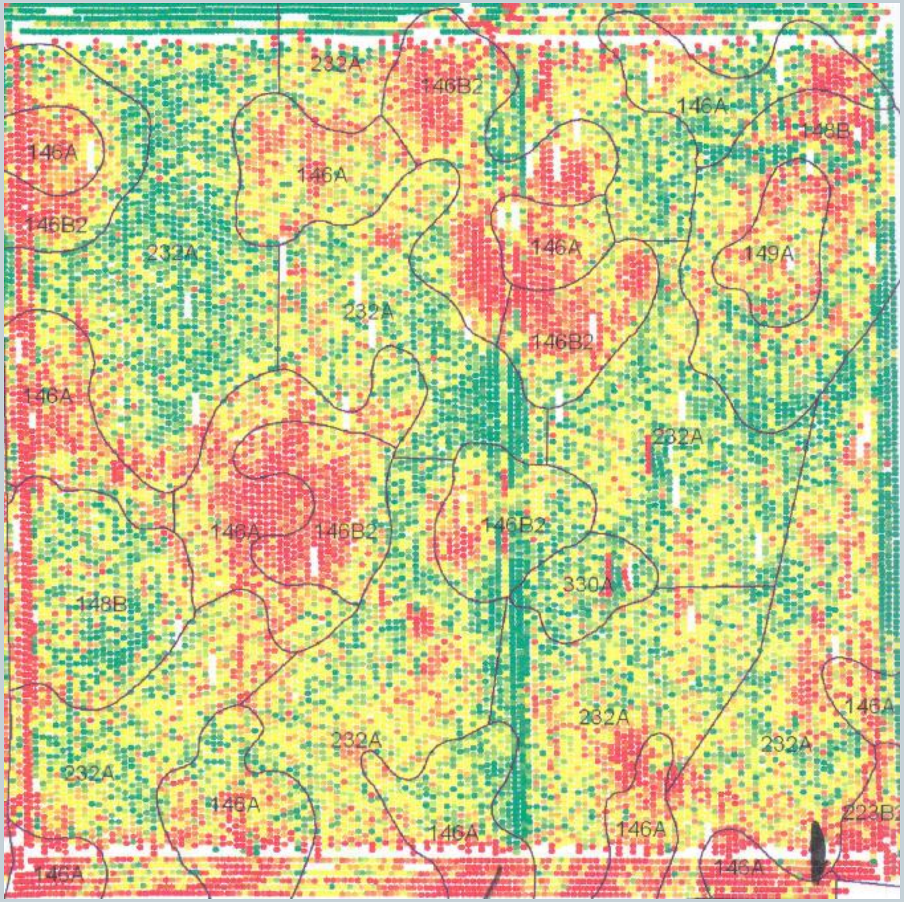
# Study Field




146A
146B2
330A
146A
146B2
330A
146B2
146A
146B2
146A
146B2
146A
330A
146B2
148B
146A
20
18
6 146A
4
9
5 146A
7
146B2
6 146A
149A
6
24
517
17
146B2
21
16
11 148B
146A
FORD
146B2
146A
4
232A
10
22
8
146B2
8 146B2
15
10 148B
330A
12
25
146A
146A
13
14
3 146A
19
23
330A
2
2
3
146A
15
146B2
146A 1
146A
146A
3
223B2
146A
146B2
146B2
146B2
146B2
223B2
146A
146A
146A
241C3
235A

# Selected Field






2008 Corn Yield Map

# VARIABLE RATE TECHNOLOGY; WATER QUALITY CREDIT TRADING ESTIMATION METHOD DEVELOPMENT

# Feasibility of Stacking Greenhouse Gas Credits and Water Quality Credits



- Michigan State University – Electric Power Research Institute Greenhouse Gas (GHG) Protocol
- Based on reducing nitrogen application rates to reduce nitrous oxide ($N_2O$) gas emissions
- Other 3 of the NRCS' 4Rs ("four rights") are good practices but the GHG emissions response is too variable to provide GHG credits

# GHG Eligibility Requirements



- No significant yield loss may occur for GHG credit generation
- Application reductions are best calculated based on site history
- Without site history; default to U.S. county average for base case

# MSU-EPRI GHG Protocol Equations



- $N_2O$ emissions = $0.67 \times e^{(0.0067 \times \text{N rate})}$

And

- $CO_2$ equivalent emissions = $468.29 \times N_2O$ emissions

Where,

N2O emissions: kg $N_2O$-N/ha/yr

N rate: kg N/ha/yr

$CO_2$ equivalent emissions: kg $CO_2$e/ha/yr

| Year | Crop | Base Case Simulated Yield | NASS Simulated Yield | TN Rate-NASS | TN Loss -Base Case | TN Loss - NASS Case | TN Loss Change |
|---|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | % |
| **2006** | Corn | 184 | 181 | 123.9 | 32.0 | 30.5 | -4.54 |
| **2007** | Bean | 50 | 50 | 32.9 | 37.6 | 35.5 | -5.67 |
| **2008** | Corn | 166 | 165 | 123.9 | 53.4 | 50.4 | -5.60 |
| **2009** | Bean | 54 | 54 | 32.9 | 48.3 | 43.4 | -10.12 |
| **2010** | Corn | 164 | 162 | 150.9 | 31.4 | 29.4 | -6.60 |
| **2011** | Bean | 44 | 44 | 32.9 | 18.7 | 17.7 | -5.12 |
| **2012** | Corn | 63 | 63 | 123.9 | 19.4 | 17.9 | -7.86 |
| **2013** | Bean | 48 | 48 | 32.9 | 40.4 | 38.8 | -3.94 |
| **Maximum** | | -- | -- | -- | 53.4 | 50.4 | -3.94 |
| **Average** | | -- | -- | -- | 35.2 | 33.0 | -6.18 |
| **Minimum** | | -- | -- | -- | 18.7 | 17.7 | -10.12 |

| Year | Crop | Base Case Yield | Yield with 20% Reduction | Nitrogen Rate after 20% Reduction | Total N Loss with 20% Reduction | % Total N Loss Difference from Base Case |
|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | % |
| 2006 | Corn | 184 | 182 | 120.2 | 30.3 | -5.28 |
| 2007 | Bean | 50 | 50 | 38.4 | 35.6 | -5.30 |
| 2008 | Corn | 166 | 165 | 121.3 | 50.5 | -5.44 |
| 2009 | Bean | 54 | 54 | 38.4 | 44.2 | -8.37 |
| 2010 | Corn | 164 | 163 | 126.0 | 29.0 | -7.79 |
| 2011 | Bean | 44 | 44 | 32.6 | 17.6 | -5.71 |
| 2012 | Corn | 63 | 63 | 152.2 | 18.4 | -4.86 |
| 2013 | Bean | 48 | 48 | 27.6 | 39.2 | -2.98 |
| Maximum | | -- | -- | -- | 50.5 | -8.37 |
| Average | | -- | -- | -- | 33.1 | -5.72 |
| Minimum | | -- | -- | -- | 17.6 | -2.98 |

| Year | Crop | TN Loss - Base Case | TN Loss - NASS | Total N Loss with 20% Fertilizer Reduction | TN Delta between NASS and Base Case | TN Delta between 20% reduction and Base Case | Potential N Credit with 20% Fertilizer Reduction and 2:1 Trading Ratio |
|---|---|---|---|---|---|---|---|
| | | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) |
| 2006 | Corn | 32.0 | 30.5 | 30.3 | -1.5 | -1.7 | 0.84 |
| 2007 | Bean | 37.6 | 35.5 | 35.6 | -2.1 | -2.0 | 1.00 |
| 2008 | Corn | 53.4 | 50.4 | 50.5 | -3.0 | -2.9 | 1.45 |
| 2009 | Bean | 48.3 | 43.4 | 44.2 | -4.9 | -4.0 | 2.02 |
| 2010 | Corn | 31.4 | 29.4 | 29.0 | -2.1 | -2.5 | 1.23 |
| 2011 | Bean | 18.7 | 17.7 | 17.6 | -1.0 | -1.1 | 0.53 |
| 2012 | Corn | 19.4 | 17.9 | 18.4 | -1.5 | -0.9 | 0.47 |
| 2013 | Bean | 40.4 | 38.8 | 39.2 | -1.6 | -1.2 | 0.60 |
| Maximum | | 53.4 | 50.4 | 50.5 | -1.0 | -0.9 | 2.02 |
| Average | | 35.2 | 33.0 | 33.1 | -2.2 | -2.0 | 1.02 |
| Minimum | | 18.7 | 17.7 | 17.6 | -4.9 | -4.0 | 0.47 |

# GHG & WQCT Stacking Could be Viable, Considering:



- Appropriate physical and chemical setting
- For 20% reduction average N credit ~1 lb/ac; minimum N credit ~0.5 with a 2:1 trade ratio
- Past application rate, when near agronomic rates can be a limiting factor
- Will need to aggregate many sites
- WQCT using VRT may be limited economically when reduction units per acre are relatively small

# GHG & WQCT Stacking Could be Viable, Considering:



- Tracking baseline is important
  - Tracking application history important
  - Without tracking NASS rates applied as background
  - At this farm site a reduction from NASS N rates may have suffered yield loss
- Surface water reductions are small compared to application rate reductions
- An approximate 23 lb N application rate reduction yields 0.5 to 1 lb N/ac edge-of-field reduction
- Data indicates an annual or longer seasonal contemporaneous averaging period is best
  - Months with little or no rain produce no credits
  - Occurrence of  zero credit months varies year-to-year

# Summary of GHG & WQCT Stacking



WQCT programs must balance the total cost of a credit (i.e., implementation of BMP and transaction overhead) while bounded by the eligibility requirement that sites with significant yield loss can not be used

Recommended for fields with documented history and operated with nitrogen application rates well above agronomic rates

# VARIABLE RATE TECHNOLOGY; WATER QUALITY CREDIT TRADING ESTIMATION METHOD DEVELOPMENT

# Multiple Linear Regression on Two SWAT HRUs



- SWAT HRU is a hydrologic resource unit
- HRU is a boundary where within that delineation all input factors are the same (e.g., soils, rates, crop, yield and weather)
- Two silt loam soils selected
- Region V model variables explains 87 % of phosphorus loading variability in HRU 1061, and 94 % in HRU 645
- Soil P is not always an independent variable
- Using a multiple linear regression analysis in HRU 1061, the *p* test results for soil P is 0.99 (This is well above the significance test threshold of 0.05 for independent variables.)

# Illinois Farm Field Evaluated for Region V Model Approach Compatibility



Region V model approach:

- Proven to work in Kentucky assessment
- Combines Universal Soil Loss Equation (USLE) or revised USLE version to load the CREAMS model (Chemicals, Runoff, and Erosion From Agricultural Management Systems) nutrient algorithms for prediction
- WQCT programs have used this method across the Midwest (Ohio, Michigan, Minnesota)

# Region V Model Approach



Region V model equations for particulate P:

- SedP = SoilP * Sed * ERP
- $ERP = AP * Sed^{BP}$

Where:

SedP: particulate phosphorus delivered (kg/ha)

SoilP: upland soil concentration of TP (fraction)

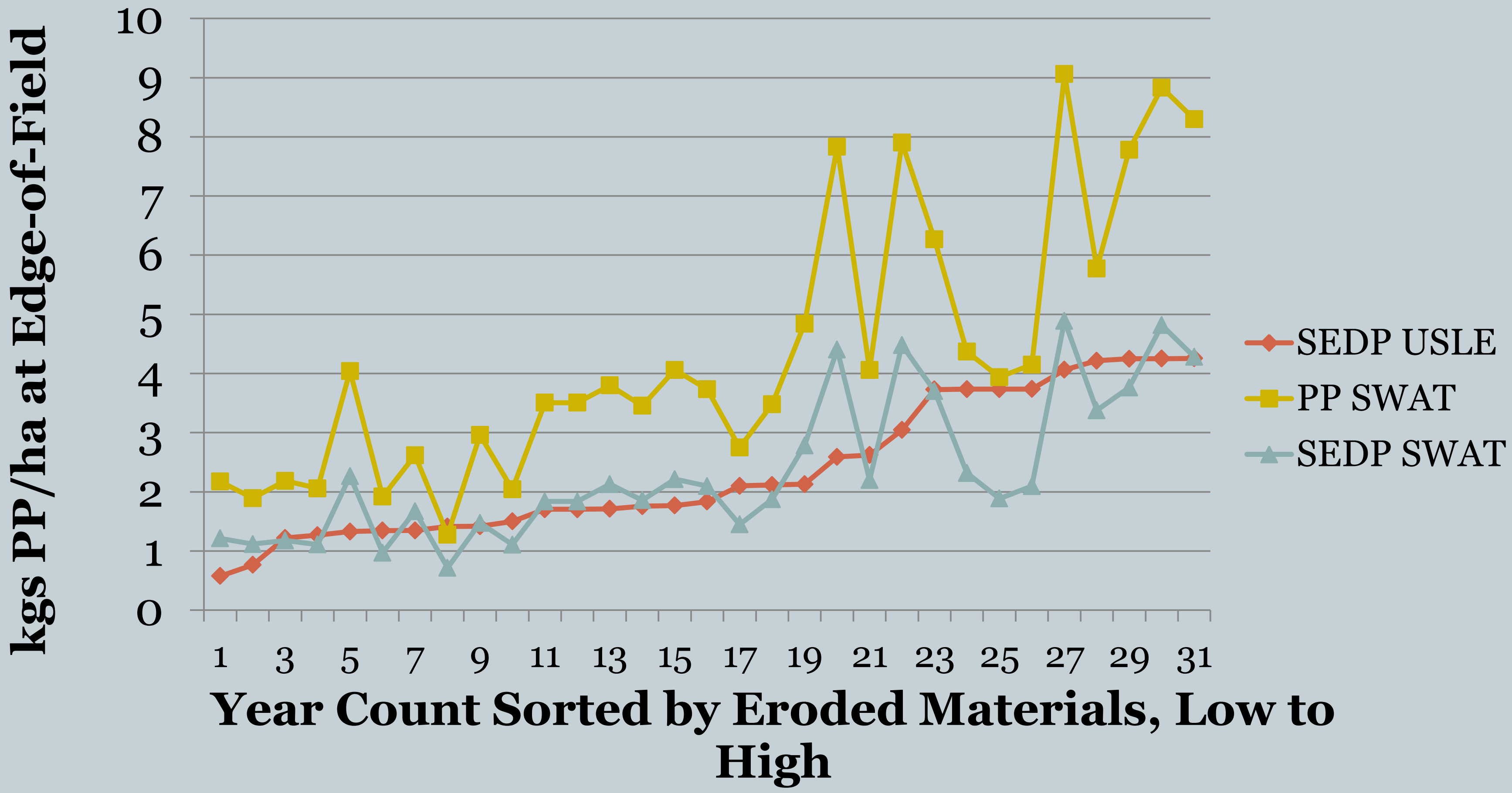
Sed: USLE or RUSLE estimate of erosion (kg/ha)

ERP: nutrient enrichment factor for P

AP: default value 7.4 & BP: default value -0.20

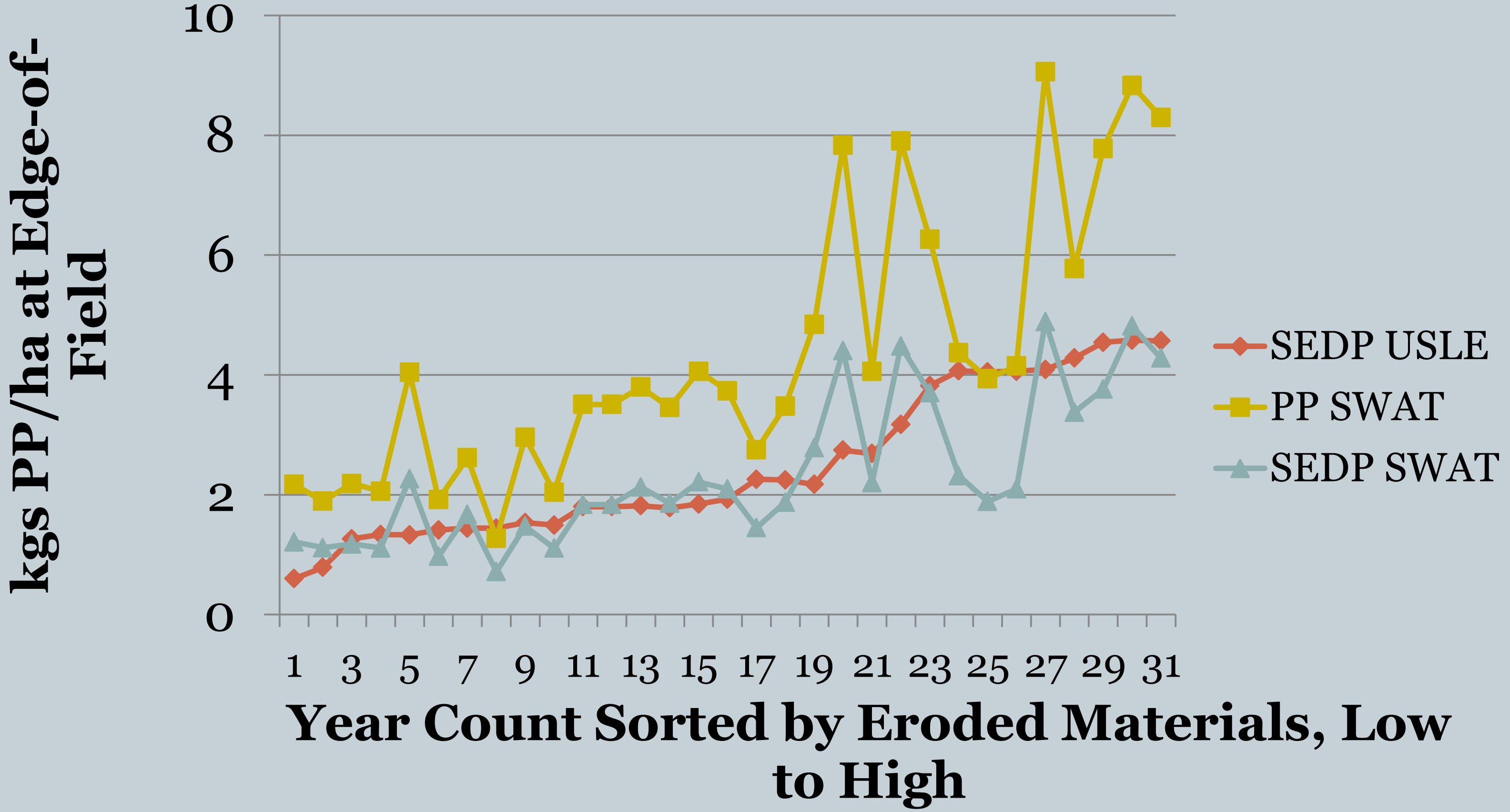
# Particulate Phosphorus Estimates; SWAT Model Versus Region V Comparisons (HRU 645, Default Values)





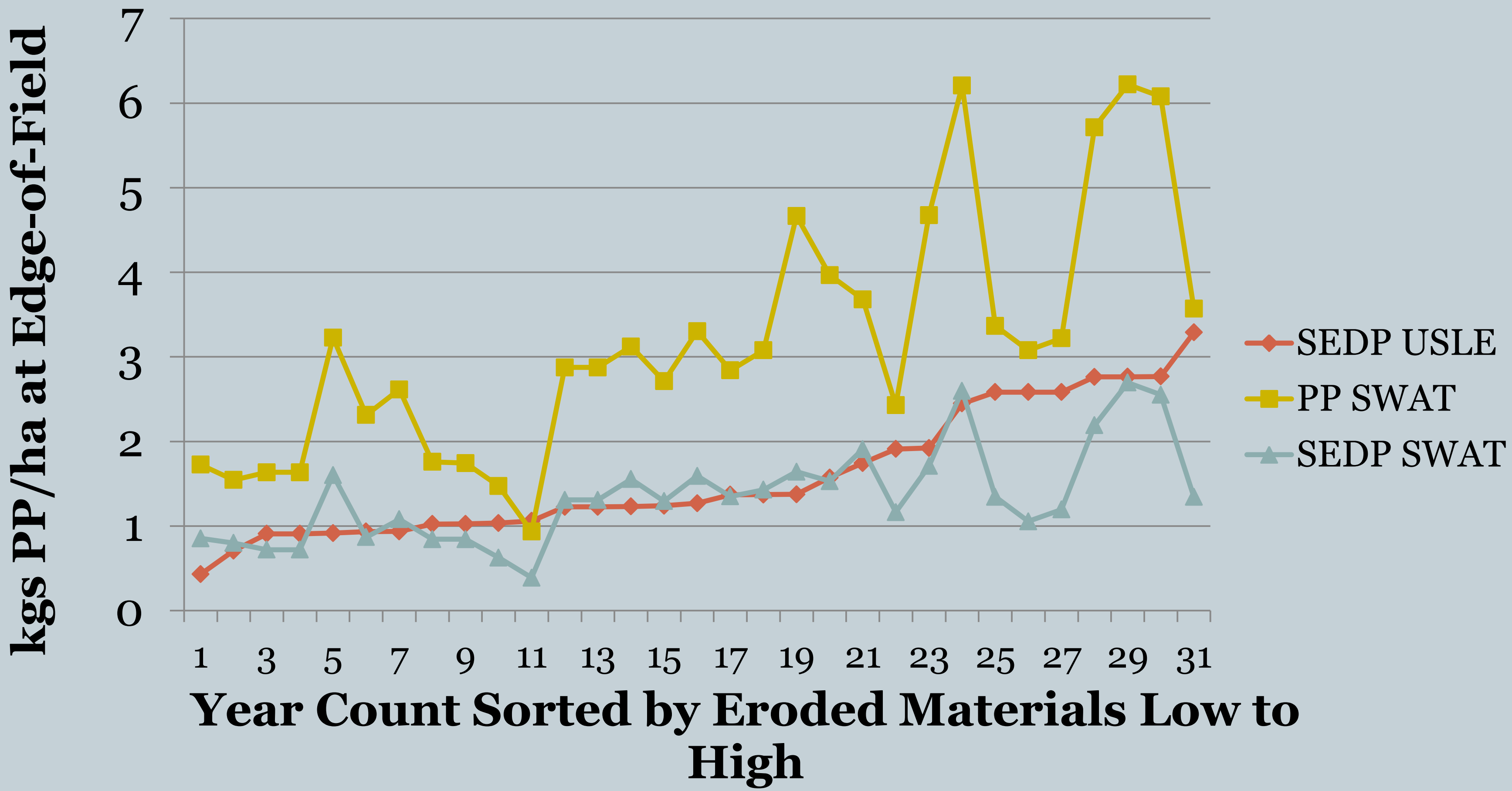
# Particulate Phosphorus Estimates; SWAT Model Versus Region V Comparisons (HRU 654, Simulated Soil Concentrations)





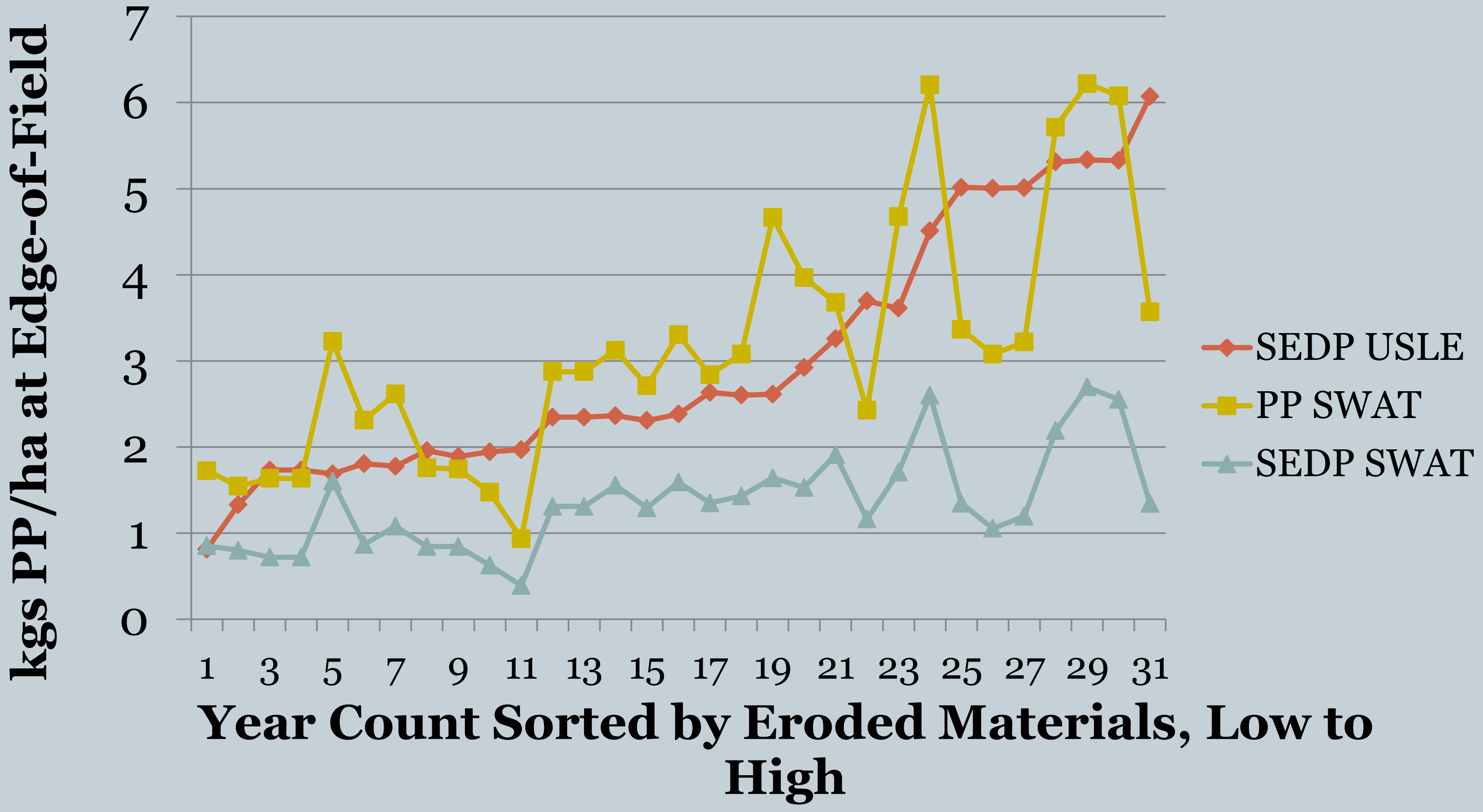
# Particulate Phosphorus Estimates; SWAT Model Versus Region V Comparisons (HRU 1061, Default Values)





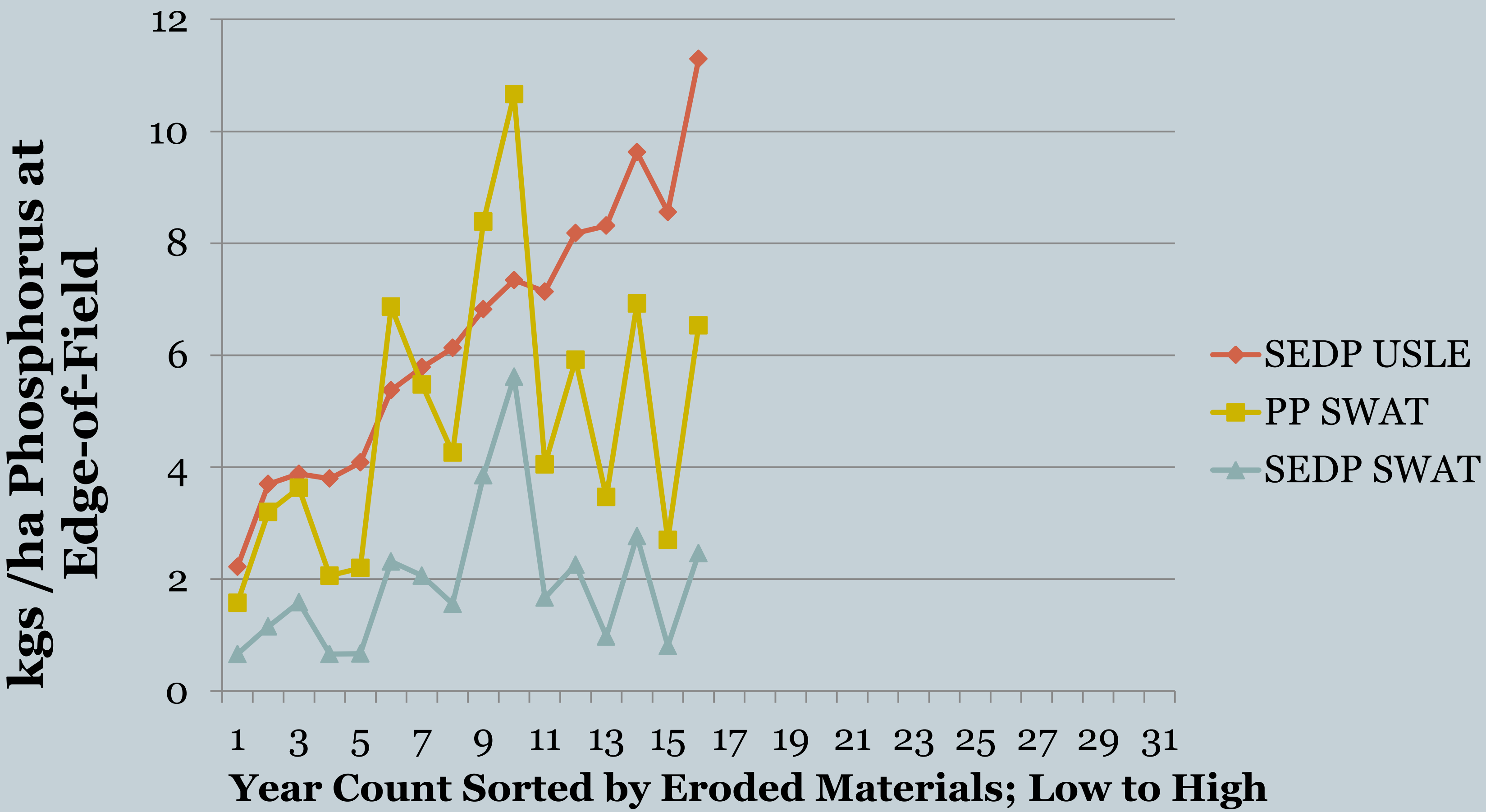
# Particulate Phosphorus Estimates; SWAT Model Versus Region V Comparisons
# (HRU 1061, Simulated Soil Concentrations)





# Checking Illinois Based Approach on Kentucky Field





# Application to KY Field Findings



- Estimated values are slightly higher at lower erosion rates
- Higher erosion rates result in over prediction of phosphorus reductions
- Possibly due eroded subsoils with lower organic and nutrient concentrations; versus eroded materials consisting of only nutrient enriched topsoils
- Considering appropriate crediting approaches (e.g., using TP soil test results times a discount factor, 75% and/or not applying equation to sites with subsoil erosion)

# Overall Findings: Measured Soil TP Benefits Credit Estimation



- Reduces uncertainty (i.e., in low TP soils)
- Introduces acknowledgement of eroded organic materials
- Should consider whether or not subsoil erosion is evident
- A conservative discount factor is suggested (e.g., 75 percent of actual test value)
- Credit volume per acre increased in soils with high soil carbon (soil organic matter)

# Nitrogen Crediting Challenges



- "The best laid plans of mice and men / Often go awry" Robert Burns' poem, "To a Mouse"
- Project Team was advised at every turn by many experts that proper nutrient management would lead to reduced nonpoint source loading; but loading reductions are frequently interrupted by weather variability

As such, the Project Team focused on the fraction that may be predictable (N associated with erodible materials), rather than the fraction that is less predictable (soluble)

# Nitrogen Loss to Surface Waters



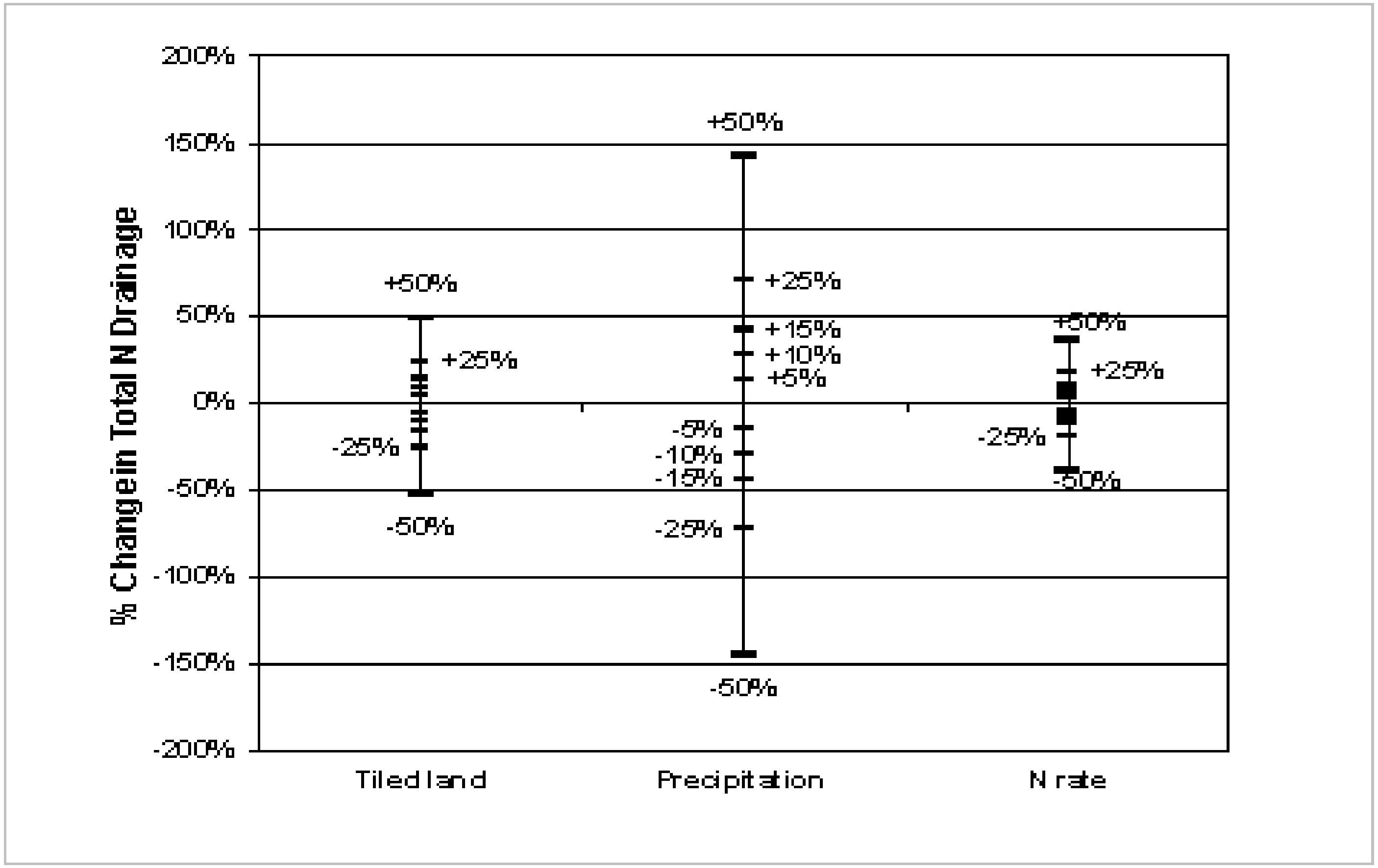
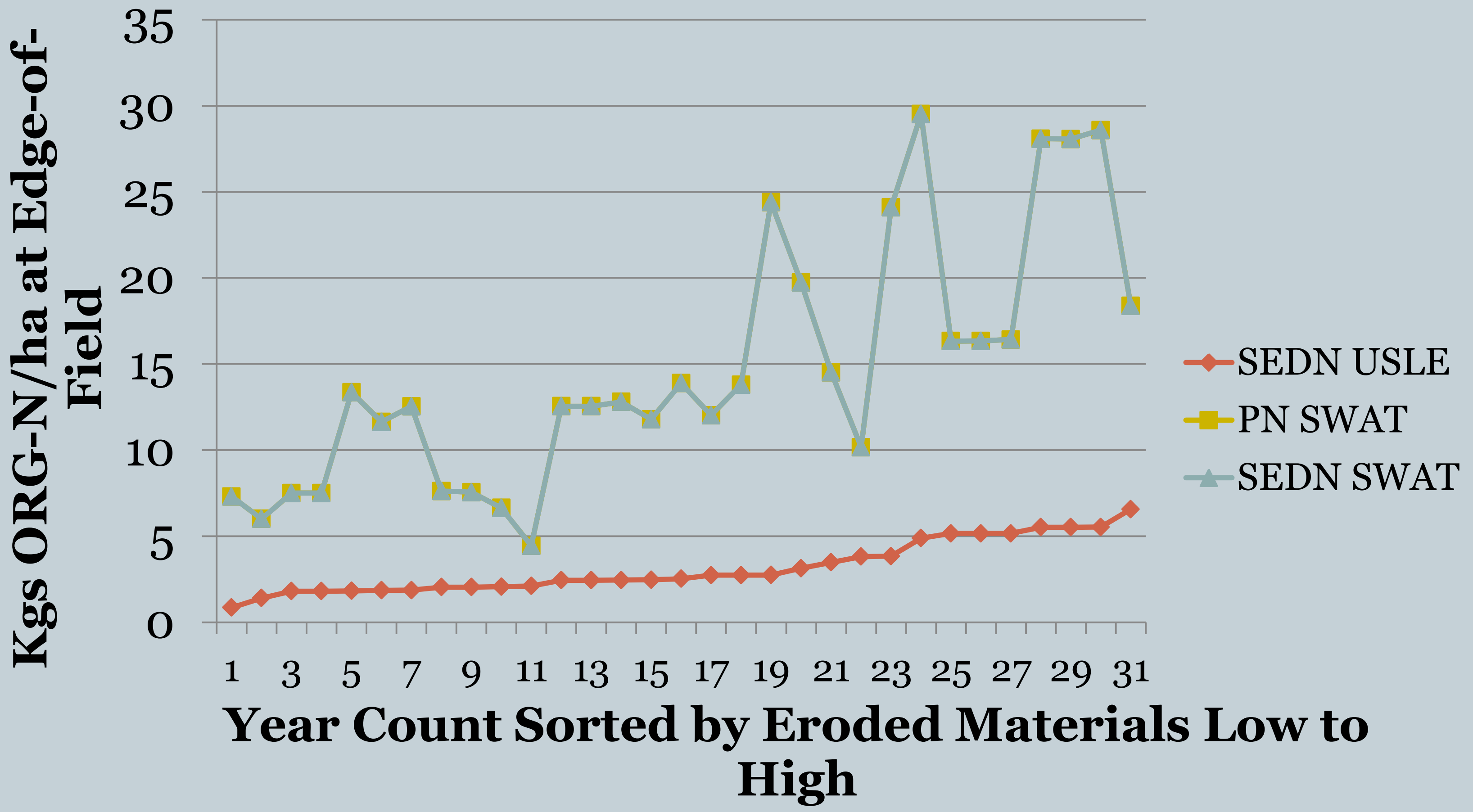



**Figure 1. Sensitivity analysis for nitrogen losses in agricultural drainage**

(MPCA. 2013. Nitrogen in Surface Waters (report). Accessed December 12, 2015 online at: http://www.pca.state.mn.us/index.php/about-mpca/mpca-news/featured-stories/report-on-nitrogen-in-surface-water.html)

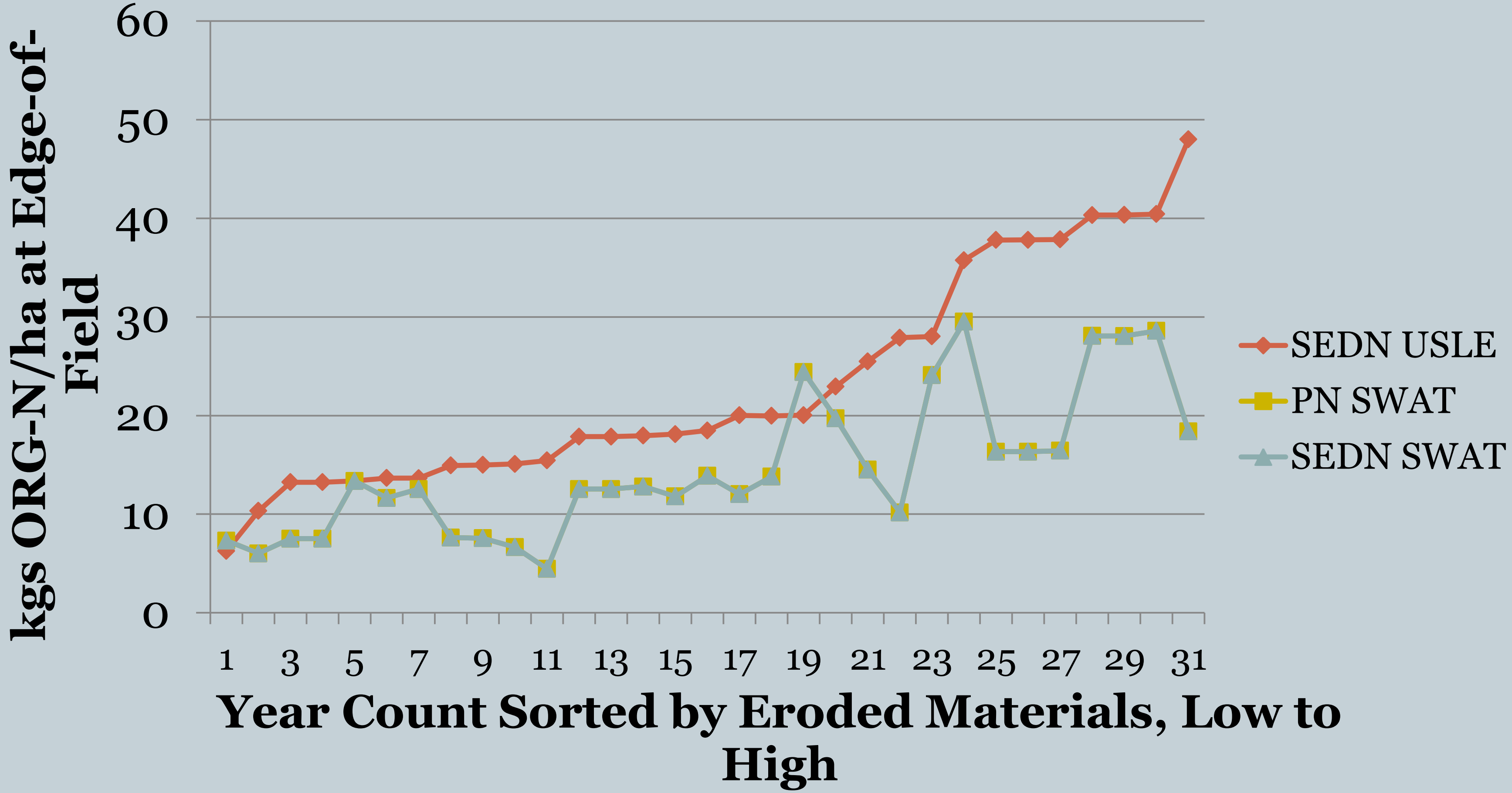
# Particulate Nitrogen Estimates; SWAT Model Versus Region V Comparisons (Default Values)





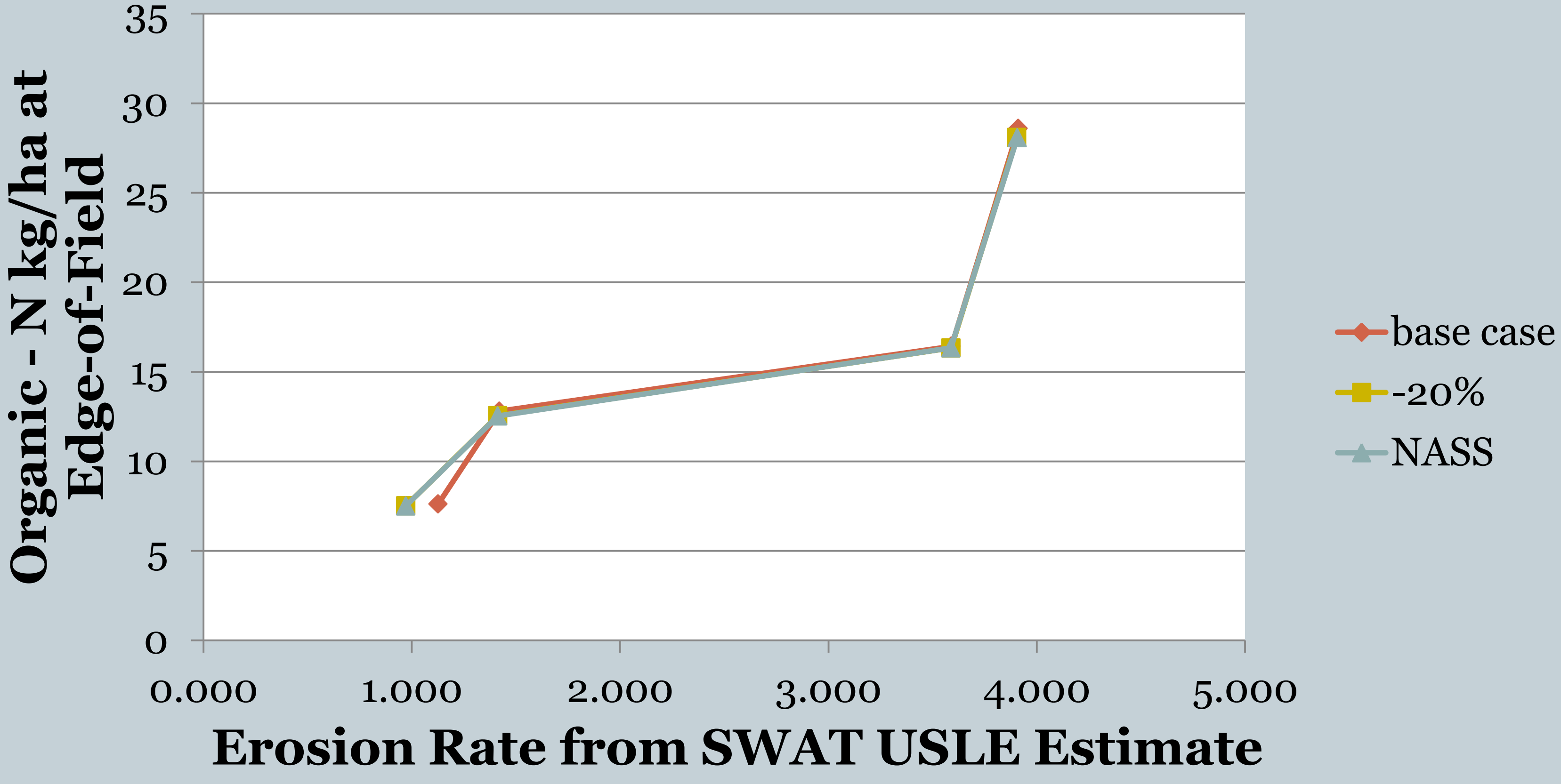
# Particulate Nitrogen Estimates; SWAT Model Versus Region V Comparisons (Simulated Soil Concentrations)





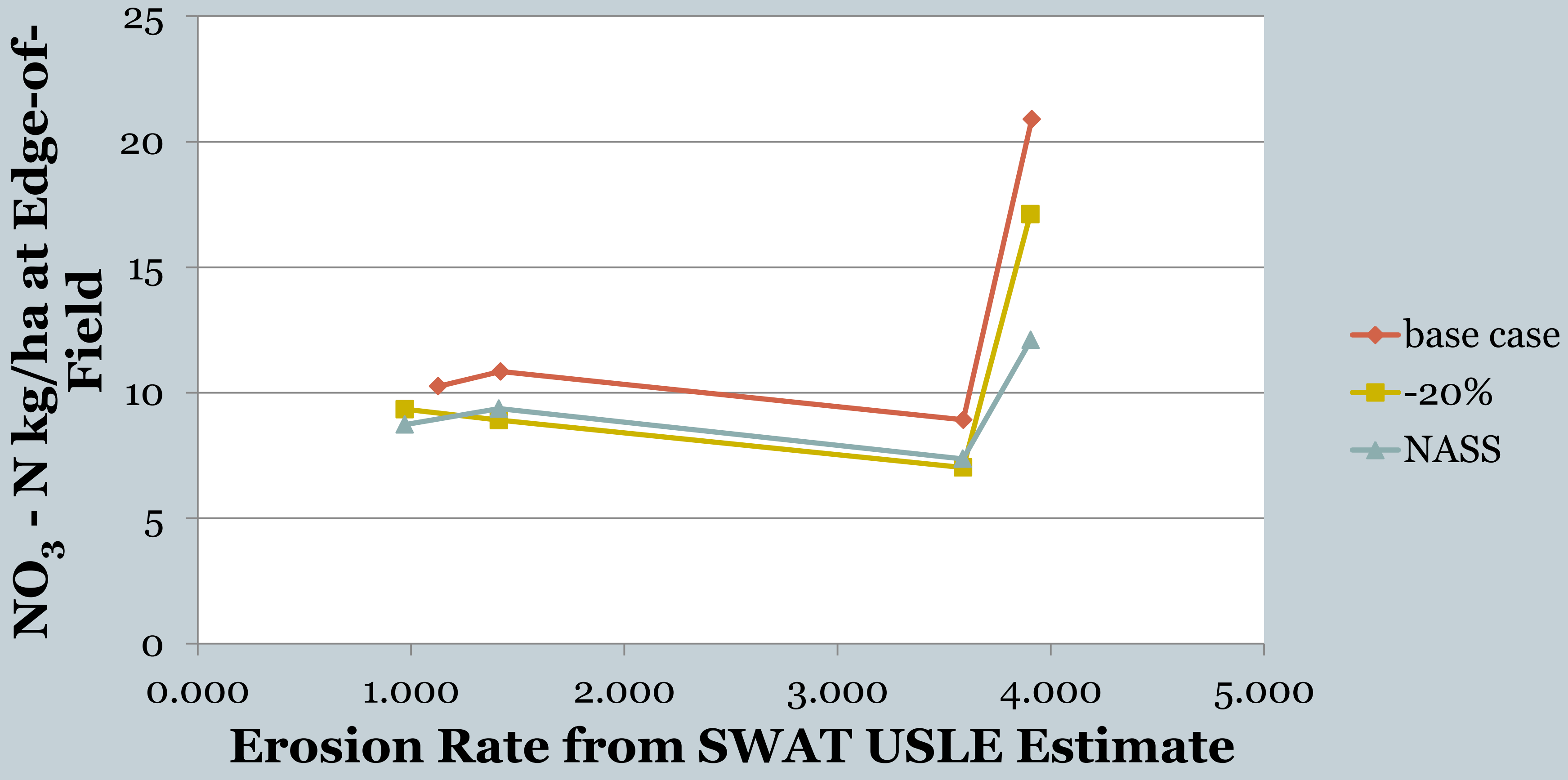
# HRU 1061 Organic Nitrogen Edge-of-Field Comparisons for Corn Years





# HRU 1061 $NO_3$ Nitrogen Edge-of-Field Comparisons for Corn Years





# Use of Soil Tested Organic Nitrogen



Evaluation illustrates:

- Region V model predicts organic – N edge-of-field loading adequately
- Method can over estimate the credit's value
- Hydrologic soil type (and enhanced drainage matter); as there is little interflow occurring in the scenario

However, nitrate nitrogen is where reductions occur when the practice is nitrogen application rate reduction

Considering options for appropriate crediting estimation

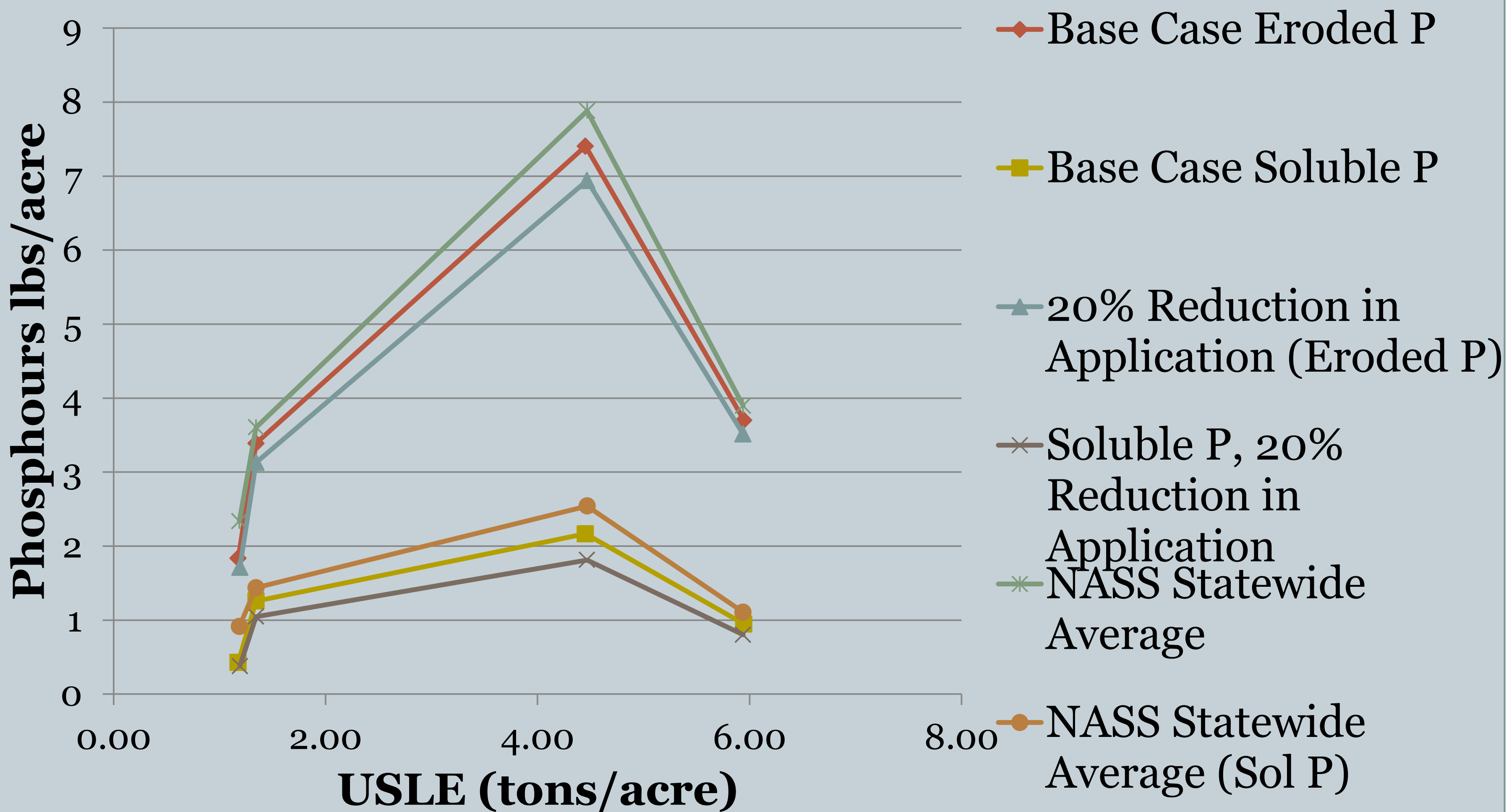
# Region V Model Considerations



- Region V estimates sediment attached nutrients and organically bound nutrients that move during erosion events
- There is a soluble nutrient reduction that is not being used in credit estimations; should consider this as an implicit margin-of-safety
- USLE (and now RUSLE) estimate is a long-term average value of tons of sediment / acre
- What is the yearly variation when using one USLE estimate?

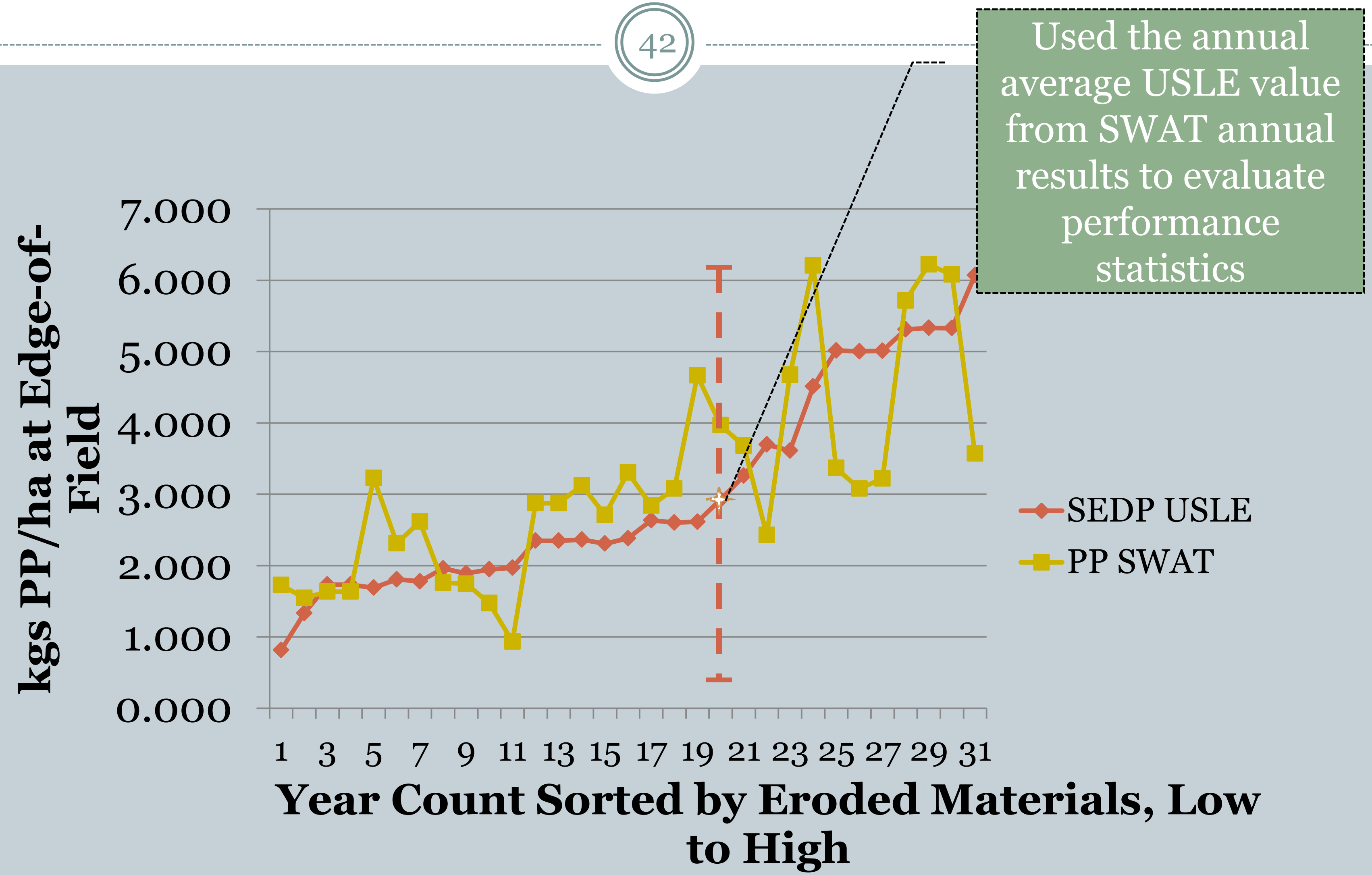
# HRU 645 Phosphorus Scenario Edge-of-Field Comparisons for Corn Years





# Particulate Phosphorus Estimates; SWAT Model Versus Region V Comparisons (HRU 1061, Simulated Soil Concentrations)





# Summary of TP Results Using Default Soil Concentrations vs. Simulated



| HRU | Soil Organic Carbon (%) | Average Soil TP Conc. (ppm) | Average SWAT USLE (kgs/ha) | SWAT PP Yearly Average (kgs/ha) [Std. Dev./CV] | Region V Model Scenario Using Soil Concentration Estimates | USLE PP Yearly Average (kgs/ha) [Std. Dev./CV] |
|---|---|---|---|---|---|---|
| 645 | 1.92 | 524 | 3,327 | 4.34 [2.26 / 0.52] | Default | 2.36 [1.17 / 0.498] |
| | | | | | Measured | 2.48 [1.26 / 0.51] |
| | | | | | | |
| 1061 | 2.92 | 949 | 2,013 | 3.17 [1.44 / 0.46] | Default | 1.58 [0.76 / 0.48] |
| | | | | | Measured | 3.01 [1.45 / 0.48] |

# Preliminary Recommendations



**VARIABLE RATE TECHNOLOGY; WATER QUALITY CREDIT TRADING ESTIMATION METHOD DEVELOPMENT**

# Preliminary Recommendations



VRT based fertilizer applications generate credits when:

- Zone mapping is used
- Agricultural producer substantially exceeds agronomic rates
- Evaluation indicates the Region V model approach to be adequate for phosphorus, if:
  - Trade ratio is 2.5 to 1.0, or 3.0 to 1.0
  - Consideration of soluble P reductions as implicit margin-of-safety may allow 2 to 1.0
- Collect soil nutrient tests for total P
- Apply a discount factor to soil's total P concentration
- Combined use of soil carbon (soil organic matter) and moderate erosion rates can be used as important indicators for high potential sites

# Next Steps



- Desire credit estimation method for nitrogen
- Data proofing
- Formalize equation protocol
- Further evaluation of Illinois equation on Kentucky site to inform use of discount factor
- Finalize calibration of Region V input coefficients AP and BP (For illustration purposes only; field scale calibration of Region V model for each soil type is not considered to be practical.)

# APPENDIX 2: TECHNICAL REPORTS

1. Soil and Water Assessment Tool Application for Developing a Credit Estimation Method for Precision Agriculture

2. Water Quality Credit Trading: Credit Estimation Method Development

3. VRT with Auto-steer Systems and Section Boom Control

4. Final Draft Report: May 2015. Viability and Potential for Stacking Greenhouse Gas (GHG) and Water Quality Credit Trading (WQCT) Credits

# APPENDIX 2

## Item #1. Soil and Water Assessment Tool Application for Developing a Credit Estimation Method for Precision Agriculture

# Soil and Water Assessment Tool Application for Developing a Credit Estimation Method for Precision Agriculture
# November 2015

## Introduction

Water Quality Credit Trading (WQCT) programs need repeatable and science-based credit estimation methodologies that provide reasonable and practical levels of precision and efficacy when assessing reductions of nutrient loads by conservation practices. For this reason, WQCT programs sometimes have created a list of eligible conservation measures that is based on those best management practices (BMPs) that have established United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS) practice standards and quantification protocols accepted by the National Pollutant Discharge Elimination System (NPDES) permitting regulatory agency. These policies provide the necessary assurance that trading estimates of nutrient reductions at the edge-of-field will be equivalent to the scenario where a discharger upgrades their treatment facility.

This paper reports the results of a Soil and Water Assessment Tool (SWAT) application for developing a credit estimation method for precision agriculture using variable rate technology (VRT). Background on credit estimation for WQCT and project goals are described. Methods to meet those goals are then outlined for two study sites, fields in Kentucky and Illinois. Model calibration is described for the two sites. Results of model scenario runs are reported for each site separately, first for the Kentucky site and then for the Illinois site. Finally, a summary of the results and conclusions drawn are provided, as well as suggestions for further work.

## Background

Programs implementing WQCT use many policies and discount factors to establish a working framework that provides equal or greater environmental protection compared to a wastewater treatment facility upgrade. In addition to the policies requiring practice standards and approved credit estimation methods, another typical trading framework component is the use of trade ratios. Trade ratios can consist of multiple components to assure equal or greater water quality protection. A common, major component is the use of margins of safety to address the uncertainty introduced by the credit estimation methods and climatic variability. For example, if there is potential for year-to-year variability in the edge-of-field loading then an adequate margin of safety must be provided to address the variability in loading rates. Likewise, if the credit estimation method does not take into account differences in soils and nutrient application rates the margin of safety must be increased accordingly. Addressing these uncertainties can be explicit in the form of a component of the trade ratio, or implicit by using conservative assumptions. Precision agriculture does not have a credit estimation method developed for use in the Midwest, primarily because many programs are using crediting methods that address only the sediment attached or organically bound fractions (particulate fractions) of nonpoint source nutrient loads. The potential environmental benefits when using precision agriculture to achieve appropriate agronomic rates often show up in reductions in soluble nutrient loadings as well as the particulate fraction.

The first goal of this project is to assess the viability of creating a credit estimation method for precision agriculture practices specific to nutrient application rates. These practices include implementing VRT which can be accomplished in many different methods including on-the-go applicators, zone mapping, and section boom control. The second goal is to create easy-to-use, conscientious credit estimation methods for practices found to be viable, that can be applied by existing field conservation technicians.

The ability to provide environmental protection in an easy to use method perceived as user-friendly by local technicians is vital to optimizing the cost-effectiveness potential of WQCT. Therefore, the development process for an approvable credit estimation method must balance three characteristics to be successful. The first characteristic, as stated, is to provide environmentally protective results. As discussed above, the use of trade ratios, implicit conservative assumptions, and approved design standards and assessment techniques can appropriately address this issue. The second characteristic is to develop a tool that can be easily run by existing field conservation staff. This characteristic assists WQCT programs by being able to leverage existing local conservation staff that can operate the tools instead of requiring a water quality modeler, which is a special skill set. The third characteristic is to manage the WQCT credit estimation method's required list of inputs. The management of this characteristic is based on assessing the model's results and improvement in accuracy when using collected field measurements versus a protocol that uses default values instead of measured values. Understanding the estimation method's inherent variability associated with the model's sensitivity to each coefficient and the range of variability of the coefficients, can be used to assist management decisions when determining if the expense of collecting field data is warranted. Mismanagement of each of these three characteristics has the potential to result in environmental impacts or higher transaction costs.

Lastly, the flexible NPDES permit compliance option of WQCT can provide cost-effective benefits for environmental compliance if applied appropriately. A WQCT program will be most viable and cost-effective when clear and transparent methods are used and the program is developed in a manner that avoids overly conservative approaches when possible.

## Methods

Key to nutrient management are the "4Rs," as identified by the USDA NRCS. The "4Rs" are the "right rate," "right time of application," and "right placement," while using the "right source."

In order to evaluate if nutrient application reductions used in precision agriculture would be able to generate WQCT credits, a water quality analysis of two farm fields was completed. The two farm fields, one in Kentucky and the other in Illinois, both have a long history of applying VRT practices. The field in Kentucky applied variable phosphorus (P) fertilizers in a corn year (2010) based on gridded soil samples from the field. The producer utilized on-the-go VRT nutrient application methods. The field in Illinois applied both nitrogen (N) and P fertilizers based on VRT map zones that in turn closely followed the SSURGO (Soil Survey Geographic Database) soil map zones of the field. A VRT zone map allows the Global Positioning System (GPS) guidance system to apply different rates of nutrients based on the agronomist recommendations considering the changes in soil classifications and historic yield records.

The project team used the SWAT model to examine changes in P and N loading at the edge-of-field to compare operations that followed precision agriculture practices with other nutrient management approaches. This evaluation considered the range of reductions achieved and the predicted variability in the reduction of edge-of-field for N and P loading across different time periods, as well as annual yield, to inform a discussion on what is needed for WQCT crediting methodologies to be technically viable. In the first stage, a base case model was developed for each field based on the unique field conditions and operation record at each study site.

To test the VRT benefits using the "4Rs" principles, two stages of modeling scenarios were developed. The first stage used data from the base case models for each site. One scenario, applied to both the Kentucky and Illinois fields, assessed the difference in the "right rate" by switching fertilizer application rates from the VRT base case to the relevant statewide National Agricultural Statistics Service (NASS) survey rates. In addition, for the Illinois field, the base case was compared to a 20 percent reduction of both N and P fertilizers. Two other scenarios assessed the "right time" and "right placement" components of the "4Rs." The differences in results for a change in the phosphorus application placement and timing were assessed at the Kentucky site.

In the second stage, to assess long-term influence of climatic and soil nutrient variability on crediting, extended period (40-year) SWAT models were built for the two study sites. These models were used to simulate the long-term effect of VRT on nutrient loading from the fields. In addition, these extended period models provided data for developing predictive tools for nutrient loading quantification.

**Study Sites**

Two study sites were provided for this project based on the availability of field operation record, including VRT implementation, and the landowners' willingness to provide data and cooperate with the project team. Both sites have a typical corn-soybean rotation of the Midwest.

The first site is a 124-acre field located in north central Kentucky (Figure 1). This field has been in no-till for over a decade. The field is not artificially drained. The majority of the soil in the field has a slope between 2~10 percent. Nicholson silt loam and Lowell silt loam are the two dominant soil series.

The second site is a 159-acre field located in north central Illinois (Figure 2). Except for a 10-12 inch deep chisel plowing before each corn planting, the field does not have any other tillage operations. The field is tile-drained in depressions with a tile depth around four feet. Nearly all of the soils in the field have a slope less than 2 percent. Ashkum silty clay loam and Elliott silty clay loam form the majority of the soil series in the field.

Figure 1: Google image of the Kentucky study field.


Figure 2: Aerial photo and soil map of the Illinois study field.

## Modeling Approach

There are three models most widely used in the United States for simulating agricultural and environmental processes in agricultural land from field to watershed scales: 1) EPIC (Erosion-Productivity Impact Calculator);2) APEX (Agricultural Policy/Environmental eXtender); and 3) SWAT (Soil and Water Assessment Tool). These models were developed by the USDA Agricultural Research Service (USDA-ARS) and Texas A&M University, Texas AgriLIFE research units located in Temple, Texas, at the Grassland, Soil and Water Research Laboratory (GSWRL), and Blackland Research and Extension Center, respectively (Gassman et al., 2010). They share algorithmic roots in hydrology simulation, sediment yield, crop growth, nutrient cycling, and sediment and nutrient routing, although various improvements and modifications have been made to these models to better suit them for different modeling purposes.

### Model Selection

Among the three models, EPIC was the first one developed in the early 1980's to simulate the field scale relation between soil erosion and soil productivity (Williams, 1990). The SWAT model was later developed to simulate watershed scale processes by integrating various related field scale models including EPIC with watershed processes such as routing flows through channels and reservoirs (Neitsch et al., 2011). APEX was then developed in the 1990's for modeling at the farm or small watershed scale. Due to its background of developing a tool for the National Pilot Project for Livestock and the Environment (NPP), APEX has additional algorithms to simulate livestock operations including pasture and feedlots (Gassman et al., 2010).

Because EPIC algorithms are integrated in APEX and SWAT and the latter two models have additional capabilities to simulate among others, nutrient cycling and groundwater hydrology, the project team considered only APEX and SWAT for use in this study. In addition, because there were no flow or water quality data available for the study, crop yield calibration became the key component in model calibration and hence model selection.

Both APEX and SWAT use the same heat units based biomass accumulation growth model adopted from EPIC and its predecessor models (Williams et al., 2012; Neitsch et al., 2011). Water, nutrient, and temperature needs/stresses were accounted for in the growth model, although APEX and SWAT have slightly different parameters in some corresponding equations. A major difference between APEX and SWAT in crop growth simulation is that APEX has the additional capability of simulating mixed stands of up to 10 crops/plants in a competitive environment. This is a particularly important function for simulating crop management practices such as cover crops. However, in this study, only a single crop growing in a single season was simulated. Therefore, in terms of crop yield simulation and calibration, either APEX or SWAT would meet the project needs.

The project technical advisory committee was inclined to recommend the APEX model for the study due to its designed application scale of a field/farm. The project team explored the possibility of using APEX and its beta-version ArcGIS interface. It was found that the beta-version ArcGIS interface had significant issues. As a result, it would require significant time to manually develop model input files and various field management scenarios. The project had a tight schedule (although it was later extended) and a longer model input development phase and difficulty in management scenario development would reduce available project time and resources for studying the relationships between VRT and nutrient load reduction and developing tools for quantifying such relationships. In addition, because the study areas in the project were two separate single fields, APEX did not offer any advantage over SWAT in terms of model scale applicability. Consequently, it was decided that SWAT would be used as the modeling tool for this study.

SWAT Model

Modeling of the two fields with VRT for nitrogen and phosphorus applications was conducted using USDA's SWAT Version 2009 (Neitsch et al., 2011; Arnold et al., 2011) and its companion ArcGIS model interface ArcSWAT Version 2009.93.7b (Winchell et al., 2010). SWAT is a basin-scale computer model designed for assessing watershed-scale impacts of conservation management, particularly for agriculture dominated watersheds. It simulates the growth of agricultural crops and other vegetation in the watershed, the interaction between the crops and the soil for water, nutrient and organic matter exchanges, and losses of soil and nutrients from the watershed.

The construction of a SWAT model requires input of various data depending on the purpose of the model. For this project, four main types of input data were collected and processed: field elevation/slopes, soil characteristics, meteorological data, and agricultural field operations.

**Model Input data for the Kentucky Site**

Field elevation data for the Kentucky site were provided by Dr. Tom Mueller (of the University of Kentucky at the time) through his research program. The elevation data were derived from the Light Detection and Ranging (LIDAR) dataset and had a resolution of about 10 feet. Slopes of the field were calculated based on the elevation data as part of the subwatershed delineation process for the study field by the ArcSWAT program.

Soil characteristics data were obtained through the USDA NRCS Soil Survey Geographic Database (SSURGO). These soil data were processed and incorporated into the SWAT model using the SWATioTools program developed by Dr. Aleksey Y. Sheshukov at Kansas State University.

Meteorological data, including daily precipitation, daily maximum and minimum temperatures, wind speed, relative humidity, and solar radiation were collected from two main sources and processed to be incorporated into the SWAT model. These sources were NOAA's National Climatic Data Center (NCDC) and the Kentucky MESONET[1]. NCDC data from the Crestwood station near the study site were used to construct the SWAT input file each for daily precipitation and daily minimum and maximum temperatures. Data from four MESONET stations from counties of and near the study site, were utilized to composite one single SWAT weather input

[1] The project team would like to acknowledge the Kentucky MESONET (http://www.kymesonet.org/) for processing and providing, free of charge, meteorological data to this project. Special thanks go to Dr. Stuart Foster and Mr. Andrew Quilligan of Western Kentucky University and the MESONET for their assistance.

file each for wind speed and relative humidity, according to the stations' record availability and distance to the study site. The NCDC's modeled solar radiation data from Lexington, Kentucky were joined with MESONET data to form the input file for solar radiation. These composited weather files have a record period of January 1, 2004 through December 31, 2011. They were used for the SWAT simulations of the study field for model calibration and the first stage of nutrient loading analysis for variable rate technology.

The second stage of model simulation and nutrient loading analysis involved the expansion of the simulation period from the five-year period of 2007-2011 where field operation and harvest data were available to the 40-year period of 1972-2011. Field operation and harvest data were not available for the earlier years of 1972-2006. Historical NCDC data from three stations near the study site, Shelbyville, Crestwood, and Frankfort Lock #4, were used to composite one single SWAT input file each for daily precipitation, and daily minimum and maximum temperatures for the 40-year period. Wind, solar radiation, and relative humidity were generated by SWAT Weather Generator.

Field operations, along with field soil fertility test results and crop yields, were provided by the landowner. Field operations include the timing of planting and harvest, fertilizer applications, and type, amount and method of fertilizer applied. Because the study field had been under no-till for over a decade, no tillage information was entered in the model.

**Model Input Data for the Illinois Site**

Federal agency data services provided field elevation/slope, soil and meteorological data. Field elevation data were downloaded from USGS's National Map Viewer (http://viewer.nationalmap.gov/viewer). The elevation data had a resolution of about 10 meters. The ArcSWAT program calculated slopes of the field based on the elevation data as part of the subwatershed delineation process for the study field. Soil characteristics data were obtained through the USDA NRCS Soil Survey Geographic Database (SSURGO). These soil data were processed and incorporated into the SWAT model using the SWATioTools program.

Meteorological data, including daily precipitation, daily maximum and minimum temperatures were collected from NOAA's National Climatic Data Center (NCDC) and processed to be incorporated into the SWAT model. Data from various available stations around the study sites were collected and composited to form a single weather record for the 40-year period of January 1, 1974 through December 31, 2013. Missing data were obtained from available stations in order of their distance from the study site. There were no reliable sources of continuous humidity, wind, or solar radiation data within a reasonable distance of the study site. As a result, the built-in SWAT Weather Generator function was utilized to produce these data based on historical records at over 1,000 weather stations in the contiguous United States.

Field operations, along with field soil fertility test results and crop yields, were provided by the landowner and their crop production consultant. Field operations include the timing of plant and harvest, tillage operations, fertilizer applications, and type, amount and method of fertilizer applied. Any missing information for the Illinois site was estimated with general crop growth practices in Illinois, the Upper Midwest and best professional judgment.

## Simulating Variable Rate Technology in SWAT

SWAT uses the concept of hydrologic response unit (HRU) to carry out basic model calculations. Each HRU is a unique combination of soil, slope and land use (or crop planted). The ArcSWAT model interface does not allow direct consideration of variable rate of fertilizer application during the formation of HRUs. To resolve this issue, variable rate application zones were created in the model for both study sites by generating different versions of the same crop ("dummy crops") that were identified under separate names in order to be able to input different nutrient application rates. The dummy crops were created in the SWAT Land Cover/Plant Cover/Plant Growth database. These dummy crops were distributed in the study field to match the variable rate zones used by the landowner and crop consultant. These zones were then used as the land use dataset in the HRU definition phase of the SWAT model development. For this study field, the variable rate zones largely follow the USDA NRCS soil survey delineation of soil series boundaries.

For the Kentucky site, initial soil soluble P in SWAT was based on soil test phosphorus (STP) analysis of soil samples from the study site in 2007, the first year of model base case simulation. The STP analysis used for soil samples from the field was Mehlich III extraction. For the Illinois site, initial soil soluble P in SWAT was based on STP analysis of soil samples from the study site in 2005, the first year of model base case simulation. The STP analysis used for soil samples from the field was Bray-P extraction. To convert the Mehlich III or Bray-P values to soil soluble phosphorus, a conversion factor of 2.5 was then used to subsequently convert from Mehlich III P (soluble P = Mehlich III phosphorus/2.5) to SWAT soil soluble phosphorus. This conversion factor was based on the SWAT definition for various mineral phosphorus components, including soluble phosphorus (Neitsch et al., 2011), and a study by White et al. (2007). Bray-P was first converted to Mehlich III phosphorus based on studies by Sawyer and Mallarino (1999) and then the same factor of 2.5 was used to obtain soil soluble P.

## Model Calibration

Because neither of the two studied fields was monitored for flow or water quality, model calibration was done only for the crop yield by modifying the crop growth factors of RUE (radiation-use efficiency of the plant) and/or GSI (maximum leaf conductance, related to plant transpiration rate). Duration of the model simulations for calibration was determined by the available farm operation data provided by the landowner.

### <u>Kentucky Site Model Calibration</u>

The model set up for yield calibration for the Kentucky site was the five-year crop rotation started in 2007 and ended in 2011: soybean-corn-soybeans-corn-soybeans. Model output from the first year of simulation (2007) was not used in the calibration so that model parameters, especially those related to nutrient and water balances in the soil, could be stabilized. Yield information was provided by the landowner.

Due to the importance of soil loss in determining nutrient loading from agricultural fields and the role of sediment loss as an indication of surface runoff from the field, adjustments of sediment yield from the fields were conducted in addition to crop yield calibration for the Kentucky site. This sediment yield adjustments were based on: 1) common literature values for SWAT parameters related to surface runoff (CN2-initial SCS runoff curve number for moisture condition II [Waidler, et al., 2009; Almendinger and Ulrich, 2012; Arabi, et al., 2008], OV_N-Manning's "n" for overland flow [Almendinger and Ulrich, 2012; Arabi, et al., 2008]) and sediment yield (USLE_C-Universal Soil Loss Equation C factor [Arabi, et al., 2008; K&A, 2005]) in the Midwest; and 2) best professional judgment by Dr. Mueller on a likely magnitude of sediment yield from the study field.

Illinois Site Model Calibration

The model setup for yield calibration for the Illinois site was the nine-year crop rotation started in 2005 and ended in 2013: soybean-corn-soybeans-corn-soybeans-corn-soybeans-corn-soybeans. Model output from the first year of simulation (2005) was not used in the calibration to stabilize the initial model nutrient and water balances. Because no single source of data could provide site specific or complete yield information for this study site, the final yield values used for calibration were a composite of 1) data provided by the landowner and the landowner's assistant, 2) grain delivery reports, 3) un-calibrated harvest maps, and 4) county averages from crop yield surveys reported by USDA-National Agricultural Statistics Service (NASS).

For the Illinois site, default SWAT parameter values were sufficient to produce model sediment yield at a reasonable average rate for no-till operations on flat slopes. No additional adjustments of sediment yield from the Illinois field were conducted.

### Model Scenario Evaluation: First Stage

Scenarios simulated by the SWAT model in this study were constructed to understand the water quality effect of VRT in the context of the "4Rs" in fertilizer application. The "right" amount was examined by estimating the edge-of-field nutrient loss reduction benefits as a result of changing the fertilizer application rates for both study sites. "Right" timing of fertilizer application and "right" placement of fertilizers were also examined for the Kentucky site. The other "R" of the "4Rs" of fertilizer management, "right" fertilizer source, was not considered in this study. The "right" fertilizer source addresses achieving a balanced agronomic supply of all nutrients at the right pH so that the crop growth is optimal. In this way unintended over applications of one nutrient occurring due to crop stress from insufficient supply of another nutrient do not occur.

It is important to note that in this study, a key factor of viability is to assess if the VRT credit generating practice reduces the crop yield. Programs increase their participation potential when designed to promote win-win BMPs, ones that help meet the producer's goals while protecting the environment. To provide this assessment the modeled results for yield and the number of days a crop was experiencing nutrient deficiency stress for either nitrogen or phosphorus was evaluated as part of the scenario review. Then by comparing the results for the different scenarios, with and without using VRT, the project team tracked any identified reductions in crop yield or increases in days the crop was stressed by nutrient deficiencies as simulated by SWAT. Having this caveat for considering WQCT a viable option will enhance producer profitability when participating in WQCT as the program will add to the net profit gained by implementing VRT.

For the Kentucky site, because only the P fertilizer application in the spring of 2010 was a VRT application, model simulations and subsequent analysis were focused on P application and loading. For the Illinois site, its long record of VRT application for both P and N allowed for model simulations and subsequent analysis for both nutrients.

The first stage of model simulations involved several models that aimed to examine nutrient load changes within the calibration time period. In this stage of the simulations, the following two questions were considered:

1) Will the VRT consistently generate nutrient load reductions for WQCT credits in various climatic and cropping conditions? Here we evaluated the ability of the management measures to produce a persistent edge-of-field nitrogen loading reduction that can be used for credit generation, given the natural variability that occurs year-to-year from climatic factors, and differences in crop nutrient dynamics in corn and bean rotations.
2) Will the load reduction variability, monthly or annually, affect the feasibility of using the generated credits in a WQCT program based on EPA trading guidance (EPA, 2003, 2004b, and 2007)? This was essentially an evaluation of VRT's ability to generate water quality credits contemporaneous with the NPDES permit effluent limit averaging period.

The second stage of model simulations expanded the simulation time frame to a 40-year period to examine the long-term effects of variable rate technology and provide data for the development of regression models for load quantification in water quality trading.

Kentucky Site Base-case Model

The Kentucky field, although a typical corn-soybean rotation operation, did not strictly alternate between the two crops every year. For the record provided (2005-2011), 2006 and 2007 were consecutive soybean years. Fertilizer application for corn years generally started with a pre-plant application of P (00-46-00) in the spring. This was also the time where VRT took place in 2010. This pre-plant application was followed by application of both P and N (10-34-00 and 32-00-00) at planting, followed by another N application (32-00-00) about four weeks after the planting. For soybean, generally only P (00-46-00) fertilizer was applied either in the spring before planting or in the fall of the previous year after harvest. An exception was for the 2011 soybean crop, both N and P (18-46-00) were applied in the fall of 2010. These operation conditions were simulated and calibrated in SWAT and are referred to as the Kentucky "base case" scenario in this report.

There were soil tests in 2003, 2007 and 2010. Because the operation record provided started from 2005, 2007 was the first year that soil test and operation record coincided. As a result, the Kentucky "base case" scenario had a five-year simulation period (2007-2011).

Illinois Site Base-case Model

For the Illinois study field operation record provided to the study team, fertilizer applications were carried out three times for corn production: pre-plant application of both N and P (18-46-00 and 21-00-00) in the previous fall of the seeding after soybean harvest, “weed and feed” of N (32-00-00) just before seeding in spring, and sidedress of N (32-00-00) approximately one month after the seeding. For soybean production, in most years neither N nor P fertilizers were applied. Occasionally, some pre-plant applications were made for specific variable rate zones in the previous fall to the seeding. These operation conditions were simulated and calibrated in SWAT and are referred to as the Illinois “base case” scenario in this report.

The application rates were determined by the landowner’s crop consultant for the field and crop using soil test results from soil samples. Soil tests were conducted every other year from 2003 through 2013, the last year of harvest data available for this study. Field operation records started in 2006. As a result, the Illinois “base case” scenario had an eight-year simulation period (2006-2013). Sulfate application was also recommended and made using ammonium sulfate as part of the pre-plant N application. Because SWAT does not simulate the dynamics of sulfate in the soil or for crop growth, sulfate was not considered in this study.

Statewide National Agricultural Statistics Service (NASS) Survey Rate Models for Both Sites

The application rates of fertilizers in both study fields were evaluated against the statewide annual nutrient application rates as surveyed by National Agricultural Statistics Service (NASS) in 2005, 2006, 2010 and 2012 (NASS, 2012) to examine the effects of VRT on the amount of fertilizers used and the subsequent nutrient loads from the fields. For the Kentucky site, because only the P fertilizer application in the spring of 2010 during the calibration period (2007-2011) was a VRT application, the state average survey P rate in that year was used in building the NASS survey rate model for the site. For the Illinois site, NASS survey N and P fertilizer application rates for corn in 2005 and 2010 were averaged to set the annual rates for the corn years of 2006, 2008, 2010 and 2012. NASS rates for soybean in 2006 and 2012 were averaged to set the annual rates for soybean years of 2007, 2009, 2011 and 2013 for the calibration periods (2006-2013).

Twenty Percent Reduction Model for the Illinois Site

The application rates at the Illinois study field were, in addition, evaluated in comparison to a 20 percent reduction of overall N and P fertilizer application rates. The rate for the sidedress N fertilizer application was not reduced so that a sufficient supply of N could be available for corn during the most active N uptake period of corn growth (Bender et al., 2013; Neitsch et al., 2011). The “weed and feed” application rate, on the other hand, was reduced disproportionately to bring the overall N rate down to 80 percent of the base case scenario (overall 20 percent reduction).

Timing of P Fertilizer Application Model for the Kentucky Site

The Kentucky field was also evaluated for a scenario where the timing of the current spring pre-planting VRT P application (late March 2010) was moved to the fall of previous year after harvest (mid-November 2009). This scenario was to explore the importance of fertilizer application timing on nutrient losses from the field or the “right” timing of the “4Rs.”

Placement of P Fertilizer Model for the Kentucky Site

The Kentucky field was further evaluated for a scenario where the current VRT P application by broadcast was changed to soil incorporation. This scenario was to study the importance of fertilizer application method on nutrient losses from the field or the “right” method of the “4Rs.”

**Model Scenario Evaluation: Second Stage**

Due to the short periods of available farm records and the need to understand long-term effects of VRT on nutrient loading from crop fields, key climatic data (temperature and precipitation) were collected over a 40-year period for each of the two study fields and the calibrated SWAT models were extended from the calibration periods to the 40-year periods. The extended 40-year models assumed that over the 40-year periods, field operations of planting, fertilizer application (including VRT applications), and harvesting carried out for the calibration periods were repeated exactly. This allowed the model to track the phosphorus dynamics in the soil and loading from the field with known crop and fertilizer use practices under actual climatic conditions.

Kentucky Site Expanded 40-Year Long-Term Models

For 40-year models, this study created for the Kentucky field a collection of model scenarios to reflect various soil, climate and fertilizer application rate conditions in addition to the base case scenario and the NASS survey rate scenario. These additional scenarios include:

1) An initial available soil P at the 2007 soil test value;
2) An initial available soil P at the highest 2007 soil test result;
3) An initial soil soluble P level at the lowest 2007 soil test result;
4) A one-year precipitation and temperature shift;
5) A VRT rate reduced by 5 percent; and
6) A two-week shift of precipitation and temperature plus a VRT rate increase by 10 percent.

Together, these eight 40-year simulations produced P loading data resulting from a range of field and climate conditions. In addition to showing variation of phosphorus loading under these conditions, results of the simulations also allowed for a statistical analysis of the relationships between P loading and various soil, environment and crop factors. These relationships were then used to build predictive tools for quantifying P load reductions resulting from field operations, including the application of VRT.

Illinois Site Expanded 40-Year Long-Term Model

For the Illinois site, only the 40-year base case model was developed and the model output was used, together with the output from various calibration period models primarily to develop predictive tools for quantifying N load reductions.

## Development of Predictive Methods

The development of predictive methods for quantifying nutrient load and load reductions was focused on using predictors that are readily available or can be estimated with widely accepted field methods, such as crop yield, volume of runoff or soil characteristics such as erosion rates. For example, soil P test and field operation record (P fertilizer applied) can be used for the predictor *plant available P*, USLE family methods for *sediment yield*, and agronomic crop growth formulae for *plant P uptake*. Two types of methods were considered in this study. Both methods were applied to each of the two study sites.

Multiple Linear Regression Method

The first method for predicting nutrient loading selected parameters from crop growth and nutrient transport processes to build multiple linear regression models. The multiple linear regression method afforded a broad applicability in estimating loadings of all nutrient fractions from readily available, calculable, or measurable operation and/or field parameters. The commonly used enrichment ratio based method, on the other hand, calculates only nutrient fractions transported with sediment.

The general format of the multiple linear regression models developed in this study follows:

$$Y = a_o + a_1 X_1 + a_2 X_2 + a_3 X_3 + \ldots + a_n X_n \quad (1)$$

Where,

Y: nutrient fraction to be predicted or the dependent variable (lbs/ac);

$X_{1\sim n}$: crop growth or nutrient transport related parameters or the independent variables (the predictors; units vary);

$a_o$: intercept of linear equation (lbs/ac); and

$a_{1\sim n}$: linear regression coefficients (units vary).

Total P, soluble P and nitrate loads were the dependent variables (Y) examined in this study, although other nutrient fractions could be accommodated as well. A host of potential independent variables were investigated and the following ones were selected as providing the best statistical significance of the resulting linear regression equations. These variables were soil soluble P, P applied as fertilizer, P uptake by crop, sediment yield and crop yield for total P load estimation; and N applied as fertilizer, soil nitrate level and surface runoff generated during the first three months of crop growth for nitrate load estimation.

The initial selection of independent variables in these regression analyses was based on best professional judgment regarding the relationships between edge-of-field nutrient loading and field or environmental factors. After several independent variables were chosen, the screening of these independent variables was conducted using the *p* value of the t statistic for each of these independent variables. If the *p* value of an independent variable in a regression analysis was greater than 0.05, this independent variable would be subtracted and another regression analysis was conducted with the remaining variables. This process was repeated until all variables had a

$p$ value for the t-statistic less than 0.05. Next, the $R^2$ value of the regression analysis was examined against a criterion of greater than 0.5. If the $R^2$ value was greater than 0.5, the regression analysis was accepted; otherwise, other independent variables were considered. Another regression analysis was then conducted with this new set of variables and the process was repeated. The $p$ value for ANOVA F-statistic was always at an acceptable value of less than 0.05 if the statistic criteria for independent variables and $R^2$ values were met. The F-statistic was used to compare to two regressions with similar $R^2$ values.

Existing Enrichment Ratio Method Used for Comparison

The second method was to compare the multiple linear regression results with an enrichment ratio based method for the calculation of sediment and organic P or N that are transported with the sediment as particles (particulate P or particulate N). This method was developed for the CREAMS model (Frere et al., 1980) and is the basis for the current EPA Region 5 as described in the Michigan Department of Environmental Quality 319 Manual of 1999 (MDEQ, 1999) and STEPL model (http://it.tetratech-ffx.com/steplweb/). The equations describing the method for particulate P are:

$$P_p = P_{soil} \times S \times e \qquad (2)$$

Where,

$P_p$: Particulate P (P transported with sediment: sediment P and organic P) from the field (kg/ha);

$P_{soil}$: soil P content (soluble and organic P; fraction, kg/kg soil);

S: sediment loss from the field (kg/ha); and

e: enrichment ratio.

By changing P to N, Equation (2) can be applied to calculate particulate N.

The enrichment ratio is calculated as:

$$e = a \times S^b \qquad (3)$$

where a and b are empirical coefficients with a default value of 7.4 and -0.2, respectively, for both P and N.

In applying the equations, sediment loss can be estimated using the family of USLE equations and the Region 5 STEPL model has a set of default values for soil P and N contents based on soil texture (MDEQ, 1999). In this study, values for these parameters were extracted from long-term SWAT simulation results and used to calibrate the coefficients of the enrichment ratio Equation (3).

The two models, the Multiple Linear Regression developed here and the existing Enrichment Ratio Method, were then compared and examined for approaches/suggestions to verify and/or improve the current protocols when using the existing model.

## Model Calibration

Results from base case model calibration and various models for the examination of effect on nutrient loading by different application rates, timing and environmental factors are described in detail below. Also discussed are applications of the load reduction results to water quality credit generation for the WQCT credit estimation model.

### Kentucky Model Calibration

For the Kentucky study field, crop yield values both as simulated by SWAT and as provided by the landowner are shown in Table 1. The average difference for the four years calibrated was -3.9 percent with a range of -10.8 percent to 6.1 percent. The SWAT simulated sediment losses had an average rate of 3.2 t/ac/yr with adjusted surface flow and sediment yield related model parameters. The rate was on the high end of the 2-3 t/ac/yr sediment loss estimated based on the general knowledge of crop fields in the area. This was likely due to fact that the four years (2008-2011) simulated had a very high average annual precipitation (57.2 in) compared to the county long-term average of 48 inches.

Table 1: SWAT model input, yield output and comparison to actual yields at the Kentucky study site.

| Year | Crop | Precipitation | Nitrogen Application Rate[1] | Phosphorus Application Rate[1] | Actual Crop Yield[2] | Simulated Crop Yield | Yield Difference | Simulated Sediment Loss |
|---|---|---|---|---|---|---|---|---|
| | | (inches) | (lbs/ac) | (lbs/ac) | (bu/ac) | (bu/ac) | % | (ton/ac) |
| 2008 | Corn | 58.0 | 168.3 | 13.6 | 157.4 | 167.0 | 6.1% | 3.6 |
| 2009 | Soybean | 59.0 | 0.0 | 3.9 | 62.8 | 56.6 | -9.8% | 2.3 |
| 2010 | Corn | 42.4 | 180.5 | 25.2 | 175.1 | 156.2 | -10.8% | 1.8 |
| 2011 | Soybean | 69.3 | 0.0 | 0.0 | 38.3 | 37.9 | -1.2% | 4.9 |
| | Total | 228.7 | 348.8 | 42.8 | -- | -- | -- | 12.7 |
| | Maximum | 69.3 | -- | -- | -- | -- | 6.1% | 4.9 |
| | Average | 57.2 | -- | -- | -- | -- | -3.9% | 3.2 |
| | Minimum | 42.4 | -- | -- | -- | -- | -10.8% | 1.8 |

[1] N and P fertilizers were applied in the fall of 2010 for the 2011 soybean crop.

[2] Data provided by the landowner.

### Illinois Model Calibration

For the Illinois study field, as noted, there were some years with incomplete data for yield, notably for the extreme drought year of 2012. Comparing the four sources of crop yield information, data provided by the landowner's assistant indicated the corn yield in the drought 2012 was exactly the same as that in 2010, a normal precipitation year. The grain delivery report and harvest map from 2012 were both incomplete. The landowner himself confirmed a substantial yield reduction in 2012. The NASS county harvest survey was deemed to be the most reliable source of yield data for 2012. The NASS 2012 county average corn yield was 64 bu/ac, very close to the SWAT simulated 63 bu/ac. In fact, SWAT simulation for corn growth showed the crop suffered on average 44 days of water stress in 2012, compared to 11 ~ 19 days for the other seven years simulated.

Comparison of the actual crop yields as reported and the calibration simulation using SWAT for the Illinois site is provided in Table 2. The average difference between simulated and actual crop yield is 0.3 percent with a maximum of 8.3 percent and minimum -8.8 percent. Excluding the extreme drought year of 2012, the average difference between simulated and actual crop yield is 0.8 percent.

Table 2 also provides the simulated sediment losses from the study field. No formal calibration was conducted in the model for sediment losses because no measured sediment data were available. However, using best professional judgment, the SWAT model results were reviewed and determined to be within a reasonable range of erosion rates given the slope of the field and tillage operation practices applied. The eight-year average sediment yield of 2.3 tons per acre per year as simulated by SWAT with default model parameter values was considered reasonable. Compared to the Kentucky site, average sediment yield was lower, likely due to the substantially lower precipitation, lower slope and lower soil erodibility factor (the K factor in USLE) at the Illinois study site.

Table 2: SWAT model input, yield output and comparison to actual yields at the Illinois study site.

| Year | Crop | Precipitation | Nitrogen Application Rate[1] | Phosphorus Application Rate[1] | Actual Crop Yield[2] | Simulated Crop Yield | Yield Difference | Simulated Sediment Loss |
|---|---|---|---|---|---|---|---|---|
| | | (inches) | (lbs/ac) | (lbs/ac) | (bu/ac) | (bu/ac) | % | (ton/ac) |
| 2006 | Corn | 39.9 | 149.9 | 0.0 | 173 | 184 | 6.2 | 2.1 |
| 2007 | Soybean | 39.5 | 48.0 | 30.3 | 46 | 50 | 8.3 | 2.7 |
| 2008 | Corn | 47.5 | 151.3 | 1.6 | 163 | 166 | 2.1 | 3.6 |
| 2009 | Soybean | 45.3 | 48.0 | 30.3 | 52 | 54 | 3.7 | 2.5 |
| 2010 | Corn | 34.5 | 157.1 | 8.1 | 163 | 164 | 0.6 | 1.6 |
| 2011 | Soybean | 36.7 | 40.8 | 17.2 | 48 | 44 | -8.8 | 1.2 |
| 2012 | Corn | 27.0 | 189.9 | 0.0 | 64 | 63 | -1.9 | 0.8 |
| 2013 | Soybean | 32.1 | 34.6 | 28.1 | 51 | 48 | -6.7 | 2.6 |
| Total | | 302.5 | 819.5 | 115.5 | -- | -- | -- | 17.2 |
| Maximum | | 47.5 | -- | -- | -- | -- | 8.3 | 3.6 |
| Average | | 37.8 | -- | -- | -- | -- | 0.3 | 2.2 |
| Minimum | | 27.0 | -- | -- | -- | -- | -8.8 | 0.8 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.
[2] Composite of 1) data provided by the landowner's assistant, 2) grain delivery reports, 3) un-calibrated harvest maps, and 4) county averages from crop yield survey reported by USDA-National Agricultural Statistics Service (NASS).

## Results from Model Calibration Period Simulations for the Kentucky Site: First Stage

As noted above, the first stage of model simulations involved models that aimed to examine nutrient load changes within the calibration time period. In the case of the Kentucky site, the models altered P fertilizer in keeping with right rate, time and placement.

### Kentucky site comparisons of current VRT phosphorus fertilizer application to alternative rate, timing and placement

For the Kentucky site, due to the fact that only the P fertilizer application in the spring of 2010 was a VRT application, the effect of VRT on P loading from the field was limited in the modeled annual results to be for the years 2010 and 2011. Table 3 shows the P annual loads (lbs P/ac) from three different scenarios representing VRT fertilizer application rate versus NASS survey state average application rate (“right” amount), spring application versus fall application (“right” timing), and broadcast application versus soil incorporated.

Table 3: SWAT modeled Phosphorus loads for the Kentucky site in three different fertilizer application scenarios

| “4 R” | Model Parameter | 2010/Corn | 2011/Soybean | Units |
|---|---|---|---|---|
| Right Rate | Current VRT P Application Rate | 59 | 0 | (lbs $P_2O_5$/ac) |
| | P NPS Loading Rate with VRT | 5.5 | 12.5 | (lbs P/ac) |
| | NASS P Application Rate | 99 | 0 | (lbs $P_2O_5$/ac) |
| | P NPS Loading Rate with NASS | 6.2 | 13.6 | (lbs P/ac) |
| | Simulated Crop Yield with NASS | 156.2 | 37.9 | (bu/ac) |
| | P Loading Rate Difference over VRT | 0.67 (+12.1%) | 1.11 (+8.9%) | (lbs P/ac; %) |
| Right Time | Current VRT P Application Timing | Spring | none | |
| | P Loading Rate with VRT | 5.5 | 12.5 | (lbs P/ac) |
| | Alternative P Application Timing | Previous fall | none | |
| | P Loading Rate with Alternative Timing | 5.5 | 12.3 | (lbs P/ac) |
| | Simulated Crop Yield with Alternative Timing | 156.2 | 37.9 | (bu/ac) |
| | P Loading Rate Difference over VRT | 0.0084 (+0.2%)[1] | -0.25 (-0.2%)[2] | (lbs P/ac; %) |
| Right Placement | Current VRT P Application Method | Broadcast | none | |
| | P Loading Rate with VRT | 5.5 | 12.5 | (lbs P/ac) |
| | Alternative P Application Method | Incorporated | none | |
| | P Loading Rate with Alternative Method | 4.8 | 11.2 | (lbs P/ac) |
| | Simulated Crop Yield with NASS | 156.2 | 37.9 | (bu/ac) |
| | P Loading Rate Difference over VRT | -0.76 (-13.7%) | -1.37 (-10.9%) | (lbs P/ac; %) |

[1,2] Differences were calculated with loading values before rounding. These differences are sufficiently small to be considered insignificant (within margin of rounding error).

Compared to VRT, the NASS statewide surveyed rate at the Kentucky study site substantially increased the P fertilizer being used (68 percent), resulting in a 12.1 percent higher P loading from the field in 2010 (Table 3). It is also important to note that this P load increase effect was carried over to the next year, resulting in an 8.9 percent higher P loading in 2011, which was a soybean year with no P fertilizer applied. Based on this model simulation with a limited two-year time frame, it was clear that VRT at the Kentucky study site had a high potential to generate P load reductions and potentially water quality trading credits.

Changing the timing of the P fertilizer application from spring (2010) to the previous fall (2009) did not provide noticeable loading changes, probably due to the fact that 2010 was a relatively dry year at the site. On the other hand, changing application method from broadcast to soil incorporated resulted in a 13.7 percent lower P loading in 2010 and a 10.9 percent lower carry-over loading in 2011. Current VRT P application was broadcast, resulting in 100 percent of the fertilizer being applied on the soil surface in the SWAT simulation; for application method change, only 10 percent was assumed to stay on the soil surface and 90 percent was incorporated in the soil in the SWAT simulation. Based on this limited model simulation, it was clear that “right” placement of a fertilizer, in this case 00-46-00 phosphate, was confirmed to be an important consideration in reducing nutrient losses from crop fields.

In all three cases, model simulation showed no change of crop yield in either of the two affected years, suggesting sufficient P existed in the soil to support crop growth both before and after the alternative practices. In addition to yield, SWAT calculates the crop’s nutrient stress by comparing the actual and optimal plant nutrient levels. It reports the days of the year where the crop is under nutrient stress. For the current VRT base case, SWAT showed virtually no P stressed days for the 2010 and 2011 crops (0.12 days in 2010 and 0 days in 2011). In all three alternative cases, SWAT showed exactly the same numbers of P stressed days for 2010 and 2011as the VRT base case, supporting the conclusion that there was sufficient P using current VRT rate and changing application timing and application method did not affect P availability to the crops. Because of the substantial P load reductions from a lower rate (VRT vs. state survey) and a different application method (soil incorporation vs. broadcast), VRT and soil incorporation would have the potential to generate P load reductions in a WQT program.

## Results from Model Calibration Period Simulations for the Illinois Site: First Stage

The following sections report the results from the Illinois site related to the base case comparisons to model calibration period simulations for NASS survey rates and a 20 percent targeted reduction in application rate. Because of differences from the other study site, Illinois data is available for both P and N fertilizer applications. The Illinois study site was also used to focus on the annual and monthly variations in nutrient loading to further assess the feasibility of using the generated credits in a WQCT program based on EPA trading guidance, which requires benefit during contemporaneous time periods (EPA, 2003).

### Illinois site comparisons of current VRT phosphorus and nitrogen fertilizer application to alternative rates

The longer period of implementing VRT at the Illinois study site allowed for a more detailed simulation and analysis of the potential of VRT fertilizer application in generating nutrient load reductions and potentially water quality credit credits.

Comparison of Illinois site current VRT fertilizer application rates to the Statewide NASS rates

Compared to the statewide rates, the Illinois study field received about 25 percent more N on average but 35 percent fewer pounds of P application for the calibration period, as shown in Tables 2 and 4. On the other hand, simulated yields showed little change between the base case and the NASS case (Table 4), suggesting an over-application of N on the study field and over-application of P for an average farm in the state. Although SWAT was not specifically designed for crop production simulation, the lack of any significant change of yield with the substantial change of nutrient input indicates the amount of P fertilizer used on our study field was appropriate and there was potential for substantially reducing the use of N fertilizers.

Table 4 shows that with the reduced N application and increased P application, the study field would on average lose 6.18 percent less total N but 17.10 percent more total P. In addition, loss difference of total P shows a general trend of acceleration over the eight years of simulation, suggesting a build-up of excess P in the soil. There were some minor losses of yield (1-3 bu/acre) for the first three corn years of the simulation, which would unlikely meet the definition of significant decrease of yield. As SWAT is foremost a hydrologic and water quality model, not a specialized agronomic model, this reduction should be interpreted cautiously as a yield response indicator.

Table 4: SWAT modeled nutrient losses from the Illinois study field: NASS surveyed Illinois state-wide rates of N and P fertilizers

| Year | Crop | Base Case Simulated Yield | NASS Simulated Yield | Nitrogen Application Rate-NASS[1] | Total N Loss - Base Case | Total N Loss - NASS Case | Total N Loss Difference | Phosphorus Application Rate-NASS[1] | Total P Loss - Base Case | Total P Loss - NASS | Total P Loss Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | % | (lbs/ac) | (lbs/ac) | (lbs/ac) | % |
| 2006 | Corn | 184 | 181 | 123.9 | 32.0 | 30.5 | -4.54 | 0.0 | 6.5 | 6.9 | 7.05 |
| 2007 | Soybean | 50 | 50 | 32.9 | 37.6 | 35.5 | -5.67 | 36.9 | 8.0 | 8.5 | 5.87 |
| 2008 | Corn | 166 | 165 | 123.9 | 53.4 | 50.4 | -5.60 | 0.0 | 11.7 | 12.6 | 7.94 |
| 2009 | Soybean | 54 | 54 | 32.9 | 48.3 | 43.4 | -10.12 | 36.9 | 7.2 | 7.6 | 4.97 |
| 2010 | Corn | 164 | 162 | 150.9 | 31.4 | 29.4 | -6.60 | 30.3 | 5.6 | 6.4 | 13.27 |
| 2011 | Soybean | 44 | 44 | 32.9 | 18.7 | 17.7 | -5.12 | 36.9 | 4.5 | 6.1 | 36.65 |
| 2012 | Corn | 63 | 63 | 123.9 | 19.4 | 17.9 | -7.86 | 0.0 | 2.9 | 4.0 | 36.49 |
| 2013 | Soybean | 48 | 48 | 32.9 | 40.4 | 38.8 | -3.94 | 36.9 | 7.7 | 9.5 | 24.59 |
| Total | | -- | -- | 654.5 | 281.2 | 263.6 | -6.26 | 178.1 | 54.1 | 61.6 | 13.95 |
| Maximum | | -- | -- | -- | 53.4 | 50.4 | -3.94 | -- | 11.7 | 12.6 | 36.65 |
| Average | | -- | -- | -- | 35.2 | 33.0 | -6.18 | -- | 6.8 | 7.7 | 17.10 |
| Minimum | | -- | -- | -- | 18.7 | 17.7 | -10.12 | -- | 2.9 | 4.0 | 4.97 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.
See Table 1 for base case application rates.

<u>Comparison of Illinois site current fertilizer application rates to a 20 percent targeted reduction</u>

The previous comparison between base case fertilizer rates and NASS survey rates showed that with the reduced N application and increased P application, crop yields were not negatively affected while nutrient losses from the field decreased or increased respectively. In this second scenario applying a rate change, a 20 percent rate reduction for both nutrients was made to examine the effect. Table 5 shows that N and P losses from the field decreased on average by 5.72 percent and 7.26 percent, respectively. These are much smaller percent reductions of nutrient losses to water resources when compared to the change in fertilizer application rates (-20 percent).

The 20 percent rate reduction for both nutrients did result in a minimal yield reduction for corn, as seen in Table 5. The loss of a bushel or two per acre would likely not be considered a significant decrease of yield. A substantial yield loss would make such fertilizer reductions economically not viable. As indicated previously, SWAT is foremost a hydrologic and water quality model, not a specialized agronomic model. Therefore, this yield reduction should be interpreted cautiously as a yield response indicator. The impact of the 20 percent rate reduction on the four corn-growing years of the model was examined in more detail. The results were very similar when compared to the evaluation for application reduction of NASS compared to base case rates. For data related to N availability, 75 percent of corn years typically show two to five days of N stress for the even years between 2006 and 2012 in most HRU's. More influential for water quality credits, P availability was limited to a lesser extent, with 57 percent of corn and soybean years typically showing one day of P stress in less than half the HRU's.

Table 5: SWAT modeled nutrient losses from the Illinois study field: base case and 20 percent reduction of applied N and P fertilizers

| Year | Crop | Base Case Simulated Yield | Simulated Yield with 20% Reduction | Nitrogen Application Rate after 20% Reduction [1] | Total N Loss with 20% Reduction | % Total N Loss Difference from Base Case[1] | Phosphorus Application Rate after 20% Reduction [1] | Total P Loss with 20% Reduction | %Total P Loss Difference from Base Case[1] |
|---|---|---|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | % | (lbs/ac) | (lbs/ac) | % |
| 2006 | Corn | 184 | 182 | 120.2 | 30.3 | -5.28 | 0.0 | 6.0 | -6.62 |
| 2007 | Soybean | 50 | 50 | 38.4 | 35.6 | -5.30 | 24.2 | 7.5 | -5.87 |
| 2008 | Corn | 166 | 165 | 121.3 | 50.5 | -5.44 | 1.2 | 10.7 | -8.18 |
| 2009 | Soybean | 54 | 54 | 38.4 | 44.2 | -8.37 | 24.2 | 6.8 | -6.31 |
| 2010 | Corn | 164 | 163 | 126.0 | 29.0 | -7.79 | 6.5 | 5.1 | -8.85 |
| 2011 | Soybean | 44 | 44 | 32.6 | 17.6 | -5.71 | 13.7 | 4.1 | -8.70 |
| 2012 | Corn | 63 | 63 | 152.2 | 18.4 | -4.86 | 0.0 | 2.7 | -7.58 |
| 2013 | Soybean | 48 | 48 | 27.6 | 39.2 | -2.98 | 22.5 | 7.2 | -5.97 |
| Total | | -- | -- | 656.7 | 264.9 | -5.79 | 92.2 | 50.2 | -7.17 |
| Maximum | | -- | -- | -- | 50.5 | -2.98 | -- | 10.7 | -5.87 |
| Average | | -- | -- | -- | 33.1 | -5.72 | -- | 6.3 | -7.26 |
| Minimum | | -- | -- | -- | 17.6 | -8.37 | -- | 2.7 | -8.85 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.
See Table 1 for base case application rates.
See Table 2 for base case N and P losses.

**Load reduction and water quality credit generation from the Illinois study site based on calibration period simulations**

With simulations of nutrient edge-of-field loading estimates from the base case and the two different alternative fertilizer application rates at the Illinois study site, we can evaluate the consistency and predictability of the change of total N (TN) and total P (TP) losses when reducing fertilizer usage.  Table 6 shows the load reductions for TN.  Because the NASS rates were similar to the 20 percent reduction rates for N, load reductions from the two lower rates compared to the base case were also similar (Columns 6 and 7 in Table 6).

<u>Annual variation of nutrient loading from the Illinois study field</u>

In nonpoint-point source water quality trading, a component of the trading ratio is generally used to account for year-to-year variation of nonpoint source available credits, uncertainties in nonpoint source load reduction calculations, attenuation of nutrients in streams from the credit generating site to the credit using site and other potential factors unrelated to load reduction quantification.  As noted above, uncertainty can be accounted for through explicit trade ratios or through implicit aspects of the model development.

An essential component of trade ratios is a margin of safety to address introduced uncertainty from credit calculations.  It is common to find a margin of safety of 2:1 (EPRI, 2011; MCD, 2005) meaning for every two units of load reduction generated by a nonpoint source, buyers get one unit of the load reduction as their water quality trading credit.  Using this ratio, Table 6

(Column 8) calculated available TN credits from the study field would potentially not be adequate if the WQCT program managers wanted to address extreme droughts. Among the eight years of simulation, the minimum credit is 0.47 lbs/ac (per year) in 2012, when a severe drought took place. The average credit of 1.02 lbs/ac is 2.17 times this minimum value. It is assumed the average credit value could be the actual trading credit assigned to our study field in a trading program. Comparing the eight-year average edge-of-field N reduction and the lowest yielding year (2012) indicates periods of low rainfall generate less than 50 percent of the average of loading years evaluated. This suggests that a 2:1 margin of safety built into the model is not fully adequate to account for climactic variability, particularly in a severe drought year.

Table 6: Summary of SWAT modeled annual total N losses from the Illinois study field

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Year | Crop | Total N Loss - Base Case | Total N Loss - NASS | Total N Loss with 20% Fertilizer Reduction | Total N loss difference between NASS and base case | Total N loss difference between 20% reduction and base case | Potential N Credit with 20% Fertilizer Reduction and 2:1 Trading Ratio |
| | | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) |
| 2006 | Corn | 32.0 | 30.5 | 30.3 | -1.5 | -1.7 | 0.84 |
| 2007 | Soybean | 37.6 | 35.5 | 35.6 | -2.1 | -2.0 | 1.00 |
| 2008 | Corn | 53.4 | 50.4 | 50.5 | -3.0 | -2.9 | 1.45 |
| 2009 | Soybean | 48.3 | 43.4 | 44.2 | -4.9 | -4.0 | 2.02 |
| 2010 | Corn | 31.4 | 29.4 | 29.0 | -2.1 | -2.5 | 1.23 |
| 2011 | Soybean | 18.7 | 17.7 | 17.6 | -1.0 | -1.1 | 0.53 |
| 2012 | Corn | 19.4 | 17.9 | 18.4 | -1.5 | -0.9 | 0.47 |
| 2013 | Soybean | 40.4 | 38.8 | 39.2 | -1.6 | -1.2 | 0.60 |
| Total | | 281.2 | 263.6 | 264.9 | -17.6 | -16.3 | 8.15 |
| Maximum | | 53.4 | 50.4 | 50.5 | -1.0 | -0.9 | 2.02 |
| Average | | 35.2 | 33.0 | 33.1 | -2.2 | -2.0 | 1.02 |
| Minimum | | 18.7 | 17.7 | 17.6 | -4.9 | -4.0 | 0.47 |

The corresponding TP load changes and credit calculations are shown in Table 7. Because the NASS phosphorus rates were actually higher than the base case rates, only the 20 percent reduction case generated TP load reductions and subsequently water quality trading credits. Similar to the TN credit analysis, the lowest TP credit of 0.11 lbs/ac in 2012 is just shy of 50 percent of the eight-year average of 0.24 lbs/ac, suggesting the 2:1 margin of safety/trading ratio built into the model is not fully adequate to account for climactic variability particularly in a severe drought year such as 2012.

The analysis above indicates that selection of an appropriate trade ratio should be completed based on evaluation of many more sites and several long-term weather records. A trade ratio can account for uncertainties as discussed above but also includes attenuation losses, bioavailable equivalence and other policy factors. An adequate trade ratio may need to be greater than the margin of safety ratio of 2:1 to ensure an equal or greater offset depending on the selection of the approved credit value. In the above example, selection of the average credit potential value would need to have a margin of safety that is greater than 2 to 1. Another way to address introduced uncertainty is to use conservative assumptions. For instance using a low percentile value instead of the average of all results could be used. If a lower percentile value based credit value were selected, such as the 35th percentile instead of the 50th percentile, the applied conservative step would allow the explicit margin of safety in the trade ratio to be substantially less.

Table 7: Summary of SWAT modeled annual total phosphorus (P) losses from the Illinois study field

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Year | Crop | Total P Loss - Base Case | Total P Loss - NASS | Total P Loss with 20% Reduction | Total P loss difference between NASS and base case | Total P loss difference between 20% reduction and base case | Potential P Credit with 20% Fertilizer Reduction and 2:1 Trading Ratio |
| | | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) |
| 2006 | Corn | 6.5 | 6.9 | 6.0 | 0.5 | -0.4 | 0.21 |
| 2007 | Soybean | 8.0 | 8.5 | 7.5 | 0.5 | -0.5 | 0.24 |
| 2008 | Corn | 11.7 | 12.6 | 10.7 | 0.9 | -1.0 | 0.48 |
| 2009 | Soybean | 7.2 | 7.6 | 6.8 | 0.4 | -0.5 | 0.23 |
| 2010 | Corn | 5.6 | 6.4 | 5.1 | 0.7 | -0.5 | 0.25 |
| 2011 | Soybean | 4.5 | 6.1 | 4.1 | 1.6 | -0.4 | 0.19 |
| 2012 | Corn | 2.9 | 4.0 | 2.7 | 1.1 | -0.2 | 0.11 |
| 2013 | Soybean | 7.7 | 9.5 | 7.2 | 1.9 | -0.5 | 0.23 |
| | Total | 54.1 | 61.6 | 50.2 | 7.5 | -3.9 | 1.94 |
| | Maximum | 11.7 | 12.6 | 10.7 | 1.9 | -0.2 | 0.48 |
| | Average | 6.8 | 7.7 | 6.3 | 0.9 | -0.5 | 0.24 |
| | Minimum | 2.9 | 4.0 | 2.7 | 0.4 | -1.0 | 0.11 |

Monthly variation of nutrient loading from the Illinois study field

In point-nonpoint source WQCT, the credit generation window is commonly required to be generated during the averaging period used in the NPDES permit for the pollutant parameter. Thereby, if offsetting a point source discharge requirement using a monthly average, the credits must be contemporaneous to the specific month's discharge load. However, while most of the point sources have relatively stable discharge volume and pollutant concentrations from month to month, load reductions generated from agricultural row crop fields vary widely depending primarily on precipitation, crop growth and field management activities. There are notable exceptions where the nonpoint source generation period allows for longer averaging periods to be used. For instance, in Chesapeake Bay, nonpoint source credit generation for trading was allowed to be averaged across a year (EPA, 2004b). In a similar context, the Wisconsin Department of Natural Resources (WI DNR, 2013) justifies using an average annual credit generation window for all nonpoint source phosphorus crediting.

The variation of nutrient load reductions in each of the 12 months over the eight-year simulation period (Table 8) showed that from year-to-year in the majority of months the coefficient of variation (CV) exceeded 100 percent for both nutrients. In other words, the consistency of credit generation in each month across different years is very poor. For example, total nitrogen load reduction in the month of May has the lowest CV at 70 percent among all months and both nutrients. Nevertheless, the minimum load reduction value of 0.122 lbs for May is about only one-fourth of the average value of 0.450 for the month. If the average value were to be used as the load reduction for trading in May, a trading ratio of 4:1 would be needed to fully compensate for this variation in a monthly time period based trading program. With the highest CV of 204 percent, the September total phosphorus trading would need a trading ratio of nearly 300:1. Such a high trading ratio would limit any potential cost benefits of a water quality trading program even if sufficient load reduction could be generated. This indicates that an annual credit generation time period would need to be applied.

Table 8: Monthly variation in load reductions over the base case with 20 percent reduction of fertilizer application across the eight-year simulation period for the Illinois study site

| | Total Nitrogen | | | | Total Phosphorus | | | |
|---|---|---|---|---|---|---|---|---|
| Month | Average | Minimum | Maximum | CV[1] | Average | Minimum | Maximum | CV[1] |
| | (lbs) | (lbs) | (lbs) | % | (lbs) | (lbs) | (lbs) | % |
| Jan | 0.083 | 0.003 | 0.201 | 88 | 0.061 | 0.000 | 0.261 | 138 |
| Feb | 0.110 | -0.004 | 0.319 | 103 | 0.043 | 0.002 | 0.155 | 116 |
| Mar | 0.133 | 0.003 | 0.488 | 149 | 0.034 | 0.005 | 0.074 | 73 |
| Apr | 0.406 | 0.021 | 1.364 | 108 | 0.058 | 0.013 | 0.185 | 102 |
| May | 0.450 | 0.122 | 0.849 | 70 | 0.066 | 0.005 | 0.137 | 81 |
| Jun | 0.186 | 0.012 | 0.607 | 110 | 0.040 | 0.001 | 0.142 | 115 |
| Jul | 0.033 | -0.006 | 0.159 | 166 | 0.036 | 0.000 | 0.145 | 137 |
| Aug | 0.029 | 0.000 | 0.093 | 138 | 0.014 | 0.000 | 0.034 | 117 |
| Sep | 0.017 | 0.000 | 0.048 | 109 | 0.017 | 0.000[2] | 0.100 | 204 |
| Oct | 0.028 | -0.001 | 0.122 | 143 | 0.019 | 0.001 | 0.059 | 110 |
| Nov | 0.243 | 0.003 | 1.077 | 147 | 0.011 | 0.001 | 0.030 | 105 |
| Dec | 0.322 | 0.009 | 1.044 | 108 | 0.086 | 0.014 | 0.220 | 79 |

[1] Coefficient of variation; [2] rounding result, actual value is 0.000057.

## Results from 40-year Simulations for the Kentucky site: Second Stage

The following results apply the Kentucky base case data to long-term climate data to create a 40-year simulation for the effect of VRT. This 40-year base case was then applied to the development of load estimation tools for Total P, Soluble P and Particulate P. Note that to extend the simulations to the 40-year period field operations from the calibration period, including the fertilizer application rates, were not adjusted for field conditions such as soil nutrient levels. They were simply repeated (see Method section). It is important to recognize that the purpose of the 40-year simulations was not to replicate the actual crop yields but to provide SWAT simulated edge-of-field nutrient loadings resulting from a wide range of precipitation, temperature and soil nutrient conditions over an extended period. These data and conditions provide a better understanding of loading variability introduced by field and environmental conditions and, more importantly to this study, the development of load estimation tools.

### Base case scenario

Table 9 lists the edge-of-field loading of P and N components, along with sediment yield, P and N applied as fertilizers, crop yield and precipitation for the 40 years of 1972-2011 as simulated by SWAT for the Kentucky site base case scenario. Phosphorus levels in the soil at the beginning of each year are also present. Excluding the results from the first year of simulation due to model stabilization, Table 9 shows that over the four decade period, for P, sediment bound P (39.5 percent) and organic P (50.7 percent) on average formed the majority of the total P leaving the field. Soluble P, which is the most readily available form of P for plants and algae,

Table 9: Summary of edge-of-field annual loading from the Kentucky study site by the 40-year SWAT base case model

| Year | Crop | Sediment P yield | Soluble P yield | Organic P yield | Organic N yield | Nitrate in surface runoff | Nitrate in lateral flow | Nitrate in groundwater | Sediment yield |
|---|---|---|---|---|---|---|---|---|---|
| | | (lbs P/ac) | (lbs P/ac) | (lbs P/ac) | (lbs/ac) | (lbs N/ac) | (lbs N/ac) | (lbs N/ac) | (tons/ac) |
| *1972* | *Soybean*[1] | *2.39* | *0.19* | *7.02* | *57.20* | *1.61* | *0.91* | *52.11* | *12.71* |
| 1973 | Corn | 1.71 | 0.50 | 2.70 | 20.10 | 1.30 | 1.60 | 83.09 | 2.92 |
| 1974 | Soybean | 0.68 | 0.26 | 1.19 | 7.79 | 0.95 | 0.39 | 17.37 | 1.07 |
| 1975 | Corn | 2.88 | 1.06 | 3.32 | 23.58 | 2.57 | 1.82 | 86.46 | 2.67 |
| 1976 | Soybean | 1.19 | 0.51 | 1.13 | 7.49 | 0.83 | 0.38 | 26.15 | 0.98 |
| 1977 | Soybean | 1.24 | 0.57 | 1.33 | 9.86 | 2.91 | 1.00 | 22.25 | 0.89 |
| 1978 | Corn | 3.19 | 0.83 | 3.40 | 23.22 | 2.50 | 0.69 | 32.30 | 2.39 |
| 1979 | Soybean | 5.18 | 1.19 | 5.59 | 37.44 | 2.32 | 0.55 | 23.29 | 4.51 |
| 1980 | Corn | 0.54 | 0.25 | 0.67 | 4.96 | 3.73 | 1.15 | 26.07 | 0.49 |
| 1981 | Soybean | 1.91 | 0.59 | 1.55 | 10.43 | 1.62 | 0.71 | 32.25 | 1.17 |
| 1982 | Soybean | 1.39 | 0.63 | 1.40 | 10.23 | 1.37 | 0.98 | 29.40 | 0.90 |
| 1983 | Corn | 4.63 | 0.94 | 3.83 | 28.28 | 3.82 | 1.26 | 68.60 | 3.13 |
| 1984 | Soybean | 2.00 | 0.50 | 1.96 | 14.35 | 2.22 | 0.72 | 31.76 | 1.51 |
| 1985 | Corn | 1.32 | 0.47 | 1.39 | 10.32 | 2.06 | 1.41 | 60.43 | 0.94 |
| 1986 | Soybean | 1.91 | 0.52 | 1.83 | 13.14 | 2.55 | 0.49 | 23.33 | 1.34 |
| 1987 | Soybean | 0.72 | 0.24 | 0.81 | 6.51 | 1.23 | 0.52 | 22.33 | 0.60 |
| 1988 | Corn | 1.16 | 0.26 | 1.59 | 13.32 | 1.59 | 0.75 | 28.82 | 1.21 |
| 1989 | Soybean | 2.44 | 0.40 | 3.76 | 29.39 | 3.07 | 0.51 | 33.59 | 3.04 |
| 1990 | Corn | 3.04 | 0.59 | 3.89 | 34.59 | 2.39 | 2.28 | 82.94 | 3.72 |
| 1991 | Soybean | 0.74 | 0.25 | 0.89 | 7.32 | 1.09 | 0.50 | 36.10 | 0.94 |
| 1992 | Soybean | 0.65 | 0.17 | 0.88 | 8.06 | 1.88 | 0.70 | 31.40 | 0.93 |
| 1993 | Corn | 2.33 | 0.34 | 3.24 | 30.79 | 2.31 | 1.41 | 46.07 | 3.72 |
| 1994 | Soybean | 0.89 | 0.15 | 1.90 | 16.71 | 1.33 | 0.53 | 22.02 | 1.93 |
| 1995 | Corn | 1.45 | 0.33 | 2.02 | 20.92 | 3.45 | 2.30 | 72.41 | 2.43 |
| 1996 | Soybean | 1.68 | 0.42 | 2.28 | 20.87 | 2.14 | 0.68 | 45.58 | 2.61 |
| 1997 | Soybean | 1.79 | 0.28 | 2.93 | 29.66 | 2.46 | 0.95 | 57.53 | 3.71 |
| 1998 | Corn | 1.44 | 0.27 | 1.81 | 18.29 | 1.02 | 1.09 | 57.19 | 2.75 |
| 1999 | Soybean | 0.58 | 0.12 | 1.23 | 11.00 | 1.24 | 0.42 | 18.10 | 1.45 |
| 2000 | Corn | 0.74 | 0.22 | 1.28 | 12.99 | 2.62 | 0.85 | 25.77 | 1.40 |
| 2001 | Soybean | 1.10 | 0.26 | 1.60 | 15.69 | 2.14 | 0.84 | 37.40 | 1.89 |
| 2002 | Soybean | 1.92 | 0.34 | 2.76 | 27.60 | 3.21 | 0.87 | 51.26 | 3.74 |
| 2003 | Corn | 1.37 | 0.20 | 2.14 | 21.09 | 1.84 | 1.10 | 52.89 | 3.08 |
| 2004 | Soybean | 1.19 | 0.26 | 2.30 | 21.24 | 3.15 | 0.53 | 30.51 | 2.88 |
| 2005 | Corn | 1.22 | 0.36 | 1.58 | 15.80 | 2.43 | 1.41 | 36.05 | 2.21 |
| 2006 | Soybean | 1.75 | 0.29 | 2.51 | 23.71 | 2.17 | 0.70 | 56.74 | 3.54 |
| 2007 | Soybean | 0.63 | 0.13 | 1.20 | 13.33 | 2.30 | 0.84 | 35.17 | 1.51 |
| 2008 | Corn | 1.85 | 0.48 | 2.81 | 28.28 | 2.62 | 0.87 | 49.07 | 4.07 |
| 2009 | Soybean | 0.82 | 0.11 | 1.79 | 16.42 | 1.34 | 0.42 | 25.80 | 2.51 |
| 2010 | Corn | 0.86 | 0.27 | 1.06 | 11.13 | 1.69 | 1.05 | 23.82 | 1.51 |
| 2011 | Soybean | 2.69 | 0.51 | 3.62 | 36.07 | 2.39 | 1.03 | 73.77 | 5.50 |
| Total | | 64.82 | 16.09 | 83.17 | 711.97 | 83.86 | 36.32 | 1,615.10 | 87.80 |
| Maximum | | 5.18 | 1.19 | 5.59 | 37.44 | 3.82 | 2.30 | 86.46 | 5.50 |
| Average | | 1.66 | 0.41 | 2.13 | 18.26 | 2.15 | 0.93 | 41.41 | 2.25 |
| Minimum | | 0.54 | 0.11 | 0.67 | 4.96 | 0.83 | 0.38 | 17.37 | 0.49 |
| Coefficient of variation | | 62.6% | 60.9% | 51.0% | 48.9% | 36.0% | 51.0% | 47.6% | 54.4% |
| Average % of Total P or N | | 39.5% | 9.8% | 50.7% | 29.1% | 3.4% | 1.5% | 66.0% | -- |

[1] First year of model simulation; model output was not considered in any of the data analyses in this study.

Table 9 (continued): Summary of edge-of-field annual loading from the Kentucky study site by the 40-year SWAT base case model

| Year | Crop | P fertilizer applied | N fertilizer applied | N fixed by plant | Crop yield | Total P yield[2] | Total N yield[3] | Soil soluble P | Soil organic P | Precipitation |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (lbs P/ac) | (lbs P/ac) | (lbs P/ac) | (bu/ac) | (lbs N/ac) | (lbs N/ac) | (lbs P/ac) | (lbs P/ac) | (in) |
| *1972* | *Soybean[1]* | *7.3* | *0.0* | *299.2* | *48.9* | *9.60* | *111.8* | *95.8* | *890.5* | *56.6* |
| 1973 | Corn | 13.5 | 167.2 | 0.0 | 154.8 | 4.92 | 106.1 | 92.0 | 889.7 | 55.5 |
| 1974 | Soybean | 3.9 | 0.0 | 375.4 | 58.5 | 2.12 | 26.5 | 77.9 | 891.4 | 44.5 |
| 1975 | Corn | 25.0 | 179.3 | 0.0 | 196.9 | 7.26 | 114.4 | 78.4 | 892.5 | 60.7 |
| 1976 | Soybean | 0.0 | 0.0 | 303.2 | 51.0 | 2.83 | 34.8 | 64.4 | 893.0 | 37.8 |
| 1977 | Soybean | 7.3 | 0.0 | 195.6 | 44.4 | 3.14 | 36.0 | 57.9 | 893.9 | 47.9 |
| 1978 | Corn | 13.5 | 167.2 | 0.0 | 187.4 | 7.42 | 58.7 | 53.8 | 892.8 | 54.9 |
| 1979 | Soybean | 3.9 | 0.0 | 361.0 | 58.0 | 11.96 | 63.6 | 40.8 | 890.8 | 63.9 |
| 1980 | Corn | 25.0 | 179.3 | 0.0 | 223.6 | 1.46 | 35.9 | 42.3 | 894.4 | 36.2 |
| 1981 | Soybean | 0.0 | 0.0 | 268.4 | 49.4 | 4.05 | 45.0 | 30.8 | 894.6 | 36.3 |
| 1982 | Soybean | 7.3 | 0.0 | 246.8 | 48.9 | 3.42 | 42.0 | 24.8 | 895.6 | 46.3 |
| 1983 | Corn | 13.5 | 167.2 | 0.0 | 134.0 | 9.40 | 102.0 | 24.6 | 893.3 | 46.5 |
| 1984 | Soybean | 3.9 | 0.0 | 400.9 | 66.6 | 4.47 | 49.1 | 12.8 | 893.6 | 47.9 |
| 1985 | Corn | 25.0 | 179.3 | 0.0 | 218.5 | 3.18 | 74.2 | 16.6 | 895.8 | 45.8 |
| 1986 | Soybean | 0.0 | 0.0 | 255.8 | 46.9 | 4.26 | 39.5 | 9.1 | 895.1 | 40.3 |
| 1987 | Soybean | 7.3 | 0.0 | 202.8 | 42.5 | 1.77 | 30.6 | 7.6 | 894.7 | 36.5 |
| 1988 | Corn | 13.5 | 167.2 | 0.0 | 185.2 | 3.00 | 44.5 | 7.4 | 893.9 | 43.2 |
| 1989 | Soybean | 3.9 | 0.0 | 309.6 | 52.2 | 6.61 | 66.6 | 4.1 | 891.1 | 52.2 |
| 1990 | Corn | 25.0 | 179.3 | 0.0 | 164.7 | 7.52 | 122.2 | 10.7 | 888.5 | 62.9 |
| 1991 | Soybean | 0.0 | 0.0 | 268.9 | 45.6 | 1.88 | 45.0 | 5.3 | 887.5 | 40.6 |
| 1992 | Soybean | 7.3 | 0.0 | 216.7 | 38.9 | 1.71 | 42.0 | 4.7 | 886.4 | 40.7 |
| 1993 | Corn | 13.5 | 167.2 | 0.0 | 181.6 | 5.91 | 80.6 | 5.5 | 883.1 | 56.6 |
| 1994 | Soybean | 3.9 | 0.0 | 259.9 | 39.4 | 2.94 | 40.6 | 4.0 | 881.6 | 42.8 |
| 1995 | Corn | 25.0 | 179.3 | 0.0 | 166.9 | 3.79 | 99.1 | 9.9 | 880.3 | 50.2 |
| 1996 | Soybean | 0.0 | 0.0 | 268.6 | 44.0 | 4.38 | 69.3 | 4.6 | 878.1 | 55.2 |
| 1997 | Soybean | 7.3 | 0.0 | 228.0 | 39.7 | 4.99 | 90.6 | 4.4 | 875.1 | 53.3 |
| 1998 | Corn | 13.5 | 167.2 | 0.0 | 172.1 | 3.52 | 77.6 | 5.4 | 873.0 | 52.3 |
| 1999 | Soybean | 3.9 | 0.0 | 227.9 | 40.8 | 1.94 | 30.8 | 3.9 | 872.0 | 39.7 |
| 2000 | Corn | 25.0 | 179.3 | 0.0 | 178.7 | 2.24 | 42.2 | 9.2 | 871.3 | 48.6 |
| 2001 | Soybean | 0.0 | 0.0 | 198.1 | 37.7 | 2.96 | 56.1 | 4.8 | 869.6 | 49.9 |
| 2002 | Soybean | 7.3 | 0.0 | 207.8 | 36.2 | 5.02 | 82.9 | 4.7 | 866.5 | 62.1 |
| 2003 | Corn | 13.5 | 167.2 | 0.0 | 165.5 | 3.71 | 76.9 | 5.4 | 864.4 | 59.1 |
| 2004 | Soybean | 3.9 | 0.0 | 241.8 | 41.4 | 3.75 | 55.4 | 4.0 | 862.3 | 62.6 |
| 2005 | Corn | 25.0 | 179.3 | 0.0 | 164.3 | 3.17 | 55.7 | 9.4 | 861.2 | 47.0 |
| 2006 | Soybean | 0.0 | 0.0 | 214.6 | 37.1 | 4.55 | 83.3 | 4.7 | 858.6 | 63.0 |
| 2007 | Soybean | 7.3 | 0.0 | 189.9 | 36.7 | 1.96 | 51.6 | 4.6 | 857.0 | 52.5 |
| 2008 | Corn | 13.5 | 167.2 | 0.0 | 169.3 | 5.14 | 80.8 | 4.9 | 854.2 | 58.0 |
| 2009 | Soybean | 3.9 | 0.0 | 215.2 | 36.7 | 2.71 | 44.0 | 3.8 | 852.4 | 60.0 |
| 2010 | Corn | 25.0 | 179.3 | 0.0 | 161.9 | 2.19 | 37.7 | 9.0 | 851.6 | 42.4 |
| 2011 | Soybean | 0.0 | 0.0 | 214.7 | 36.1 | 6.82 | 113.3 | 4.6 | 848.0 | 69.3 |
| | Total | 390.7 | 2772.3 | 5871.7 | 3853.8 | 164.08 | 2,447.2 | 772.9 | 34,308.8 | 1,965.1 |
| | Maximum | 25.0 | 179.3 | 400.9 | 223.6 | 11.96 | 122.2 | 92.0 | 895.8 | 69.3 |
| | Average | 10.0 | 71.1 | 150.6 | 98.8 | 4.21 | 62.7 | 19.8 | 879.7 | 50.4 |
| | Minimum | 0.0 | 0.0 | 0.0 | 36.1 | 1.46 | 26.5 | 3.8 | 848.0 | 36.2 |
| | Coefficient of variation | 89.5% | 121.6% | 89.6% | 68.3% | 54.2% | 42.2% | 123.8% | 1.7% | 17.8% |

[1] First year of model simulation; model output was not considered in any of the data analyses in this study.
[2] Total P yield = Sediment P + Soluble P + Organic P
[3] Total N yield = Organic nitrogen + Nitrate in surface runoff + Nitrate in lateral flow + Nitrate in groundwater

made up about 10 percent of the total P load. Sediment bound P actively exchanges with soluble

P in the water, depending on the chemical composition of sediment particles and the pH and redox conditions of the solution. Organic P is mostly tightly bound within plant residue and soil humic substances. As such, this fraction of phosphorus is generally not quickly available for plants and algae, but influences water quality of receiving waters in a longer timeframe. Losses of both sediment P and organic P are associated with sediment loss in SWAT. Nitrogen, on the other hand, left the field mostly as nitrate with groundwater (66.0 percent) that drains into the receiving stream.

Over the 39 years, the total P load ranged from 1.46 to 11.96 lbs/ac/yr, a ten-fold difference. It generally followed the amount of precipitation and sediment yield (Figure 3) with the lowest load coinciding with lowest precipitation of 36.2 inches and sediment yield of 0.49 tons/ac in 1980, a corn year, and the highest with second highest precipitation of 63.9 inches and sediment yield of 4.51 tons/ac in 1979, a soybean year. These extreme precipitation and sediment values were also associated with the highest and lowest loads of sediment P and organic P, suggesting the main pathway for P loss from the field was through sediment loss (soil erosion) caused by surface runoff. Total N generally follows a similar pattern with respect to its relationship with precipitation and soil erosion (Figure 4). Because most of the nitrogen loss was through nitrate in the groundwater and to a lesser degree sediment attached organic N, it stands to reason that higher precipitation also generated more groundwater, in addition to more soil losses, both leading to more N losses from the field.

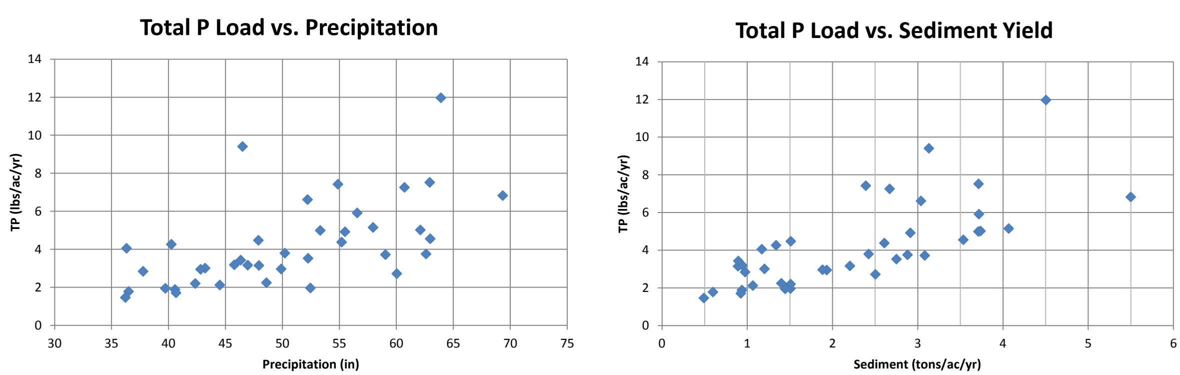



Figure 3: Edge-of-field annual total P loading vs precipitation (left) and total P loading vs sediment yield (right) at the Kentucky study site by the 40-year SWAT base case model simulation

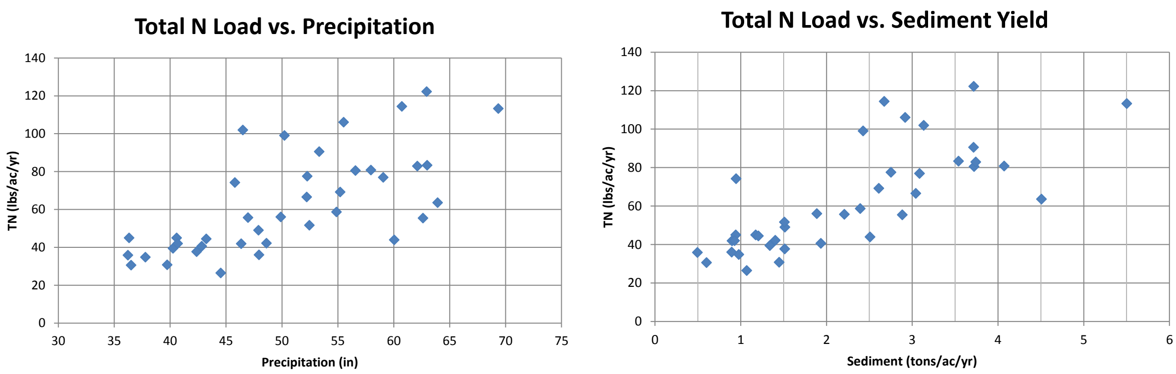



Figure 4: Edge-of-field annual total N loading vs precipitation (left) and total N loading vs sediment yield (right) at the Kentucky study site by the 40-year SWAT base case model simulation

Breaking the 39 years into corn and soybean years showed a higher average annual total P loading from the corn years (4.61 lbs/ac) than that from soybean (3.92 lbs/ac), coinciding with a higher average annual precipitation (51.2 vs 49.8 in). Soybean years, however, had a greater highest load (11.96 vs 9.40 lbs/ac) and a smaller lowest load value (1.71 vs 1.46 lbs/ac), suggesting that that total P load from soybean years was more variable from year-to-year. This variability was confirmed by a higher coefficient of variation of 63.9 percent for the soybean years compared to 49.8 for corn. It was notable that there was much less P fertilizer applied for soybean than corn (average 3.6 vs 19.3 lbs/ac) while total P loading in soybean years was only on average 0.7 lbs less than that in corn years. The same pattern of differences in sediment yield existed for these two crops, i.e., higher average sediment yield in corn years but higher variability in soybean years, confirming erosion and consequently particulate P was the main contributing factor for total P loading.

Table 9 and Figure 5 also show the 40-year model simulated a steady decline of soluble P in the soil for the first 15 years before stabilization under 10 lbs/ac. On the other hand, soil organic P started with a small but steady rise in the first 15 years before declining quickly. A possible explanation is that due to the expansion of the five-year calibration to the 40-year simulation, soil soluble P depletion driven by both crop uptake and soil erosion was not adequately compensated by P fertilizer application. That is because the use of VRT every five years was designed primarily to meet the crop growth needs based on soil P test. In practice, soil P test would be conducted before VRT rates were determined. Repeating the same VRT rates in the 40-year simulation did not allow such "real time" adjustment, leading to depletion of plant available soil soluble P. On the other hand, because of the no-till operation in the Kentucky, organic P from crop residue started accumulating in the soil and after an extended period of about 15 years, became a source of soluble P for the crop to take up. That also explains the generally steady crop yield for both crops, compared to the soil P changes, over the long simulation period. Figure 5 also showed that soil total P level (soil soluble P + soil organic P) steadily declined over the simulation period while total P load from the field did not exhibit a clear trend of change, suggesting factors other than soil P level had more influence (or counter effect) on the losses of P from the field.

## Total P load estimation tool development

The evaluation of total P estimations using multiple linear regression (Equation 1) was completed on two HRUs in the Kentucky field: #851 and #1933. Both HRUs have silt loam soils. HRU #851 has a high slope (5-10 percent) with low initial soil test P and thus higher P application rate in the VRT year. HRU #1933 has a lower slope (2-5 percent) with high soil test P and thus lower P application rate in the VRT year. Comparing the results of linear regression for total P estimation from two different soils from the same field can inform decision makers of the transferability of estimation methods. Data used for an estimation tool concept and evaluation were extracted from the eight 40-year simulations (except 1972, the first year of simulation). Note that because HRU #1933 already had the highest initial soil test P level among the HRUs, Scenario #2 (see Method section) was not run for HRU #1933, reducing the number of data points available for this HRU's statistical analysis.

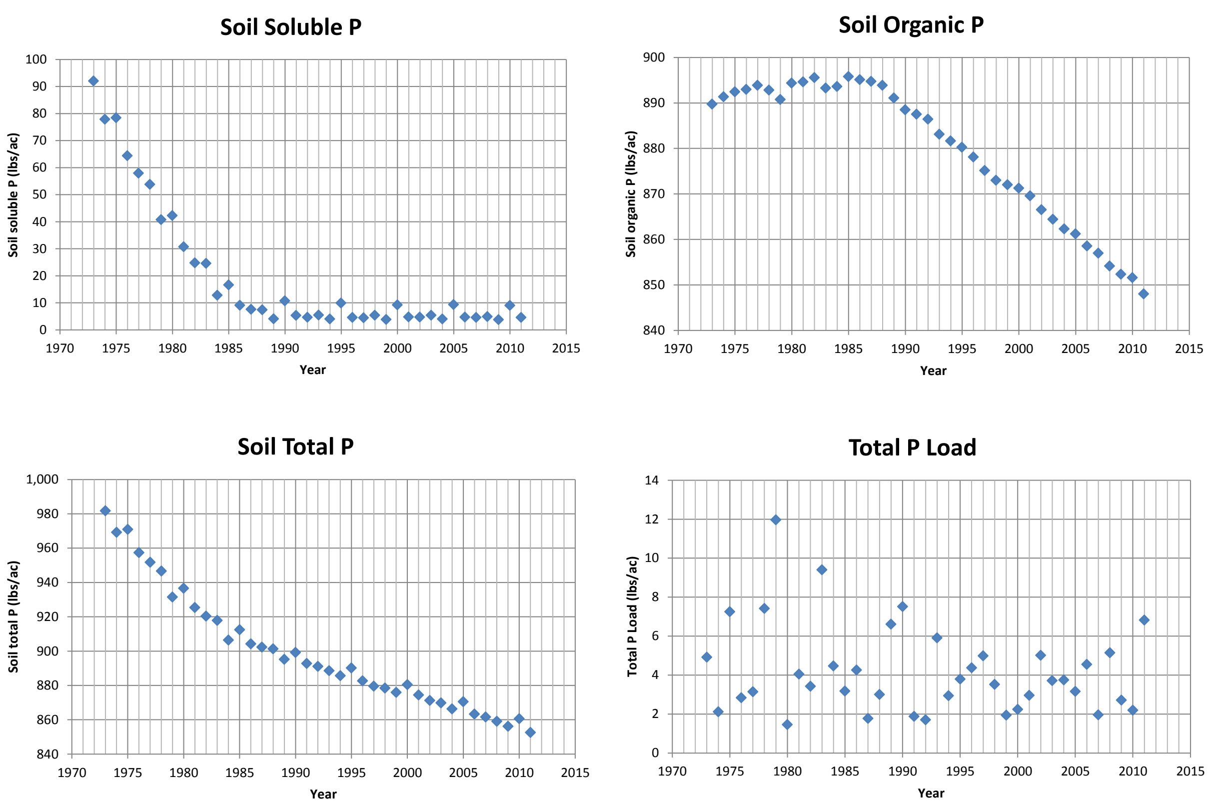



Figure 5: Level changes for soil soluble P (upper left), soil organic P (upper right), soil total P (lower left), and total P load from the Kentucky field over the 40-year SWAT base case model simulation

To examine the response of total P loading to field and environmental conditions in different crop years, multiple linear regression analysis was conducted for corn and soybean years separately. Corn years were further divided into "VRT corn years" and non-VRT or "regular corn years." Soybean years were divided into "soybean after corn years," "soybean after VRT corn years," "soybean after regular corn years," and "soybean after soybean years" (Tables 10 and 11). In addition, each crop scenario was examined through two different plant available P levels (soil soluble P + fertilizer P), higher and lower, as determined through graphic interpretation of the plant available P data. Together with the plant available P data before the splitting (the "All data" results in Tables 10 and 11), each crop scenario had three multiple linear regression equations developed.

Table 10: Coefficient values and other statistics of regression equations for edge-of-field annual **total P** load (lb/ac) based on eight 40-year SWAT models for **HRU #851** of the Kentucky field

| **All Corn Years** | All data | Plant available P category (22 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -7.885 | -32.551 | -9.127 |
| Plant available P (lb/ac; $a_1$)[1] | N/S[3] | 2.353 | N/S |
| Sediment yield (ton/ac; $a_2$) | 2.206 | 1.206 | 2.602 |
| Plant P uptake (lb/ac; $a_3$) | 0.239 | N/S | 0.245 |
| $R^2$ | 0.664 | 0.737 | 0.834 |
| Standard Error (lb/ac) | 1.562 | 1.141 | 1.214 |
| Total P Load Average (lb/ac) | 5.252 | 5.355 | 5.190 |
| Observations | 126 | 47 | 79 |
| **VRT Corn Years** | All data | Plant available P category (27 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -6.260 | -8.618 | 0.207 |
| Plant available P (lb/ac; $a_1$) | 0.123 | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 2.124 | 2.168 | 2.872 |
| Plant P uptake (lb/ac; $a_3$) | 0.086 | 0.258 | N/S |
| $R^2$ | 0.898 | 0.888 | 0.982 |
| Standard Error (lb/ac) | 0.868 | 0.746 | 0.507 |
| Total P Load Average (lb/ac) | 4.602 | 4.428 | 5.083 |
| Observations | 64 | 47 | 17 |
| **Regular Corn Years** | All data | Plant available P category (24 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -8.037 | -32.551 | 9.918 |
| Plant available P (lb/ac; $a_1$) | N/S | 2.353 | -0.263 |
| Sediment yield (ton/ac; $a_2$) | 1.620 | 1.206 | 1.863 |
| Plant P uptake (lb/ac; $a_3$) | 0.332 | N/S | N/S |
| $R^2$ | 0.572 | 0.737 | 0.781 |
| Standard Error (lb/ac) | 1.693 | 1.141 | 1.447 |
| Total P Load Average (lb/ac) | 5.922 | 5.355 | 7.697 |
| Observations | 62 | 47 | 15 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicates the divide of the data set into two sets, one with lower plant available P and one with higher plant available P.
[3] Not significant at $p = 0.05$

Table 10 (continued): Coefficient values and other statistics of regression equations for edge-of-field annual **total** P (lb/ac) load based on eight 40-year SWAT models for **HRU #851** of the Kentucky field

| **Bean Years (after Corn)** | All data | Plant available P category (11 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -2.770 | -0.133 | -1.865 |
| Plant available P (lb/ac; $a_1$)[1] | -0.099 | -1.545 | -0.114 |
| Sediment yield (ton/ac; $a_2$) | 1.600 | 1.715 | 1.549 |
| Plant P uptake (lb/ac; $a_3$) | 0.153 | 0.339 | 0.140 |
| $R^2$ | 0.872 | 0.915 | 0.875 |
| Standard Error (lb/ac) | 0.962 | 0.574 | 1.060 |
| Total P Load Average (lb/ac) | 4.899 | 4.189 | 5.321 |
| Observations | 126 | 47 | 79 |
| **Bean Years (after VRT Corn)** | All data | Plant available P category (16 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -2.117 | 20.622 | -2.802 |
| Plant available P (lb/ac; $a_1$) | -0.112 | -2.528 | N/S[3] |
| Sediment yield (ton/ac; $a_2$) | 1.389 | 1.527 | 5.491 |
| Plant P uptake (lb/ac; $a_3$) | 0.166 | 0.384 | N/S |
| $R^2$ | 0.918 | 0.979 | 0.887 |
| Standard Error (lb/ac) | 0.488 | 0.277 | 0.348 |
| Total P Load Average (lb/ac) | 4.709 | 4.773 | 4.532 |
| Observations | 64 | 47 | 17 |
| **Bean Years (after Regular Corn)** | All data | Plant available P category (13 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -4.116 | -0.133 | -0.648 |
| Plant available P (lb/ac; $a_1$) | -0.211 | -1.545 | N/S |
| Sediment yield (ton/ac; $a_2$) | 1.998 | 1.715 | 2.711 |
| Plant P uptake (lb/ac; $a_3$) | 0.181 | 0.339 | N/S |
| $R^2$ | 0.938 | 0.915 | 0.978 |
| Standard Error (lb/ac) | 0.870 | 0.574 | 0.790 |
| Total P Load Average (lb/ac) | 5.094 | 4.189 | 7.931 |
| Observations | 62 | 47 | 15 |
| **Bean Years (after Bean)** | All data | Plant available P category (19 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -1.928 | -1.624 | -6.569 |
| Plant available P (lb/ac; $a_1$) | N/S | N/S | 0.056 |
| Sediment yield (ton/ac; $a_2$) | 1.431 | 1.387 | 2.861 |
| Plant P uptake (lb/ac; $a_3$) | 0.107 | 0.096 | 0.153 |
| $R^2$ | 0.903 | 0.918 | 1.000 |
| Standard Error (lb/ac) | 0.529 | 0.500 | 0.028 |
| Total P Load Average (lb/ac) | 3.576 | 3.430 | 4.340 |
| Observations | 56 | 47 | 9 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicates the divide of the data set into two sets, one with lower plant available P and one with higher plant available P.
[3] Not significant at $p = 0.05$

Table 11: Coefficient values and other statistics of regression equations for edge-of-field annual **total** P load (lb/ac) based on eight 40-year SWAT models for **HRU #1933** of the Kentucky field

| **All Corn Years** | All data | Plant available P category (14 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -3.536 | -2.176 | -8.307 |
| Plant available P (lb/ac; $a_1$)[1] | 0.037 | N/S[3] | N/S |
| Sediment yield (ton/ac; $a_2$) | 1.956 | 1.672 | 2.546 |
| Plant P uptake (lb/ac; $a_3$) | 0.106 | 0.098 | 0.223 |
| $R^2$ | 0.664 | 0.812 | 0.598 |
| Standard Error (lb/ac) | 1.694 | 0.724 | 1.921 |
| Total P Load Average (lb/ac) | 5.115 | 3.375 | 5.893 |
| Observations | 110 | 34 | 76 |
| **VRT Corn Years** | All data | Plant available P category (14 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -3.955 | -2.176 | -8.207 |
| Plant available P (lb/ac; $a_1$) | N/S | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 2.398 | 1.672 | 3.318 |
| Plant P uptake (lb/ac; $a_3$) | 0.112 | 0.098 | 0.175 |
| $R^2$ | 0.825 | 0.812 | 0.927 |
| Standard Error (lb/ac) | 1.038 | 0.724 | 0.892 |
| Total P Load Average (lb/ac) | 3.977 | 3.375 | 4.907 |
| Observations | 56 | 34 | 22 |
| **Regular Corn Years** | All data | Plant available P category (21 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -9.855 | 9.951 | 5.439 |
| Plant available P (lb/ac; $a_1$) | N/S | -1.316 | N/S |
| Sediment yield (ton/ac; $a_2$) | 2.052 | 1.571 | -0.109 |
| Plant P uptake (lb/ac; $a_3$) | 0.332 | 0.379 | 2.338 |
| $R^2$ | 0.585 | 0.906 | 0.762 |
| Standard Error (lb/ac) | 1.874 | 0.450 | 1.429 |
| Total P Load Average (lb/ac) | 6.295 | 4.704 | 8.794 |
| Observations | 54 | 33 | 21 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicates the divide of the data set into two sets, one with lower plant available P and one with higher plant available P.
[3] Not significant at $p = 0.05$

Table 11 (continued): Coefficient values and other statistics of regression equations for edge-of-field annual **total** P (lb/ac) load based on eight 40-year SWAT models for **HRU #1933** of the Kentucky field

| **Bean Years (after Corn)** | All data | Plant available P category (11 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -2.956 | -6.175 | -3.212 |
| Plant available P (lb/ac; $a_1$)[1] | N/S[3] | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 1.643 | 1.823 | 1.634 |
| Plant P uptake (lb/ac; $a_3$) | 0.114 | 0.246 | 0.118 |
| $R^2$ | 0.770 | 0.916 | 0.758 |
| Standard Error (lb/ac) | 1.224 | 0.542 | 1.348 |
| Total P Load Average (lb/ac) | 4.888 | 4.011 | 5.264 |
| Observations | 110 | 33 | 77 |
| **Bean Years (after VRT Corn)** | All data | Plant available P category (21 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -2.288 | -3.687 | -2.627 |
| Plant available P (lb/ac; $a_1$) | -0.075 | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 1.261 | 1.288 | 5.382 |
| Plant P uptake (lb/ac; $a_3$) | 0.165 | 0.181 | N/S |
| $R^2$ | 0.841 | 0.919 | 0.643 |
| Standard Error (lb/ac) | 0.627 | 0.507 | 0.468 |
| Total P Load Average (lb/ac) | 4.561 | 4.684 | 4.255 |
| Observations | 56 | 40 | 16 |
| **Bean Years (after Regular Corn)** | All data | Plant available P category (11 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -4.924 | -6.175 | -7.672 |
| Plant available P (lb/ac; $a_1$) | N/S | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 2.722 | 1.823 | 3.033 |
| Plant P uptake (lb/ac; $a_3$) | 0.098 | 0.246 | 0.131 |
| $R^2$ | 0.921 | 0.916 | 0.967 |
| Standard Error (lb/ac) | 0.930 | 0.542 | 0.776 |
| Total P Load Average (lb/ac) | 5.227 | 4.011 | 7.138 |
| Observations | 54 | 33 | 21 |
| **Bean Years (after Bean)** | All data | Plant available P category (27lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -1.718 | -5.470 | 0.565 |
| Plant available P (lb/ac; $a_1$) | 0.052 | 0.701 | N/S |
| Sediment yield (ton/ac; $a_2$) | 1.305 | 1.249 | 2.939 |
| Plant P uptake (lb/ac; $a_3$) | 0.068 | 0.012 | N/S |
| $R^2$ | 0.923 | 0.996 | 0.951 |
| Standard Error (lb/ac) | 0.459 | 0.106 | 0.283 |
| Total P Load Average (lb/ac) | 3.318 | 3.184 | 4.122 |
| Observations | 49 | 42 | 7 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicates the divide of the data set into two sets, one with lower plant available P and one with higher plant available P.[3] Not significant at $p = 0.05$

Tables 10 and 11 showed that for both HRUs, three field or crop growth parameters: plant available P, sediment yield and plant P uptake were independent variables (or predictors) that together explained from 57 percent to 100 percent (the $R^2$ value) of the total P variation in various scenarios. The majority of the $R^2$ values were in the 0.80 to 0.99 range. Total P loading in the soybean years in both HRUs was better predicted by the three predictors than that in the corn years. The lowest $R^2$ value appeared in regular corn years for both HRUs, while the highest $R^2$ value for corn years were in the VRT years for both HRUs. A possible explanation is that VRT, by reducing the fluctuation of plant available P, improved the correlation of the other two predictors with total P, resulting in better $R^2$ values.

Splitting each scenario into high and low plant available P in general improved the $R^2$ values. However, this resulted in a drop-off of plant available P as a statistically significant predictor of total loading. Removing plant available P does not substantially impact how much of the phosphorus loss at the edge-of-field is being explained by the resulting multiple linear regression. In addition, regression equation coefficients for plant available P, where it was statistically significant, fluctuated between positive and negative values. Together, these two observations may be an indication that response of total P to plant available P level in the soil was rather weak and any statistically significant correlation between the two shown ($p < 0.05$) in multiple linear regression equations should be applied with caution.

Of the three predictors, sediment yield always had the strongest (and positive) correlation with total P load ($p < 0.001$; data not shown), indicating the tight relationship between sediment and sediment P and organic P, the latter two of which constituted the majority of total P. Fang et al. (2002) explains that the soil release of Soluble Reactive Phosphorus is determined by both the soil phosphorus holding capacity and the strength of the soil sorption binding sites. Soils with unused P binding sites can be expected to have TP edge-of-field loading dominated by particulate phosphorus fraction. Plant uptake of P in most cases had a significant correlation with total P and the regression coefficient was always positive. It is somewhat counterintuitive that more plant uptake of P would lead to more total P being lost from the field. There are many possible explanations for this finding. One possible explanation is that the plant uptake of P is more of an indication of P levels in the soil, both in the soluble form and particularly the attached sediment or organic form, than what was taken out of the soil by the crop. Alternatively, greater plant uptake of P could also indicate increased biomass susceptible to lysis and subsequent release of phosphorus in this no-till operation.

Comparing the coefficient values of the linear regression equations and statistics between HRU #861 (Table 10) and HRU #1933 (Table 11) showed that there is a general consistency in terms of the magnitude of the coefficient values and predictor correlations with total P load. However, it is also apparent that these multiple linear regression equations are HRU specific because more often than not, there is significant difference in coefficient values between the HRUs, particularly for predictors: plant available P and plant P uptake. This indicates that even a wider range of variability exists when considering other soils. Considering the variability and associated margin of safety to address the variability is necessary to develop a transferable estimation equation that achieves the “easy to use” characteristic desired for WQCT programs.

For water quality trading, the multiple linear equations provide a means to develop the estimation tool, if viable, for total P load changes introduced by VRT application. The implementation of VRT practices by the producer, as shown in these equations, would not only change the total amount of fertilizers applied in specific areas of a field, but also alter how a credit valuation method is constructed. The implications to water quality credit trading in such a situation is that tools developed for quantifying total P loading changes would need to be site specific or they should be based on a more general and transferable algorithm that requires more of a margin of safety.

**Soluble P load estimation tool development**

Because the importance of soluble P being immediately available for algal growth in the waters receiving agricultural runoff, multiple linear regression were also assessed for the viability of developing estimation tools for soluble P for HRU #851. Table 12 presents the coefficients and relevant statistics for the same scenarios examined for total P estimation.

Using the same three predictors, soluble P was estimated with $R^2$ values ranging from 0.614 for “Regular Corn Years” to 0.986 for “Soybean Years (after Soybean)” with a high plant available P. The majority of the $R^2$ values were in the 0.80 to 0.99 range. Compared to the results for total P (Table 10), the most obvious difference is the much smaller coefficient values for soluble P at an order of magnitude less. This is not surprising as the same three predictors were used and soluble P accounted for less than 10 percent of the total P load from the Kentucky field. The $R^2$ values for soluble P in general were somewhat lower than those for total P, but actually improved for the “Regular Corn Years” scenario, which had the lowest $R^2$ value for both total P and soluble P.

Statistical significance of the correlations between the three predictors and soluble P was similar to that of total P with plant available P and plant P uptake at times becoming statistically not significant. Sediment yield kept its close association with soluble P, a reflection of the correlation between surface runoff, where soluble P was transported, and soil erosion.

In summary, the multiple linear regression equations developed were well suited as a tool to estimate soluble P load from HRU #851. Dividing the scenarios into high and low plant available P categories could further improve the predictive power of the equations.

**Particulate P load estimation tool development**

Particulate P load estimation tool is based on the enrichment ratio method. The result of the tool development for the Kentucky field is discussed together with the result from the Illinois field later in this report.

Table 12: Coefficient values and other statistics of regression equations for edge-of-field annual **soluble P** load (lb/ac) based on eight 40-year SWAT models for **HRU #851** of the Kentucky field

| **All Corn Years** | All data | Plant available P category (22 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -1.120 | -3.690 | -1.194 |
| Plant available P (lb/ac; $a_1$)[1] | 0.012 | 0.256 | 0.012 |
| Sediment yield (ton/ac; $a_2$) | 0.193 | 0.097 | 0.233 |
| Plant P uptake (lb/ac; $a_3$) | 0.026 | N/S[3] | 0.025 |
| $R^2$ | 0.668 | 0.829 | 0.760 |
| Standard Error (lb/ac) | 0.170 | 0.087 | 0.154 |
| Soluble P Load Average (lb/ac) | 0.439 | 0.315 | 0.514 |
| Observations | 126 | 47 | 79 |
| **VRT Corn Years** | All data | Plant available P category (27 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -0.828 | 0.038 | 0.032 |
| Plant available P (lb/ac; $a_1$) | 0.034 | N/S | N/S |
| Sediment yield (ton/ac; $a_2$) | 0.180 | 0.151 | 0.379 |
| Plant P uptake (lb/ac; $a_3$) | N/S | N/S | N/S |
| $R^2$ | 0.882 | 0.846 | 0.985 |
| Standard Error (lb/ac) | 0.110 | 0.073 | 0.061 |
| Soluble P Load Average (lb/ac) | 0.479 | 0.408 | 0.676 |
| Observations | 64 | 47 | 17 |
| **Regular Corn Years** | All data | Plant available P category (24 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -1.059 | -3.690 | 1.049 |
| Plant available P (lb/ac; $a_1$) | N/S | 0.256 | -0.025 |
| Sediment yield (ton/ac; $a_2$) | 0.135 | 0.097 | 0.120 |
| Plant P uptake (lb/ac; $a_3$) | 0.039 | N/S | N/S |
| $R^2$ | 0.614 | 0.829 | 0.761 |
| Standard Error (lb/ac) | 0.164 | 0.087 | 0.125 |
| Soluble P Load Average (lb/ac) | 0.399 | 0.315 | 0.661 |
| Observations | 62 | 47 | 15 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicate the divide of low and high.
[3] Not significant at $p = 0.05$

Table 12 (continued): Coefficient values and other statistics of regression equations for edge-of-field annual **soluble P** (lb/ac) load based on eight 40-year SWAT models for **HRU #851** of the Kentucky field

| **Bean Years (after Corn)** | All data | Plant available P category (11 lb/ac)[2] | |
|---|---|---|---|
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -0.319 | -0.894 | -0.202 |
| Plant available P (lb/ac; $a_1$)[1] | N/S | 0.185 | N/S[3] |
| Sediment yield (ton/ac; $a_2$) | 0.095 | 0.069 | 0.096 |
| Plant P uptake (lb/ac; $a_3$) | 0.014 | N/S | 0.011 |
| $R^2$ | 0.741 | 0.853 | 0.675 |
| Standard Error (lb/ac) | 0.120 | 0.050 | 0.132 |
| Soluble P Load Average (lb/ac) | 0.354 | 0.192 | 0.450 |
| Observations | 126 | 47 | 79 |
| **Bean Years (after VRT Corn)** | All data | Plant available P category (16 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -0.411 | -0.361 | -0.379 |
| Plant available P (lb/ac; $a_1$) | N/S | N/S | 0.005 |
| Sediment yield (ton/ac; $a_2$) | 0.099 | 0.096 | 0.620 |
| Plant P uptake (lb/ac; $a_3$) | 0.019 | 0.017 | N/S |
| $R^2$ | 0.788 | 0.805 | 0.887 |
| Standard Error (lb/ac) | 0.071 | 0.058 | 0.033 |
| Soluble P Load Average (lb/ac) | 0.408 | 0.350 | 0.566 |
| Observations | 64 | 47 | 17 |
| **Bean Years (after Regular Corn)** | All data | Plant available P category (13 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -0.451 | -0.894 | 0.004 |
| Plant available P (lb/ac; $a_1$) | -0.017 | 0.185 | N/S |
| Sediment yield (ton/ac; $a_2$) | 0.121 | 0.069 | 0.198 |
| Plant P uptake (lb/ac; $a_3$) | 0.019 | N/S | N/S |
| $R^2$ | 0.917 | 0.853 | 0.978 |
| Standard Error (lb/ac) | 0.084 | 0.050 | 0.058 |
| Soluble P Load Average (lb/ac) | 0.298 | 0.192 | 0.631 |
| Observations | 62 | 47 | 15 |
| **Bean Years (after Bean)** | All data | Plant available P category (19 lb/ac) | |
| Coefficients | | Low | High |
| Intercept (lb/ac; $a_o$) | -0.389 | -0.760 | -1.009 |
| Plant available P (lb/ac; $a_1$) | 0.008 | 0.084 | 0.006 |
| Sediment yield (ton/ac; $a_2$) | 0.085 | 0.072 | 0.259 |
| Plant P uptake (lb/ac; $a_3$) | 0.017 | 0.007 | 0.028 |
| $R^2$ | 0.871 | 0.858 | 0.986 |
| Standard Error (lb/ac) | 0.075 | 0.065 | 0.019 |
| Soluble P Load Average (lb/ac) | 0.302 | 0.248 | 0.585 |
| Observations | 56 | 47 | 9 |

[1] Plant available P is the sum of soil soluble P and fertilizer P.
[2] Number in parentheses indicate the divide of low and high.
[3] Not significant at $p = 0.05$

## Results from 40-year Simulations for the Illinois site: Second Stage

For the Illinois study site a similar 40-year simulation model was built, with the addition of N values as well as P. Load estimation tools were developed using the 40-year data for the Illinois site for Particulate P, Particulate N and Nitrate-N.

**Base case scenario**

Table 13 lists the edge-of-field loads of P and N components, sediment yield, P and N applied as fertilizers, crop yield and precipitation for the 40-years of 1974-2013 as simulated by SWAT for the Illinois site base case scenario. In addition to P levels in the soil at the beginning of each year, N levels in the soil are also present in the table. The analysis and tool development for the Illinois site focused more on N because the VRT application at the Illinois field used the fertilizer diammonium phosphate (DAP; 18-46-00), effectively varying rates for both P and N. Compared to the Kentucky field, where only P rate was varied, the Illinois site provided an opportunity to examine both nutrients for long-term effects of VRT, especially N.

Table 13 shows that for P, sediment and organic P on average constituted the majority of the total P load from the field at 40.0 percent and 44.2 percent, respectively. Soluble P, transported mostly with surface runoff and soil lateral flow (through tile drain) from the field, contributed 15.8 percent of the total. Compared to the Kentucky field (9.8 percent), soluble P made up a much larger portion of the total P loading reflecting the more prominent role of surface runoff and tile drain in nutrient loading from the Illinois field. This role was further demonstrated clearly by the components of the total N load from the Illinois field. Organic N, transported with sediment by surface runoff, constituted on average 63.0 percent of the total N load while nitrate in surface runoff contributed 30.8 percent. For the Kentucky site, nitrate in groundwater drained off the field was the major component at 66.0 percent with organic N contributing another 29.1 percent. As a comparison, groundwater accounted for only 6.0 percent of total N load from the Illinois field. The difference between the two sites can be attributed to the drainage capacity of the soils. The Illinois field has mostly poorly drained silty clay loam soils, generating relatively more soil erosion than the silt loam soils in the Kentucky field on a per inch precipitation basis (0.050 vs 0.045 ton/ac/in).

Further evidence of more relative erosion at the Illinois site and its impact on total P and N loading can be seen in Figures 6 and 7 (below). Compared to the corresponding plots from the Kentucky site, there is a much more defined positive linear relationship in each of the four plots, especially between total nutrient loads and sediment yield (erosion).

Separating the long-term simulation dataset into corn and soybean years showed similar average annual total P and total N loads with corn years having a slightly higher total N and soybean years a slightly higher total P. Phosphorus loads from corn years, however, had a higher coefficient of variation (CV; 49.3 percent) than that of the soybean years (37.6 percent), probably an indication of the higher variability of both precipitation and sediment yield of the corn years. It was noteworthy that although much more N fertilizer was applied in the corn years (average 162.7 lbs/ac/yr) than the soybean years (42.8 lbs/ac/yr N applied after soybean harvest in the fall in preparation for next year's corn crop), the higher rate seemed to be balanced out by

Table 13: Summary of edge-of-field annual loading from the Illinois study site by the 40-year SWAT base case model

| Year | Crop | Sediment P yield | Soluble P yield | Organic P yield | Organic N yield | Nitrate in surface runoff | Nitrate in lateral flow | Nitrate in groundwater | Sediment yield | Crop yield |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (lbs P/ac) | (lbs P/ac) | (lbs P/ac) | (lbs/ac) | (lbs N/ac) | (lbs N/ac) | (lbs N/ac) | (tons/ac) | (bu/ac) |
| *1974* | *Corn*[1] | *2.39* | *0.19* | *7.02* | *57.20* | *1.61* | *0.91* | *52.11* | *12.71* | *134.5* |
| 1975 | Soybean | 1.71 | 0.50 | 2.70 | 20.10 | 1.30 | 1.60 | 83.09 | 2.92 | 45.7 |
| 1976 | Corn | 0.68 | 0.26 | 1.19 | 7.79 | 0.95 | 0.39 | 17.37 | 1.07 | 159.7 |
| 1977 | Soybean | 2.88 | 1.06 | 3.32 | 23.58 | 2.57 | 1.82 | 86.46 | 2.67 | 37.6 |
| 1978 | Corn | 1.19 | 0.51 | 1.13 | 7.49 | 0.83 | 0.38 | 26.15 | 0.98 | 168.0 |
| 1979 | Soybean | 1.24 | 0.57 | 1.33 | 9.86 | 2.91 | 1.00 | 22.25 | 0.89 | 49.9 |
| 1980 | Corn | 3.19 | 0.83 | 3.40 | 23.22 | 2.50 | 0.69 | 32.30 | 2.39 | 131.6 |
| 1981 | Soybean | 5.18 | 1.19 | 5.59 | 37.44 | 2.32 | 0.55 | 23.29 | 4.51 | 51.1 |
| 1982 | Corn | 0.54 | 0.25 | 0.67 | 4.96 | 3.73 | 1.15 | 26.07 | 0.49 | 177.9 |
| 1983 | Soybean | 1.91 | 0.59 | 1.55 | 10.43 | 1.62 | 0.71 | 32.25 | 1.17 | 42.8 |
| 1984 | Corn | 1.39 | 0.63 | 1.40 | 10.23 | 1.37 | 0.98 | 29.40 | 0.90 | 128.0 |
| 1985 | Soybean | 4.63 | 0.94 | 3.83 | 28.28 | 3.82 | 1.26 | 68.60 | 3.13 | 51.8 |
| 1986 | Corn | 2.00 | 0.50 | 1.96 | 14.35 | 2.22 | 0.72 | 31.76 | 1.51 | 160.2 |
| 1987 | Soybean | 1.32 | 0.47 | 1.39 | 10.32 | 2.06 | 1.41 | 60.43 | 0.94 | 44.8 |
| 1988 | Corn | 1.91 | 0.52 | 1.83 | 13.14 | 2.55 | 0.49 | 23.33 | 1.34 | 52.8 |
| 1989 | Soybean | 0.72 | 0.24 | 0.81 | 6.51 | 1.23 | 0.52 | 22.33 | 0.60 | 49.2 |
| 1990 | Corn | 1.16 | 0.26 | 1.59 | 13.32 | 1.59 | 0.75 | 28.82 | 1.21 | 192.2 |
| 1991 | Soybean | 2.44 | 0.40 | 3.76 | 29.39 | 3.07 | 0.51 | 33.59 | 3.04 | 37.5 |
| 1992 | Corn | 3.04 | 0.59 | 3.89 | 34.59 | 2.39 | 2.28 | 82.94 | 3.72 | 210.6 |
| 1993 | Soybean | 0.74 | 0.25 | 0.89 | 7.32 | 1.09 | 0.50 | 36.10 | 0.94 | 46.6 |
| 1994 | Corn | 0.65 | 0.17 | 0.88 | 8.06 | 1.88 | 0.70 | 31.40 | 0.93 | 81.6 |
| 1995 | Soybean | 2.33 | 0.34 | 3.24 | 30.79 | 2.31 | 1.41 | 46.07 | 3.72 | 39.5 |
| 1996 | Corn | 0.89 | 0.15 | 1.90 | 16.71 | 1.33 | 0.53 | 22.02 | 1.93 | 186.0 |
| 1997 | Soybean | 1.45 | 0.33 | 2.02 | 20.92 | 3.45 | 2.30 | 72.41 | 2.43 | 50.0 |
| 1998 | Corn | 1.68 | 0.42 | 2.28 | 20.87 | 2.14 | 0.68 | 45.58 | 2.61 | 162.4 |
| 1999 | Soybean | 1.79 | 0.28 | 2.93 | 29.66 | 2.46 | 0.95 | 57.53 | 3.71 | 45.8 |
| 2000 | Corn | 1.44 | 0.27 | 1.81 | 18.29 | 1.02 | 1.09 | 57.19 | 2.75 | 135.9 |
| 2001 | Soybean | 0.58 | 0.12 | 1.23 | 11.00 | 1.24 | 0.42 | 18.10 | 1.45 | 42.4 |
| 2002 | Corn | 0.74 | 0.22 | 1.28 | 12.99 | 2.62 | 0.85 | 25.77 | 1.40 | 155.9 |
| 2003 | Soybean | 1.10 | 0.26 | 1.60 | 15.69 | 2.14 | 0.84 | 37.40 | 1.89 | 48.7 |
| 2004 | Corn | 1.92 | 0.34 | 2.76 | 27.60 | 3.21 | 0.87 | 51.26 | 3.74 | 165.4 |
| 2005 | Soybean | 1.37 | 0.20 | 2.14 | 21.09 | 1.84 | 1.10 | 52.89 | 3.08 | 47.2 |
| 2006 | Corn | 1.19 | 0.26 | 2.30 | 21.24 | 3.15 | 0.53 | 30.51 | 2.88 | 185.1 |
| 2007 | Soybean | 1.22 | 0.36 | 1.58 | 15.80 | 2.43 | 1.41 | 36.05 | 2.21 | 48.5 |
| 2008 | Corn | 1.75 | 0.29 | 2.51 | 23.71 | 2.17 | 0.70 | 56.74 | 3.54 | 170.0 |
| 2009 | Soybean | 0.63 | 0.13 | 1.20 | 13.33 | 2.30 | 0.84 | 35.17 | 1.51 | 53.6 |
| 2010 | Corn | 1.85 | 0.48 | 2.81 | 28.28 | 2.62 | 0.87 | 49.07 | 4.07 | 163.2 |
| 2011 | Soybean | 0.82 | 0.11 | 1.79 | 16.42 | 1.34 | 0.42 | 25.80 | 2.51 | 42.1 |
| 2012 | Corn | 0.86 | 0.27 | 1.06 | 11.13 | 1.69 | 1.05 | 23.82 | 1.51 | 58.7 |
| 2013 | Soybean | 2.69 | 0.51 | 3.62 | 36.07 | 2.39 | 1.03 | 73.77 | 5.50 | 47.2 |
| Total | | 89.88 | 35.54 | 99.27 | 810.21 | 395.83 | 2.17 | 77.45 | 69.80 | 3767.3 |
| Maximum | | 4.58 | 2.07 | 5.64 | 42.14 | 21.28 | 0.12 | 13.86 | 3.94 | 210.6 |
| Average | | 2.30 | 0.91 | 2.55 | 20.77 | 10.15 | 0.06 | 1.99 | 1.79 | 96.6 |
| Minimum | | 0.76 | 0.31 | 0.73 | 6.06 | 2.76 | 0.02 | 0.00 | 0.53 | 37.5 |
| Coefficient of variation | | 45.1% | 42.6% | 44.1% | 43.0% | 49.2% | 38.2% | 156.0% | 45.7% | 62.6% |
| Average % of Total P or N | | 40.0% | 15.8% | 44.2% | 63.0% | 30.8% | 0.2% | 6.0% | -- | -- |

[1] First year of model simulation; model output was not considered in any of the data analyses in this study.

Table 13 (continued): Summary of edge-of-field annual loading from the Illinois study site by the 40-year SWAT base case model

| Year | Crop | P fertilizer applied | N fertilizer applied | N fixed by plant | Total P yield[2] | Total N yield[3] | Soil soluble P | Soil organic P | Soil nitrate-N | Soil organic N | Precipi-tation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (lbs P/ac) | (lbs P/ac) | (lbs P/ac) | (lbs N/ac) | (lbs N/ac) | (lbs P/ac) | (lbs P/ac) | (lbs N/ac) | (lbs N/ac) | (in) |
| *1974* | *Corn*[1] | *0.0* | *149.9* | *0.0* | *5.52* | *39.7* | *135.1* | *1,554* | *57.7* | *12,435* | *34.4* |
| 1975 | Soybean[4] | 30.3 | 48.0 | 212.4 | 3.39 | 22.4 | 126.7 | 1,551 | 38.2 | 12,404 | 36.2 |
| 1976 | Corn | 1.5 | 151.3 | 0.0 | 4.75 | 36.4 | 127.8 | 1,550 | 94.4 | 12,389 | 29.0 |
| 1977 | Soybean | 30.3 | 48.0 | 126.2 | 5.53 | 40.3 | 117.2 | 1,549 | 38.2 | 12,378 | 40.7 |
| 1978 | Corn | 8.1 | 157.1 | 0.0 | 4.49 | 33.3 | 120.9 | 1,548 | 73.8 | 12,364 | 33.8 |
| 1979 | Soybean | 17.2 | 40.8 | 219.5 | 8.66 | 38.6 | 114.2 | 1,549 | 70.9 | 12,356 | 37.2 |
| 1980 | Corn | 0.0 | 189.9 | 0.0 | 4.84 | 29.9 | 107.7 | 1,547 | 102.2 | 12,339 | 31.7 |
| 1981 | Soybean | 28.1 | 34.6 | 130.7 | 7.66 | 41.9 | 101.9 | 1,547 | 152.7 | 12,331 | 41.7 |
| 1982 | Corn | 0.0 | 149.9 | 0.0 | 10.30 | 47.6 | 100.1 | 1,544 | 86.7 | 12,314 | 43.4 |
| 1983 | Soybean | 30.3 | 48.0 | 180.4 | 4.92 | 35.8 | 90.1 | 1,542 | 56.6 | 12,297 | 36.4 |
| 1984 | Corn | 1.5 | 151.3 | 0.0 | 5.39 | 29.3 | 93.0 | 1,541 | 85.1 | 12,291 | 30.1 |
| 1985 | Soybean | 30.3 | 48.0 | 182.2 | 7.59 | 39.5 | 87.5 | 1,541 | 89.8 | 12,287 | 45.0 |
| 1986 | Corn | 8.1 | 157.1 | 0.0 | 5.72 | 28.9 | 86.7 | 1,538 | 89.0 | 12,275 | 33.3 |
| 1987 | Soybean | 17.2 | 40.8 | 146.1 | 3.27 | 15.7 | 82.8 | 1,539 | 96.8 | 12,271 | 29.7 |
| 1988 | Corn | 0.0 | 189.9 | 0.0 | 3.05 | 20.9 | 79.5 | 1,539 | 98.0 | 12,275 | 20.4 |
| 1989 | Soybean | 28.1 | 34.6 | 79.9 | 3.86 | 23.3 | 77.9 | 1,539 | 206.2 | 12,278 | 29.8 |
| 1990 | Corn | 0.0 | 149.9 | 0.0 | 10.53 | 50.1 | 77.2 | 1,538 | 87.5 | 12,277 | 47.7 |
| 1991 | Soybean | 30.3 | 48.0 | 138.6 | 5.19 | 33.8 | 67.4 | 1,536 | 52.1 | 12,264 | 33.8 |
| 1992 | Corn | 1.5 | 151.3 | 0.0 | 2.99 | 19.0 | 73.5 | 1,535 | 75.9 | 12,261 | 31.4 |
| 1993 | Soybean | 30.3 | 48.0 | 213.4 | 11.50 | 57.6 | 62.7 | 1,535 | 34.4 | 12,265 | 50.0 |
| 1994 | Corn | 8.1 | 157.1 | 0.0 | 2.85 | 29.5 | 66.8 | 1,532 | 95.5 | 12,240 | 22.9 |
| 1995 | Soybean | 17.2 | 40.8 | 68.7 | 7.67 | 45.4 | 66.6 | 1,534 | 146.9 | 12,245 | 37.2 |
| 1996 | Corn | 0.0 | 189.9 | 0.0 | 5.26 | 43.4 | 64.0 | 1,531 | 73.3 | 12,236 | 35.1 |
| 1997 | Soybean | 28.1 | 34.6 | 212.4 | 4.64 | 21.1 | 55.9 | 1,531 | 61.2 | 12,231 | 34.8 |
| 1998 | Corn | 0.0 | 149.9 | 0.0 | 8.33 | 54.6 | 58.0 | 1,530 | 95.1 | 12,228 | 38.1 |
| 1999 | Soybean | 30.3 | 48.0 | 187.2 | 3.85 | 18.4 | 50.3 | 1,529 | 53.4 | 12,218 | 30.6 |
| 2000 | Corn | 1.5 | 151.3 | 0.0 | 1.86 | 11.5 | 54.4 | 1,528 | 92.3 | 12,218 | 28.6 |
| 2001 | Soybean | 30.3 | 48.0 | 121.7 | 3.66 | 19.2 | 49.1 | 1,529 | 69.6 | 12,224 | 33.4 |
| 2002 | Corn | 8.1 | 157.1 | 0.0 | 6.30 | 26.3 | 54.6 | 1,529 | 102.6 | 12,225 | 34.6 |
| 2003 | Soybean | 17.2 | 40.8 | 162.7 | 4.24 | 26.1 | 51.1 | 1,528 | 103.1 | 12,221 | 34.6 |
| 2004 | Corn | 0.0 | 189.9 | 0.0 | 4.38 | 33.5 | 47.3 | 1,528 | 90.5 | 12,222 | 37.1 |
| 2005 | Soybean | 28.1 | 34.6 | 168.2 | 4.72 | 34.4 | 41.8 | 1,528 | 91.9 | 12,223 | 32.5 |
| 2006 | Corn | 0.0 | 149.9 | 0.0 | 7.64 | 35.2 | 44.1 | 1,526 | 83.9 | 12,221 | 39.9 |
| 2007 | Soybean | 30.3 | 48.0 | 202.5 | 7.67 | 34.1 | 36.2 | 1,524 | 55.0 | 12,214 | 39.5 |
| 2008 | Corn | 1.5 | 151.3 | 0.0 | 11.58 | 52.2 | 39.0 | 1,522 | 86.3 | 12,204 | 47.5 |
| 2009 | Soybean | 30.3 | 48.0 | 225.0 | 7.01 | 48.4 | 31.3 | 1,519 | 42.1 | 12,184 | 45.3 |
| 2010 | Corn | 8.1 | 157.1 | 0.0 | 5.44 | 31.7 | 34.3 | 1,518 | 93.2 | 12,176 | 34.5 |
| 2011 | Soybean | 17.2 | 40.8 | 126.8 | 4.17 | 18.2 | 31.6 | 1,518 | 93.5 | 12,173 | 36.7 |
| 2012 | Corn | 0.0 | 189.9 | 0.0 | 2.62 | 18.6 | 31.2 | 1,518 | 98.9 | 12,176 | 27.0 |
| 2013 | Soybean | 28.1 | 34.6 | 77.6 | 7.17 | 39.5 | 30.7 | 1,518 | 206.5 | 12,183 | 32.1 |
| Total | | 577.5 | 3948.1 | 3182.1 | 224.68 | 1,285.7 | 2,733.2 | 59,830 | 3,463.5 | 478,182 | 1,383.1 |
| Maximum | | 30.3 | 189.9 | 225.0 | 11.58 | 57.6 | 127.8 | 1,551 | 206.5 | 12,404 | 50.0 |
| Average | | 14.8 | 101.2 | 81.6 | 5.76 | 33.0 | 70.1 | 1,534 | 88.8 | 12,261 | 35.5 |
| Minimum | | 0.0 | 34.6 | 0.0 | 1.86 | 11.5 | 30.7 | 1,518 | 34.4 | 12,173 | 20.4 |
| Coefficient of variation | | 87.5% | 61.2% | 107.6% | 43.0% | 35.3% | 41.5% | 0.6% | 42.2% | 0.5% | 18.3% |

[1] First year of model simulation; model output was not considered in any of the data analyses in this study.

[2] Total P yield = Sediment P + Soluble P + Organic P

[3] Total N yield = Organic nitrogen + Nitrate in surface runoff + Nitrate in lateral flow + Nitrate in groundwater

[4] Note that N fertilizer applied in soybean years took place AFTER the soybean harvest in the fall and was intended as the pre-plant fertilization for the next year's corn crop.

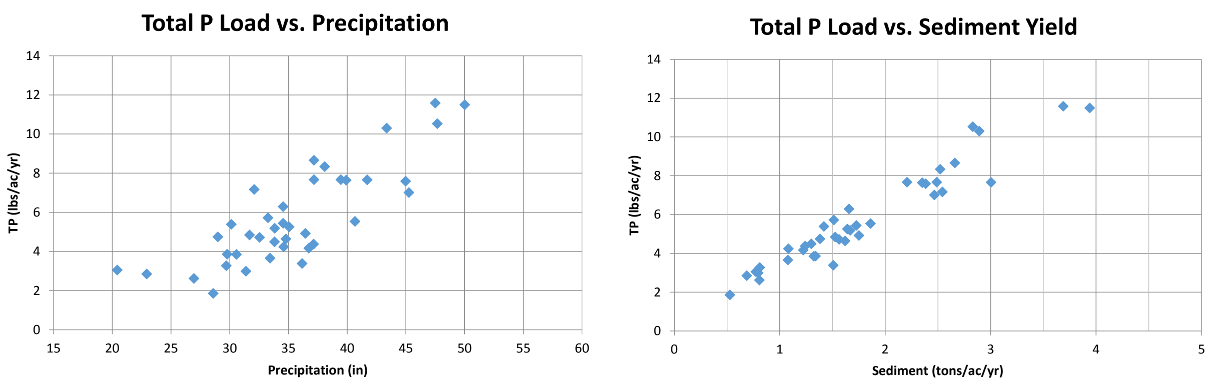



Figure 6: Edge-of-field annual total P loading vs precipitation (left) and total P loading vs sediment yield (right) at the Illinois study site by the 40-year SWAT base case model simulation

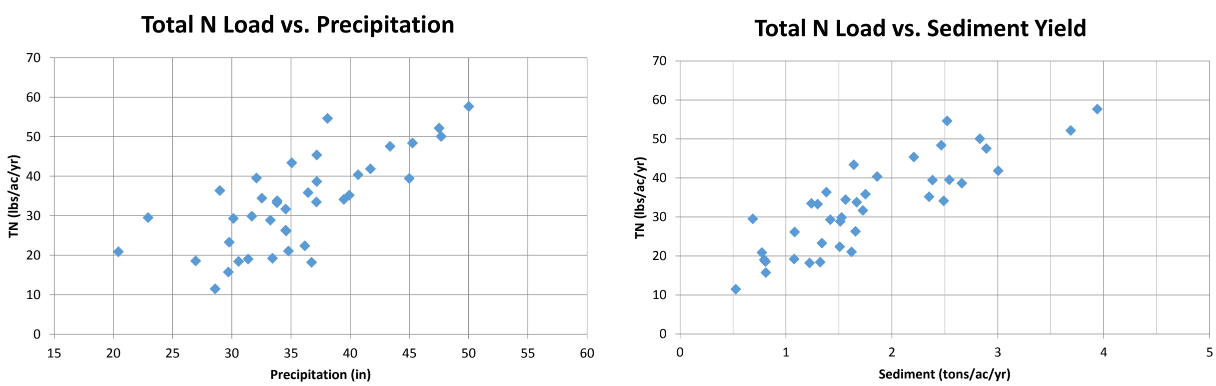



Figure 7: Edge-of-field annual total N loading vs precipitation (left) and total N loading vs sediment yield (right) at the Illinois study site by the 40-year SWAT base case model simulation

higher sediment yield (1.93 ton/ac on average vs. 1.65 ton/ac) and higher precipitation (36.9 in vs. 34.0 in) in soybean years, resulting in similar long-term annual total N load for the two crops. The same effect seemed to be at work for total P as well, with much more P fertilizers in the soybean years (again, applied after soybean harvest) but lower sediment yield and lower precipitation in the corn years.

### Particulate P load estimation tools development

The development of estimation tools based on the enrichment ratio method (Equations 2 and 3) was examined for two particular HRUs in the Illinois field: #645 and #1061. These two HRUs both have silty clay loam soils, representing the majority of the soil texture type in the field. HRU #645 has a soil carbon content of 1.92 percent and average USLE sediment yield rate of 3,327 kg/ha/yr (1.48 ton/ac/yr per SWAT simulation) while HRU #1061 has a much higher soil carbon content of 2.91 percent, lower sediment yield rate of 2013 kg/ha/yr (0.89 ton/ac/yr), and higher organic P and N contents. Comparing the results of enrichment ratio based load estimation tools from two different soils from the same field can give an indication of the generalizability of such a method.

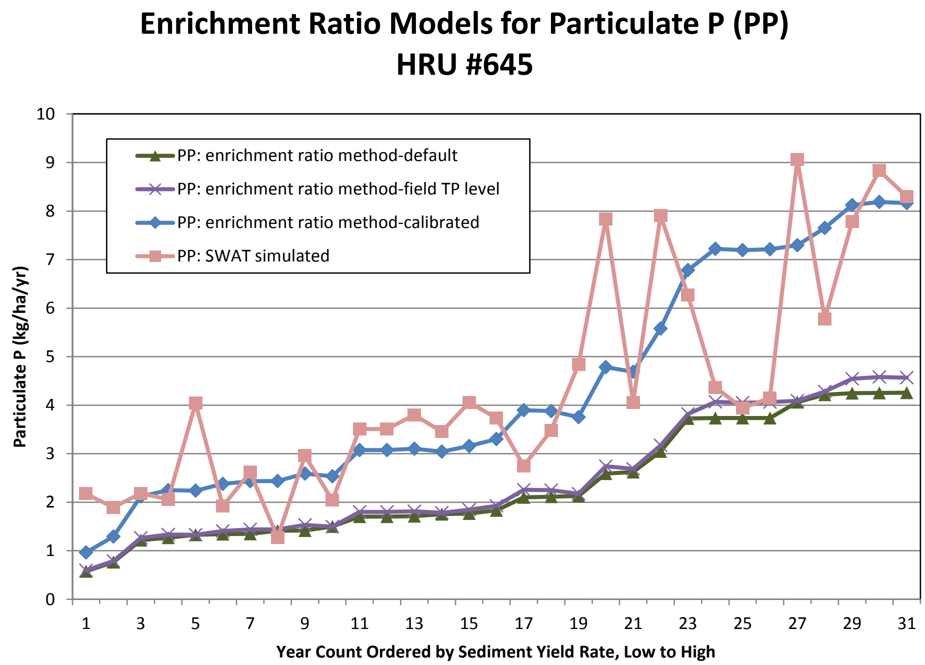
Data used for the tool development were extracted from the corn years of the SWAT 40-year simulation (except 1974, the first year of simulation) and the three scenarios of the calibration period for a total of 31 (19+12) sets of yearly data points. Because the fertilizer applications were mostly applied in corn years or targeted for corn growth, any future VRT or other fertilizer reduction practices would also be a corn focused effort. Consequently, developing tools for corn year load estimation makes most sense.

Table 14 presents the input and results of the three enrichment ratio method models examined for predicting particulate P (PP) in the two HRUs. These three models are:

1. Default soil total P value and enrichment ratio coefficients;
2. Actual field level as simulated by SWAT and default enrichment ratio coefficients a and b; and
3. Actual field level as simulated by SWAT and enrichment ratio coefficients a and b calibrated against SWAT simulated PP loads.

Additionally, the USLE (as calculated by the SWAT simulations) sediment yield values were used as the sediment loss from the field in Equation (2) in all three models. Figure 8 shows the annual PP loads of the 31 corn years predicted by these three models arranged from the lowest to the highest of the USLE soil losses calculated by the SWAT models. Particulate P (sediment P + organic P) load simulated by SWAT, as the actual load, was also shown in the figure (pink line with square markers).

Table 14 indicates that the default soil total P level of 500 ppm was very close to the actual field level as simulated by SWAT in HRU #651 but vastly underestimated in HRU #1061. With all default parameter values, Model 1 substantially underestimated the average PP load in both HRUs compared to those simulated by SWAT. With their soil P levels calibrated to the actual values but enrichment ratio coefficients still at default levels (Model 2), the enrichment ratio method still underestimated the average PP load substantially in HRU #645 but came close in HRU #1061. With the additional calibration of the coefficients, both HRUs had average PP loads, standard deviation of the loads, and the coefficients of variation of the loads that all closely resembled those simulated by the SWAT models. However, both enrichment ratio coefficients were now very different from the default values. More importantly, these two sets of coefficients were also very different from each other, suggesting the necessity of localized equation parameter values for the application of the enrichment ratio method. Figure 8 also clearly demonstrated the fact that enrichment ratio method at best can only represent the average magnitude and tendency of PP loading from agricultural fields. To fully grasp the year-to-year variation, sometimes very substantial, sophisticated models such as SWAT or edge-of-field monitoring would be required.



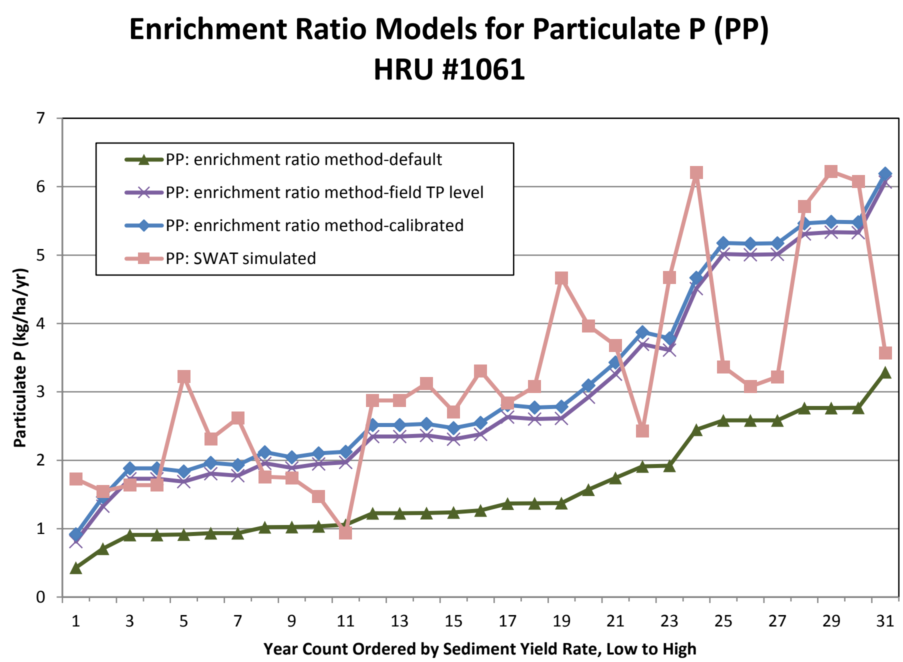




Figure 8: Particulate P (PP) load estimated by three enrichment ratio models and as simulated by SWAT for corn years in HRU #645 (upper) and HRU #1061 (lower) of the Illinois site

Table 14: Summary of model input and parameters for particulate P for the Illinois site

| Model | Average Soil Total P | Average Sediment Loss by USLE | Enrichment Ratio Coefficients | | Particulate P (PP) Load | | |
|---|---|---|---|---|---|---|---|
| | | | a | b | Average Load | Standard Deviation | Coefficient of Variation |
| | (ppm) | (kg/ha/yr) | | | (kg/ha/yr) | (kg/ha/yr) | |
| **HRU #645** | | | | | | | |
| Default[1] | 500 | 3,327 | 7.4 | -0.2 | 2.326 | 1.177 | 49.8% |
| Field Total P[2] | 524 | 3,327 | 7.4 | -0.2 | 2.482 | 1.255 | 50.6% |
| Calibrated[3] | 524 | 3,327 | 9.3 | -0.16 | 4.335 | 2.291 | 52.8% |
| SWAT[4] | 524 | 3,327 | -- | -- | 4.341 | 2.262 | 52.1% |
| **HRU #1061** | | | | | | | |
| Default | 500 | 2,013 | 7.4 | -0.2 | 1.584 | 0.760 | 48.0% |
| Field Total P | 949 | 2,013 | 7.4 | -0.2 | 3.010 | 1.454 | 48.3% |
| Calibrated | 949 | 2,013 | 10.6 | -0.24 | 3.168 | 1.456 | 46.0% |
| SWAT | 949 | 2,013 | -- | -- | 3.170 | 1.444 | 45.5% |

[1] Default soil total P level (silt soil) and the enrichment ratio coefficients from the enrichment ratio method (see also Figure 8).
[2] Model with actual field total P (simulated by SWAT) and default enrichment ratio coefficients (see also Figure 8).
[3] Model with actual field total P (simulated by SWAT) and enrichment ratio coefficients a and b calibrated against SWAT simulated PP loads (see also Figure 8).
[4] Simulated by SWAT.

## Particulate P load estimation tools development for the Kentucky site

The enrichment ratio based particulate P load estimation tool was also examined for the Kentucky site (Table 15 and Figure 9). HRU #1933 was chosen to demonstrate the applicability of the method in a completely different field in another state than the Illinois site and at the same time validate the conclusions drawn from the results from the Illinois site models.

It can be seen in Table 15 that the default soil P concentration of 500 ppm was very close to that simulated by SWAT for HRU #1933 of the Kentucky field. With a very high USLE sediment loss rate of 11,608 kg/ha (or 5.2 tons/ac), the default enrichment ratio model predicted a much higher average PP load than that simulated by SWAT. After adjusted for enrichment ratio coefficients of a and b, particularly a, the average PP load predicted by the model was brought down to near the SWAT estimate. However, standard deviation and coefficient of variation did not calibrate well.

Table 15: Summary of model input and parameters for particulate P for the Kentucky site

| Model | Average Soil Total P | Average Sediment Loss by USLE | Enrichment Ratio Coefficients | | Particulate P (PP) Load | | |
|---|---|---|---|---|---|---|---|
| | | | a | b | Average Load | Standard Deviation | Coefficient of Variation |
| | (ppm) | (kg/ha/yr) | | | (kg/ha/yr) | (kg/ha/yr) | |
| **HRU #1933** | | | | | | | |
| Default[1] | 500 | 11,608 | 7.4 | -0.2 | 6.495 | 2.475 | 38.1% |
| Field Total P[2] | 491 | 11,608 | 7.4 | -0.2 | 6.390 | 2.480 | 38.8% |
| Calibrated[3] | 491 | 11,608 | 5.1 | -0.19 | 4.839 | 1.899 | 39.2% |
| SWAT[4] | 491 | 11,608 | -- | -- | 4.869 | 2.534 | 52.0% |

[1] Default soil total P level (silt soil) and the enrichment ratio coefficients from the enrichment ratio method (see also Figure 9).
[2] Model with actual field total P (simulated by SWAT) and default enrichment ratio coefficients (see also Figure 9).
[3] Model with actual field total P (simulated by SWAT) and enrichment ratio coefficients a and b calibrated against SWAT simulated PP loads (see also Figure 9).
[4] Simulated by SWAT.

Figure 9 shows that PP loads as simulated by SWAT did not follow a general trend of increase with the increase of sediment yield calculated by USLE as the HRUs of the Illinois field did. It actually decreased substantially to a low of 2.7 kg/ha after reaching a high of 10.7 kg/ha. Due to the monotonic increase nature of the enrichment ratio method equations[2], it was difficult to adjust the enrichment ratio coefficients against SWAT simulated PP loads to have both similar standard deviation and average value, resulting in less-than-optimal calibration for the model.

As can be seen in Figure 9, the enrichment ratio method began to over-predict PP loading as sediment erosion rates increase. The modeled results where this began to occur were approximately at or above 13,500 kg/ha (6 tons/acre). It is presumed that this rate of erosion on no-till fields began to remove soils that were lower in the soil horizon, ones that were less enriched with P from the unincorporated fertilizer applications. The model fit was better at the lower soil erosion rates. Therefore, when applying this estimation method the practitioner should also consider the soil nutrient concentrations at different depths in the profile, especially when the estimated erosion rate is high (> 6 t/ac in this case).

By applying the enrichment ratio method to a different field it can be derived that a general increasing trend of PP loading with increasing sediment yield is necessary for the method to work properly. Intuitively, this condition is satisfied in most cases because PP loading is sediment erosion related by definition. However, in the few cases where this condition is not satisfied, such as HRU #1933 of the Kentucky field, estimating PP using the enrichment method would not reflect the year-to-year variability of PP load. On the other hand, the Region 5 model applies the enrichment ratio method by using a long-term average soil erosion rate. As long as

[2] Equation 3 for enrichment ratio calculation is in fact a negative fraction power curve of sediment yield that decreases first before leveling off. Substituting Equation 3 into Equation 2, however, results in a monotonically increasing curve.

the long-term average soil erosion rate does not imply the loss of soils with lower P concentrations, long-term PP load can still be estimated with good accuracy. This could be achieved, for example, by placing a screening process or cap on which rate should be used to establish the correlation. Such an approach would also need to consider if there is a drop in PP loading at the higher erosion rates when compared to the cap-adjusted high end of the range.

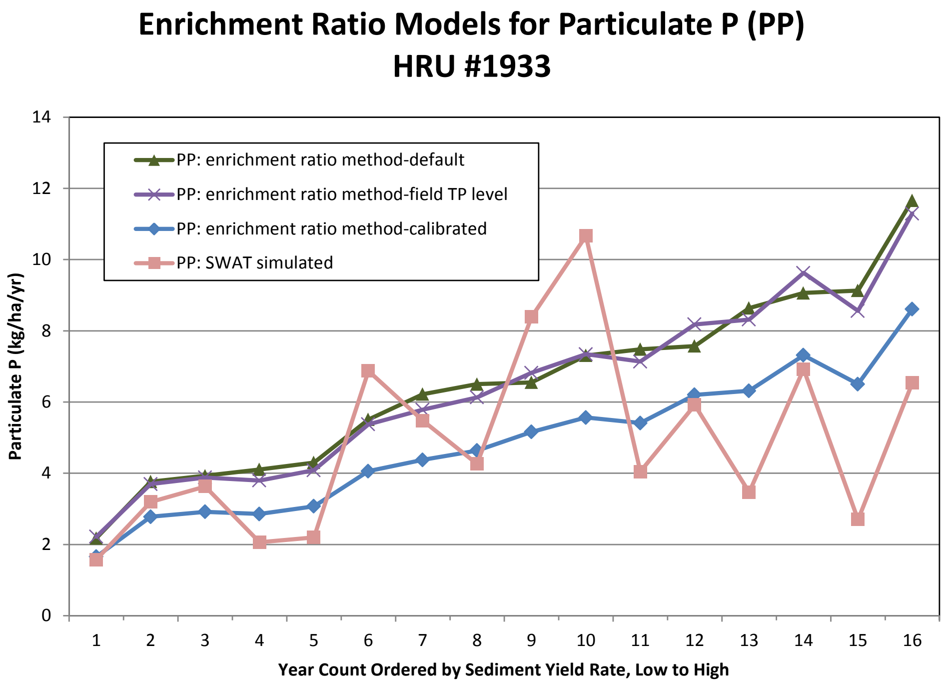
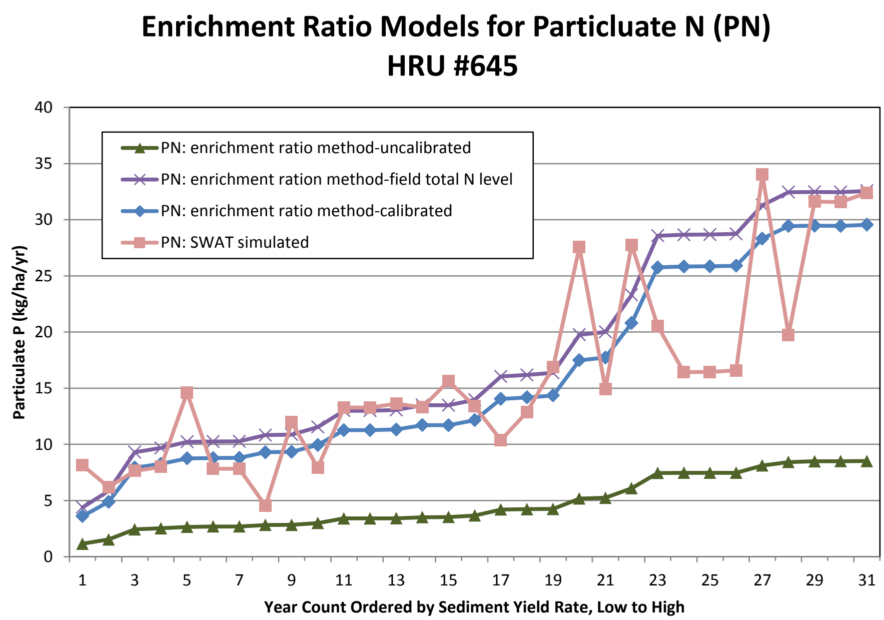



Figure 9: Particulate P load estimated by three enrichment ratio models and as simulated by SWAT for corn years in HRU #1933 for the Kentucky site

### Particulate N load estimation tool development

Because N fertilizer was included in the Illinois field VRT applications, a particulate N (PN) tool was developed as well using the enrichment ratio method for HRUs #645 and #1061.

Figure 10 and Table 16 show that the default soil total N level of 1,000 ppm for silty soils vastly under-represented field conditions for either HRU. As a result, the enrichment ratio model using the default value under-estimated the average PN loads by a wide margin. Therefore, using the default approach can be considered a conservative assumption in the PN credit estimation process. However, that may leave a sizeable amount of potential PN load reduction unaccounted for in a water quality credit program. Similar to the models developed for PP, default enrichment ratio coefficients did not predict the average annual load and its variability as well as measured conditions for either HRU. Likewise, adjusting the approach by using field measurements instead of default values had mixed results. After calibration, however, values of these parameters were closely matched against those simulated by SWAT, suggesting excellent applicability of the enrichment ratio method for PN load estimation. Figure 10 demonstrates the general upward trend of PN load with increased USLE sediment yield, indicating the importance of such trends in successfully applying the enrichment ratio method on a year-to-year basis.



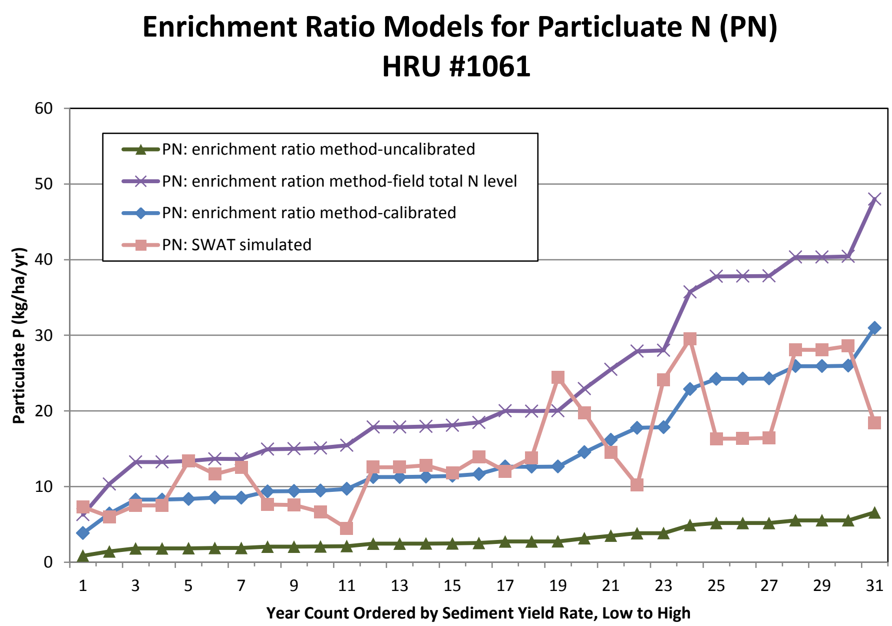




Figure 10: Particulate N (PN) load estimated by three enrichment ratio models and as simulated by SWAT for corn years in HRU #645 (upper) and HRU #1061 (lower) for the Illinois site

Table 16: Summary of model input and parameters for particulate N for the Illinois site

| Model | Average Soil Total N | Average Sediment Loss by USLE | Enrichment Ratio Coefficients | | Particulate N (PN) Load | | |
|---|---|---|---|---|---|---|---|
| | | | a | b | Average Load | Standard Deviation | Coefficient of Variation |
| | (ppm) | (kg/ha) | | | (kg/ha/yr) | (kg/ha/yr) | |
| **HRU #645** | | | | | | | |
| Default[1] | 1,000 | 3,327 | 7.4 | -0.2 | 4.724 | 2.354 | 49.8% |
| Field Total N[2] | 3,828 | 3,327 | 7.4 | -0.2 | 18.091 | 9.035 | 49.9% |
| Calibrated[3] | 3,828 | 3,327 | 4.72 | -0.16 | 16.037 | 8.379 | 52.2% |
| SWAT[4] | 3,828 | 3,327 | -- | -- | 16.029 | 8.380 | 52.3% |
| **HRU #1061** | | | | | | | |
| Default | 1,000 | 2,013 | 7.4 | -0.2 | 3.169 | 1.520 | 48.0% |
| Field TN | 7,299 | 2,013 | 7.4 | -0.2 | 23.134 | 11.110 | 48.0% |
| Calibrated | 7,299 | 2,013 | 4.03 | -0.18 | 14.700 | 7.233 | 49.2% |
| SWAT | 7,299 | 2,013 | -- | -- | 14.717 | 7.234 | 49.2% |

[1] Default soil total N level (silt soil) and the enrichment ratio coefficients from the enrichment ratio method (see also Figure 10).
[2] Model with actual field total N (simulated by SWAT) and default enrichment ratio coefficients (see also Figure 10).
[3] Model with actual field total N (simulated by SWAT) and enrichment ratio coefficients a and b calibrated against SWAT simulated PN loads (see also Figure 10).
[4] Simulated by SWAT.

Compared to the coefficient values (a and b) calibrated for PP for the two HRUs (Table 14), the values here for PN were much closer to each other between the two HRUs (Table 16). This seems to suggest that load estimation tools developed with the enrichment ratio method for PN may have a better generalizability than those for PP. More studies are needed to confirm this observation. This study was limited by the availability of study sites and field operation records. Ideally, it would be good to examine this observation and other findings from this study not only for more different HRUs in the studied fields but also for fields from other regions of the country.

### Nitrate-N load estimation tool development

Among all nutrient fractions, nitrate ($NO_3^-$) loading is near the top of the list of those most difficult to estimate with commonly measured or calculated parameters such as precipitation or sediment yield. This is due to: 1) the highly complex and dynamic nature of the nitrogen cycle in the soil; 2) the high mobility of nitrate in the water solution; and 3) the weak association of nitrate with soil particles. In this study, nitrate and other data were extracted from corn years from the SWAT models built for the Illinois field (see description in previous sections) and a multiple linear regression model was developed for nitrate. HRUs #645 and 1061 were again used as testing ground for the model development to represent two soils with different properties. Nitrate loading from soybean years was not examined because little N fertilizer was applied for soybean and because of the complication of N fixation by soybean plants. Because the Illinois field applied VRT and followed strict corn-soybean rotation through the years of record provided to this study, no additional scenarios based on different crop rotations were developed. Soil N levels at the times of agronomic significance (e.g., just before planting or sidedress) also did not vary substantively, leading to no additional splitting of the regression analysis for two or more levels of soil N.

An extensive examination of a host of potential measurable or calculable field and environmental parameters as the predictor (or independent variable) was conducted. Nitrate loading from the crop year (from one month before planting to one month before planting of next year's crop) was also examined as an alternative to the calendar year loading for the dependent variable in the linear regression analysis. Four independent variables were eventually selected, along with the calendar year nitrate load as the dependent variable, to develop multiple linear regression equations for nitrate load, as they yielded the best regression statistics. These variables are: N applied from fertilizers (*N applied*), the three month surface runoff volume from one month before the planting to two months after (*runoff 3mo*), soil nitrate level two weeks before planting, (*soil nitrate at planting*), and soil nitrate level two weeks before nitrogen sidedress (*soil nitrate at sidedress*).

Tables 17 and 18 present the results of the multiple linear regression analysis for nitrate loading from the two HRUs. Table 17 has *soil nitrate at sidedress* as one of the independent variables (predictors) while Table 18 has *soil nitrate at planting*. The highest $R^2$ value achieved by the two HRUs with soil nitrate levels measured at different times of the crop growth cycle was 0.639, and lowest was only 0.546. Comparing these to the $R^2$ values from the multiple linear regression analyses conducted for the total P or soluble P load from the Kentucky field, which most often were in the 0.8's or 0.9's, demonstrates the difficulty of predicting nitrate loads from agricultural fields. This also is an indicator that when working with a WQCT program an increase in the margin of safety for this parameter will be necessary, as this method is only explaining a little over half of the nitrate fate and transport dynamics taking place. In addition, the most important parameter in predicting total P or soluble P loading was sediment yield. Sediment yield was a strong independent variable for TP due to the large influence erosion has on delivering PP when that is the dominant fraction of phosphorus in TP. For soluble P loadings, sediment yield is a valuable input as it acts as a surrogate parameter for the volume and level of energy associated with precipitation in any given year. However, sediment yield did not show any statistical significance in predicting nitrate loading. That fact not only inferred the weak association between soil particles and nitrate but also deprived us of a widely estimated and thus most available field parameter for nitrate load estimation. A potential explanation for why sediment yield does not work as well for nitrate prediction is that nitrate is a soluble parameter, one without ionic bonding potential when it comes in contact with soil particles. As such, nitrates can move through and across the soils during all precipitation and snow melt events and not just those with sufficient energy to erode soils or form channelized flow paths.

Table 17: Multiple linear regression results for nitrate loading in corn years from HRUs #645 and #1061 with *soil nitrate at sidedress* as one of the independent variables

| HRU #645 | | $R^2$ | | 0.639 |
|---|---|---|---|---|
| | | Standard Error (lb/ac) | | 4.092 |
| | | Nitrate Load Average (lb/ac) | | 13.513 |
| | | Observations | | 31 |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
| Intercept | 9.322 | 7.988 | 1.167 | 0.253 |
| Runoff 3mo (in) | 1.658 | 0.483 | 3.431 | 0.002 |
| N applied (lb/ac) | 0.239 | 0.045 | 5.309 | 0.000 |
| Soil nitrate at sidedress (lb/ac) | -0.202 | 0.051 | -3.985 | 0.000 |

| HRU #1061 | | $R^2$ | | 0.608 |
|---|---|---|---|---|
| | | Standard Error (lb/ac) | | 3.876 |
| | | Nitrate Load Average (lb/ac) | | 12.974 |
| | | Observations | | 31 |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
| Intercept | 5.010 | 6.901 | 0.726 | 0.474 |
| Runoff 3mo (in) | 1.494 | 0.458 | 3.259 | 0.003 |
| N applied (lb/ac) | 0.218 | 0.048 | 4.587 | 0.000 |
| Soil nitrate at sidedress (lb/ac) | -0.156 | 0.045 | -3.496 | 0.002 |
| | | | | |

Table 18: Multiple linear regression results for nitrate loading in corn years from HRUs #645 and #1061 with *soil nitrate planting* as one of the independent variables

| HRU #645 | | $R^2$ | | 0.546 |
|---|---|---|---|---|
| | | Standard Error (lb/ac) | | 4.590 |
| | | Nitrate Load Average (lb/ac) | | 13.513 |
| | | Observations | | 31 |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
| Intercept | 12.550 | 11.508 | 1.090 | 0.285 |
| Runoff 3mo (in) | 2.261 | 0.516 | 4.380 | 0.000 |
| N applied (lb/ac) | 0.079 | 0.040 | 1.980 | 0.058 |
| Soil nitrate at planting (lb/ac) | -0.191 | 0.072 | -2.658 | 0.013 |

| HRU #1061 | | $R^2$ | | 0.573 |
|---|---|---|---|---|
| | | Standard Error (lb/ac) | | 4.047 |
| | | Nitrate Load Average (lb/ac) | | 12.974 |
| | | Observations | | 31 |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
| Intercept | 10.068 | 8.706 | 1.157 | 0.258 |
| Runoff 3mo (in) | 1.906 | 0.446 | 4.271 | 0.000 |
| N applied (lb/ac) | 0.103 | 0.033 | 3.104 | 0.004 |
| Soil nitrate at planting (lb/ac) | -0.181 | 0.061 | -2.997 | 0.006 |

Comparing Tables 17 and 18 showed that the set of predictors including *soil nitrate at sidedress* (Table 17) performed better than the set of predictors including *soil nitrate at planting* (Table 18) in terms of statistical significance of the predictors (smaller *p* values) and overall regression $R^2$ values. This pointed to the importance of the timing of taking soil N samples for estimating nitrate loading. In addition, agronomically, the sidedress of the N application is generally the most important component of the "right timing" in the "4Rs". Therefore, taking soil N samples just before the sidedress also makes agronomical sense. When sidedress applications are not used the spring pre-plant period test results can be substituted. Note that the multiple linear regression input coefficient for the soil nitrate level always has a negative correlation. The inverse relationship is an indicator of how testing is used in the equation to determine the nitrogen lost based on a mass balance approach. For illustration, the following mass balance is provided; the project team acknowledges the presentation is overly simplified but none-the-less useful to discuss the concept. A mass balance equation tallies the total nitrogen in the soil at the time of the first test and adds the amount of fertilizer applied after that test. Then when a second test is taken (after the fertilizer applications), that test result provides what is left after losses to the environment (leaching and/or N gases released into the atmosphere). Therefore, the negative correlation of soil nitrate levels reflects the prediction of edge-of-field nitrate loading on using the mass budget to solve for losses from leaching, surface runoff and gases. Thus collecting information as late in the planting/crop emergence period as possible increases the predictive capability regarding what happened in the pre-canopy period. The improved multiple linear regression R squared values support this concept.

Although neither annual surface runoff nor sediment yield was a statistically viable predictor for nitrate loading, a related parameter, the three month surface runoff volume from one month before the planting to two months after (*runoff 3mo*), was introduced as to consider the precipitation and snow melt influence on soluble parameters. These three months overlapped the field preparation period through just after canopy closure. During this period both the planting (a.k.a. "weed and feed") and sidedress applications of nitrogen fertilizers occur. Therefore, any rain that occurred during this period would result in higher nutrient loading rates in runoff that carry some of the applied N off the field. Estimation of this three month runoff could be completed in a WQCT crediting method by using the SCS curve number method or other simple hydrological models.

## Summary and Conclusions

This study applied SWAT modeling to two Midwest corn-soybean fields to simulate the effect of VRT on nutrient loading and evaluate the potential for generating load reduction for WQCT programs. Due to the lack of water quality monitoring data, the models developed were calibrated against crop yields and literature value based adjustment was conducted for sediment yield.

The calibrated models were used to evaluate the VRT's ability to generate WQCT program credits for the calibration periods. These calibrated models were then extended using NOAA NCDC historic weather data to develop 40-year long-term models. These models were used to simulate the long-term effects of VRT on nutrient loading and develop tools for predicting nutrient loads using commonly measured or calculated field and environmental parameters. This summary will review the conclusions regarding the impacts of VRT on generation of WQCT and the right time of application, with the right placement, while using the right source. It will then outline implications of the second stage of model simulations, the expanded simulation time frame of a 40-year period, and the long-term effects of VRT on generation of WQCT.

**Conclusions from Model Calibration Period Simulations: First Stage**

The evaluation of VRT's ability to generate WQCT program credits focused on answering two questions. Each of these questions is discussed here.

1) <u>Will VRT generate nutrient load reductions for WQCT credits in various climatic and cropping conditions?</u>

The answer to this question is a strong affirmative. Applying VRT for only one year for corn in the Kentucky field for P reduced P used in the field by 40 percent compared to the state average rate according to NASS state survey. This reduction led to 11 percent lower P loading from the field in the application year and 8.2 percent lower P loading the next year.

For the Illinois field, which had a longer calibration period (eight years) and more years of VRT application, model evaluation indicated that edge-of-field N load reduction persisted even during the severe drought year of 2012 for the Illinois field, although the reduction was less than half of the eight year average. On the other hand, the fact that the drought year load reduction was small indicates that to appropriately provide assurances that nonpoint sources consistently provide equal or greater environmental protection than point sources can achieve, trading ratios providing a margin of safety need to be designed based on longer-term weather records. In addition, the low load reduction per acre rate under extreme weather conditions points to the need to include and aggregate larger blocks of acres, working with more farmland parcels in order to generate a sizable, stable source of credits to be used in a trading program.

2) <u>Will the load reduction variability, monthly or annual, affect the feasibility of using the generated credits in a WQCT program based on EPA trading guidance?</u>

Based on the result from the Illinois field, the evaluation found the use of a monthly time step to generate WQCT credits would require some extraordinary trading ratios (in the hundreds) to ensure a margin of safety to compensate for monthly variation in load reduction. Therefore, monthly average credit generation is not a viable time step. However, when using an annual time step for credit generation, trading ratios required would fall within the commonly used value range (2~3:1). Annual time step credits can be set by either adjusting the NPDES permit effluent averaging periods or through Clean Water Act delegated authority WQCT rule, policy or guidance that allows for long-term credit generation periods to offset monthly averaged effluent limits.

In addition to "right" rates of the VRT, two other "Rs" of the "4Rs" of fertilizer application, "right" timing and "right" placement, were examined using the SWAT model developed for the Kentucky field. It was shown that "right" placement (incorporating fertilizer into the soil) could reduce P loading from the field by over 10 percent. Changing the timing from spring to previous fall, however, did not result any discernible change of P loading from the field.

### Conclusions from 40-year Simulations: Second Stage

The second stage of model simulations expanded the simulation time frame to a 40-year period to examine the long-term effects of variable rate technology and provide data for the development of regression models for load quantification in water quality trading. Long-term 40-year simulations for the two study fields showed that most of the total P loading from both fields was associated with sediment. On the other hand, the Kentucky field, which had relatively less erodible soils, exported most (66.0 percent) of the total N in the soluble nitrate form through groundwater drained off the field while eroded organic N also accounted for a substantial portion (29.1 percent). For the Illinois field, organic N was the majority (63.0 percent) component of total N while nitrate in surface runoff was the second at 30.8 percent. These differences pointed to the more dynamic and local nature of N cycle in the cropland system and its effect on N loading from the system.

In addition, the base case long-term simulation for the Kentucky field showed that it took about 15 years for the soil soluble P level to decrease to a stable level when the below state average level of P fertilizer application rate introduced through the VRT for corn growth was maintained continuously. On the other hand, soil total P level steadily declined over the simulation period while total P load from the field did not exhibit a clear trend of change, suggesting factors other than soil P level had more influence (or counter effect) on the losses of P from the field.

The long-term simulations also provided data for the development of nutrient load estimation tools for representative HRUs of the study fields. The first set of tools used *plant available P* (sum of soil soluble P and fertilizer P added), *sediment yield*, and *plant P uptake* as the independent variables (the predictors) to develop multiple linear regression models to predict the annual total P and soluble P loads from two different HRUs in the Kentucky field. Among the three predictors, *sediment yield* was the most consistent and the strongest one in these regression models. Overall, the regression models, designed individually for the two crops (corn and soybean) with various rotation sequences and a two-tier *plant available P* division, were able to achieve high statistical significance in most cases.

Multiple linear regression models were also developed to predict the annual nitrate load from two different HRUs in the Illinois field. Nitrate movement in the soil-crop-environment system was highly dynamic and was not closely associated with sediment erosion. As a result, it was difficult to construct simple multi-variable linear equations to estimate nitrate load with commonly used field or crop growth parameters. Nevertheless, multiple linear equations were developed for the Illinois field using three new measurable or calculable parameters: N applied from fertilizers (*N applied*), the three month surface runoff volume from one month before the planting to two months after (*runoff 3mo*), and soil nitrate level two weeks before planting (*soil nitrate at planting*) or soil nitrate level two weeks before nitrogen sidedress (*soil nitrate at sidedress*). These equations were able to explain a majority of the variance of nitrate loading from the field ($R^2 > 0.5$). These results showed that nitrate credit estimation would be viable but require a high margin of safety.

The second set of tools, based on EPA Region 5's sediment enrichment ratio method (the Region 5/STEPL model), was also successfully developed for estimating particulate P and N loads for two HRUs in the Illinois study field. Applicability of this method for the Kentucky field was also demonstrated. It was shown that adapting the EPA Region 5/STEPL method to the study fields required 1) the use of actual soil nutrient concentrations (total P and total N) of the fields, and 2) the calibration of the coefficients in the method equation.

In addition, results showed that this method could over-estimate particulate P loads when soil erosion rate was very high, possibly due to the erosion of under-layer soils with lower P concentration than the surface layer. Although calibrating the coefficients of the enrichment ratio equation for each testing HRU produced a better model for the HRU than the default coefficients, this result seemed to be HRU specific. Therefore, such a calibration would likely be impractical in a WQT program.

Based on the results, the following steps should be taken to reduce the potential uncertainty when applying the Region 5/STEPL model in a WQT program for load reduction quantification:

- Rather than the default values defined in the current Region 5/STEPL model, or soil P tests commonly used for soil fertility determination, a total P test of the studied field should be used to quantify P loading potential with the model.
- Adjustment should be made for over-prediction of P loading at high erosion rates by applying a cap on the erosion rate applicable for the method.
- If the soluble P fraction is low, a decision should be made whether to exclude it as part of the total P load estimate (effectively using soluble P as an implicit margin of safety) or include it as part of the total P but with a high explicit margin of safety.

In summary, results from this study indicate that it is a viable approach to use measurable (e.g., soil test P and N fertilizer applied) or calculable (e.g., sediment yield and surface runoff) parameters to construct estimation tools to quantify loadings of various fractions of nutrients from agricultural fields. These tools, with modification and adaption to specific local conditions, can then be used to quantify loading changes induced by crop management practices such as the VRT. These changes will form the basis for calculating credits for WQCT programs.

## Recommendations for Further Studies

This study proved the viability of VRT as a crop management practice with potential to generate credits for WQCT programs. It has completed the first steps toward development of credit estimation methods for quantifying these credits. For the further development and improvement of these methods, one obvious need is the availability of long-term farm operation records and environmental monitoring data including soil test, runoff, sediment and nutrient loading monitoring.

In the absence of a long-term farm record (several decades), long-term simulation of the VRT in this study had to rely on applying recent VRT field operations to past climatic records. Ideally, for a true long-term simulation of soil nutrients and their loading from the field, soil nutrient levels simulated by the models could be extracted periodically and compared to desired values for crop production and environment needs. VRT fertilizer application rates would then be adjusted to achieve these values by working with experienced agronomists or crop technicians. Such an approach would be able to provide results that enable us to truly track the effect of the VRT and thus provide a more realistic basis for load quantification tools development.

Other recommendations are presented as follows for next steps for the development of WQCT components in various ecosystem service crediting programs:

- Testing findings on sites with edge-of-field water quality and quantity measurements.
- Further developing the credit estimation method for nutrient management. This could include comparing findings from this study with similar evaluations from fields with different physical settings and/or agricultural operations (for example, in the current study, only commercial fertilizer was used, and no manure applications were considered).
- Developing a life-cycle economic analysis.  An economic analysis is intended to inform decision makers regarding long-term average costs and the related break point where generating credits provides a reasonable profit to compensate for the occasional and nominal yield loses incurred due to nitrogen rate reductions.
- Developing field nutrient measurement protocols for determining TP and TN concentrations in soils; and
- Soliciting peer review of findings.

## References

Almendinger, J. E. and J. Ulrich, 2012,  *Applying a SWAT model of the Sunrise River watershed, eastern Minnesota, to predict water-quality impacts from land-use changes*, report pursuant to the project: “Sunrise River Watershed SWAT Modeling Phase 5,” funded by the Minnesota Pollution Control Agency under contract No. B47177.

Arabi, M., J. R. Frankenberger, B. A. Engel, and J. G. Arnold,  2008,  Representation of Agricultural Conservation Practices with SWAT, *Hydrological Processes* 22(16): 3042-3055, DOI: 10.1002/hyp.6890

Arnold, J., J.R. Kiniry, J.R. Williams, E.B. Haney, and S.L. Neitsch,  2011,  *Soil and Water Assessment Tool Input/Output File Documentation – Version 2009*, Texas Water Resources Institute Technical Report No. 365, Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, and Blackland Research Center, Texas AgriLife Research, September 2011.

Bender, R. R., J. W. Haegele, M. L. Ruffo, and F. E. Below,  2013,  Nutrient Uptake, Partitioning, and Remobilization in Modern, Transgenic Insect-Protected Maize Hybrids, *Agronomy Journal* 105(1):161-170.

EPRI,  2011,  Creating Nitrous Oxide ($N_2O$) Emissions Offsets in Agricultural Crop Production in the United States (aka "Nutrient Management").

EPRI,  2013,  Pilot Trading Plan 1.0 for the Ohio River Basin Interstate Water Quality Trading Project.  Accessed April 17, 2015 online at http://wqt.epri.com/pdf/Full-Trading-Plan-as-amended.pdf

EPA,  2003,  Water Quality Trading Policy.  Accessed April 20, 2015 on line at: http://water.epa.gov/type/watersheds/trading/tradingpolicy.cfm

EPA, 2004a. Annual Permit Limits for Nitrogen and Phosphorus for Permits Designed to Protect Chesapeake Bay and its tidal tributaries from Excess Nutrient Loading under the National Pollutant Discharge Elimination System accessed 11/6/15 at: http://www3.epa.gov/reg3wapd/npdes/pdf/ches_bay_nutrients_hanlon.pdf

EPA, 2004b, Water Quality Trading Assessment Handbook. EPA 841-B-04-001.

EPA, 2007, Water Quality Trading Toolkit for Permit Writers, EPA 833-R-07-004.

Fang, F. Brezonik, P.L., Mulla, D.J. and L.K. Hatch, 2002, Estimating Runoff Phosphorus Losses from Calcareous Soils in the Minnesota River Basin. *J. Environmental Qual.* 31:1918-1929.

Frere, M. H., J. D. Ross and L. J. Lane, 1980, Chapter 4. The Nutrient Submodel, *In* W.G. Knisel (ed.) *CREAMS, A Field Scale Model For Chemicals, Runoff, and Erosion From Agricultural Management SystemsVolume I. Model Documentation*. USDA Conservation Research Report No. 26. Accessed October 19, 2015 on line at: http://www.tifton.uga.edu/sewrl/Gleams/creams2.pdf

Gassman, P. W., J. R. Williams, X. Wang, A. Saleh, E. Osei, L. M. Hauck, R. C. Izaurralde, 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(3): 711-740

K&A (Kieser & Associates, LLC), 2005, *SWAT Modeling of the St Joseph River Watershed, Michigan and Indiana.* Prepared for the Friends of the St Joseph River (June 2005).

MCD (Miami Conservancy District), 2005, Great Miami River Watershed Water Quality Credit Trading Program Operations Manual. Accessed April 17, 2015 on line at: https://www.miamiconservancy.org/water/documents/TradingProgramOperationManualFeb8b2005secondversion.pdf

MDEQ (Michigan Department of Environmental Quality), 1999, *Pollutants Controlled Calculation and Documentation for Section 319 Watersheds*, Lansing, June 1999.

National Agricultural Statistics Service (NASS), 2012, *Agricultural Chemical Usage Reports*: *2010 Upland Cotton*, *Fall Potatoes* and *2012 Soybeans and Wheat*, Training Manual United States Department of Agriculture, http://www.nass.usda.gov/Statistics_by_Subject/Environmental/index.asp (last verified March 6, 2015).

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, 2011, *Soil and Water Assessment Tool Theoretical Documentation – Version 2009*, Texas Water Resources Institute Technical Report No. 406, Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, and Blackland Research Center, Texas AgriLife Research, September 2011.

Sawyer, J.E. and A. P. Mallarino, 1999, *Differentiating and Understanding the Mehlich III, Bray, and Olsen Soil Phosphorus Tests,* presented at the 19th Annual Crop Pest Management Short Course, University of Minnesota, St. Paul, MN, November 22, 1999. Available at http://www.agronext.iastate.edu/soilfertility/presentations/mbotest.pdf (last verified March 3, 2015)

USGS's National Map Viewer, http://viewer.nationalmap.gov/viewer (last visited March 3, 2015)

Waidler, D., M. White, E. Steglich, S. Wang, J. Williams, C. A. Jones, and R. Srinivasan, 2009, *Conservation Practice Modeling Guide for SWAT & APEX*, Texas A&M University. Available at http://oaktrust.library.tamu.edu/handle/1969.1/94928?show=full; last accessed on October 9, 2015.

White, M., D. Storm, H. Zhang, C. Penn, P. Busteed, G. Fox, and M. Smolen, 2007, *Proposed Updates to the Soil and Water Assessment Tool (SWAT) Phosphorus Model*, Poster, Southern Extension and Research Activity (SERA) - 17 Annual Meeting, Fayetteville, AR, June 11-13, 2007.

Williams, J.R., 1990, The Erosion-Productivity Impact Calculator (EPIC) Model: A Case History, *Philosophical Transactions: Biological Sciences*: *Quantitative Theory in Soil Productivity and Environmental Pollution (Sep. 29, 1990)*, 329(1255): 421-428

Williams, J. R., R. C. Izaurralde, and E. M. Steglich, 2012, *Agricultural Policy/Environmental Extender model: Theoretical Documentation. Version 0806.* Temple, Tex.: Texas A&M University, Texas AgriLIFE Research, Blackland Research and Extension Center. Available at: http://apex.tamu.edu/documentation. Accessed 10 August 2015.

Winchell, M., R. Srinivasan, M. Di Luzio, and J. Arnold, 2010, *ArcSWAT Interface for SWAT2009*, Blackland Research and Extension Center, Texas AgriLife Research, and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, August 2010.

Wisconsin DNR, 2013, Guidance for Implementing Water Quality Trading in WPDES Permits. Guidance Number: 3800-2013-04. 08/21/2013. Accessed 11/06/2015 online at: http://dnr.wi.gov/topic/surfacewater/documents/WQT_guidance_Aug_21_2013signed.pdf

# APPENDIX 2

## Item #2. Water Quality Credit Trading: Credit Estimation Method Development

# Water Quality Credit Trading: Credit Estimation Method Development
# November 2015

Water Quality Credit Trading (WQCT) credit estimation methods are being developed for precision agriculture applications of variable rate technology (VRT). Using improved nutrient management techniques for water quality credit generation can be complex. Not all fields where VRT methods are adopted end up reducing the nutrient load that is lost to surface waters, when compared to the previous nutrient application methods used on that field. Water quality parameters such as phosphorus, nitrogen, and nitrates are necessary for crop growth. However, the nature of nutrient management, especially nitrates, is that the nutrient must be in place before the crop needs to use it, making it vulnerable to climatic events and associated potential release into the water resources. Therefore, to provide guidance on how to reduce nutrient nonpoint source loading while maintaining nutrient resources for crop needs, the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS) has developed the "4Rs." The "4Rs" represent the four right types of practices when planning nutrient management. The "4Rs" consist of the right:

1. Application rate for crop needs
2. Timing of applications
3. Method of application
4. Form/source of nutrients

The "4Rs" provide general guidance on how to optimize plant uptake of applied nutrients and minimize the amount lost to the environment. The agricultural producer, agronomy technical service provider, and NRCS staff can tailor a farm specific approach given the farm's cropping practices, soils, regional climate patterns, farm equipment, and nutrient sources (e.g., synthetic versus manure) available. The "4Rs" recommend a farmer's nutrient management plan emphasize incorporation of agronomic rate applications that are timed as close to the crop's nutrient uptake as practical. In addition, the crop's entire nutrient needs (macro and micro nutrients) should be met along with pH, so that the full crop yield potential is achieved. This minimizes nutrient releases to the environment when lower yields are caused by the plants suffering a nutrient deficiency because one type of nutrient was not available when needed. When using a nutrient management plan that has addressed all four "rights" an agricultural producer benefits from robust crops while minimizing the loss of nutrients to the water resources. Based on the assumption that these sound principles provide the foundation of environmental protection, the project team structured an evaluation of VRT implementation practices. The evaluation results provided sufficient information to develop four credit estimation methods for edge-of-field phosphorus and nitrogen nonpoint source loading for WQCT purposes.

Development of a defensible WQCT credit estimation method uses science based decision making and strives to provide repeatable results in a predictable process regardless of who is running the estimation method. As indicated, the primary outcome of the credit estimation method is to provide environmental protection. Assuring environmental protection when developing a prediction method can be accomplished by combining policies that limit the method's use in the wrong setting and guide the development process towards providing a conservative estimate. When surrounded by the appropriate mix of multiple policy options even a simple "model's" answer can provide an environmentally protective result. Policies to consider that surround an edge-of-field credit estimation method include evaluation of which model to use, conservative assumptions used in gathering the input data, providing an adequate margin of safety to address the uncertainty introduced by the estimation method, and adding site and/or conservation measure eligibility policies to avoid using the method in a wrong setting.

A second consideration is that a WQCT program will only be used when it offers a compliance option that is cost-effective. As such, WQCT program protocols must be evaluated based on whether or not the method is too conservative to be useful. Stated another way, providing equal or greater environmental protection must be achieved, but excessively conservative approaches come with costs that are not affordable. An overly conservative process has a potential to introduce unwarranted high transaction costs and/or staff resource commitments that are too challenging for practitioners. Therefore, the second appropriate development consideration is to manage the transaction cost impacts. One example is that the estimation method should be an easy-to-use tool that allows local conservation and agricultural service providers access to the credit estimation process. Often WQCT program managers reach out to local conservation technicians to participate as site assessors. The use of local conservation technicians is highly desirable. Local conservation technicians can provide a contact point to many potential agricultural producers, producers who already trust the technician. Plus, the technician already has an understanding of the agricultural producer needs. This firsthand knowledge can reduce the program's credit transaction costs, as it may minimize the number of sites where the producer is not interested in participation (i.e., minimizes "cold call" rejections). In addition, local conservation technicians can reduce mobilization costs, and may provide marketing opportunities when they already are visiting potential farms to work on other business activities.

The guiding principles described above were used by the project team to develop a science based approach that results in a WQCT credit estimation method based on tools local conservationists already apply. The project team based the nutrient load estimate on a process that used modeling results provided by creating a Soil and Water Assessment Tool model (SWAT) of two independent fields. This fulfills the objective of using a science based approach. Each field, one in Kentucky and another in Illinois, have a history of using VRT applications. For more information on the SWAT setup, calibration and nutrient application scenarios please see Appendix 2- #1 - *SWAT Application for Developing a Credit Estimation Method for Precision Agriculture* (K&A, 2015). The SWAT model provides an appropriate blend of crop agronomy and water quality response for evaluating changes in nutrient management techniques. However, requiring WQCT practitioners to run the SWAT model in order to estimate a credit transaction's value would not be a pragmatic approach. Only a small percentage of local agronomy and conservation service providers have the training necessary to run the SWAT model. Requiring this special skill set to evaluate the site crediting values would increase transaction costs and reduce the number of practitioners that could participate. The statistical analysis of the SWAT modeling results allowed the identification of critical parameters to use when estimating VRT benefits. This list of equation inputs then can be gathered from field testing and other modeling tools which are both more available and are already commonly used by the local experts described above, addressing the objective of providing a user-friendly method.

In order to address the variability in year-to-year results when working with weather, soil nutrient concentrations, and crop yields for many different fields with different soil classifications, the credit estimation method must be combined with a margin of safety. Most often this measure is based on using an input tool that incorporates a long-term record. A tool like the USDA NRCS model Revised Universal Soil Loss Equation v2 (RUSLE2) commonly provides the average expected soil erosion estimates, based on an empirical fit to long-term data. Likewise, the USDA Technical Release 55, Small Watershed Hydrology model, also develops peak flow estimation given a typical storm recurrence interval (USDA NRCS, 1986). This model has been adapted by other pollution control programs. The EPA (1976), method calculates monthly or yearly runoff using TR-55 and a long-term period of record for rainfall events. The runoff is summed for each event and then averaged for like months or on an annual basis. WQCT programs such as the earlier 2008 Pennsylvania Department of Environmental Quality approved phosphorus calculators uses a simpler method. The PA DEP, supported by World Resources Institute, Penn State University, and others, chose to divide the annual average precipitation amount by the 2-year recurrence storm event to arrive at the number that is used as a multiplier for the 2-year recurrence interval storm runoff. PA DEP later transferred trading activities over to PENNVEST so this calculator is no longer available on the internet. In addition, the NRCS is currently working on calibrating the Nutrient Tracking Tool (NTT). NTT is a windows interface that allows local service providers to run the Agricultural Policy/Environmental eXtender model (APEX). The NTT platform uses a long-term 40-year weather record to produce an averaged edge-of-field nonpoint source nutrient loading result. Each of these methods can be applied successfully when combined with an appropriate margin of safety. Likewise, the methods to credit VRT nutrient reductions are based on the average best fit of the multiple year SWAT model results and then assessed for determining an adequate and appropriate margin of safety.

## Equations and Data Inputs for Load Estimation Methods from Model

The following equations were derived from evaluation of SWAT model results summarized in Appendix 2- #1 - *SWAT Application for Developing a Credit Estimation Method for Precision Agriculture.* These credit estimation methods show strong indications that promise environmentally protective estimates for reductions when applied in the right settings. It is further noted that additional evaluation on other sites is necessary to verify both the equation based methods and adequacy of the margin of safety. The four equations and associated margins of safety recommended are for:

1. VRT nutrient management for particulate phosphorus loading rates
2. VRT nutrient management for particulate nitrogen loading rates
3. VRT nutrient management with the use of nitrogen testing just before sidedress nitrogen applications for nitrates
4. VRT nutrient management without soil testing before sidedress nitrogen applications for nitrates (may be applied conservatively to operations not using sidedress applications).

Each of these methods should only be applied after the WQCT program has considered the short list of eligibility policies recommended to provide assurances that appropriate site selection was determined. In addition, this project considered the viability of crediting section boom control which is a precision agriculture VRT method to reduce overlaps and skips during fertilizer applications. Section boom control VRT approaches can use these credit estimation methods as appropriate.

Policy considerations for determining eligible sites

Policy Consideration 1: The "4Rs" right source emphasizes that appropriate nutrient availability for all nutrients and pH be managed to enhance the crop uptake of nutrients. This approach minimizes the loss of one nutrient to the environment caused by crop yield reductions due to deficiency of another nutrient. Therefore, WQCT should not be considered when implementing the VRT nutrient management approach results in a substantial yield loss.

Policy Consideration 2: The project team found that on-the-go VRT systems were far more complicated to assess because of the ever changing rates, yields, and soils. It is more manageable, and therefore more conservative, to provide a credit estimation method for zone map applications of VRT. The use of zone map application recommendations allow the credit estimation methods to be applied on a reasonable scale for input requirements such as soil erosion estimates. Inversely, on-the-go VRT produced over 1,000 different combinations of soil erosion rates, crop yields, nutrient application rates, and soil nutrient concentrations in the124-acre Kentucky field.

Policy Consideration 3: Particulate nutrient equations should not be applied to sites where the depth of soil erosion exceeds the soil profile depth of enriched nutrients to support crop production. The sediment attached nutrient estimation method will produce an overestimate if erosion occurs at depths where soil nutrient concentrations are substantially less than the surface concentration (e.g., high erosion rates on fields with no-till management and surface applications without incorporation).

Policy Consideration 4: Nitrate credit estimation should only be applied when nitrogen applications precede corn years and spring nitrogen soil samples are collected. Spring testing is a critical component of determining the nitrate lost to the environment based on using a mass balance approach.

Policy Consideration 5: Particulate phosphorus estimation methods are considered an adequate-conservative estimate for crediting TP when the particulate form dominates the total phosphorus edge-of-field loading. When a substantial fraction of soluble phosphorus is in the edge-of-field loading, the bioavailability ratio for agricultural row crop loading may change. That is to say the soluble fraction, which is very bioavailable, may begin to dominate the bioavailable fraction of total phosphorus even when the soluble fraction is slightly below 50 percent. Therefore, watershed characteristics and edge-of-field bioavailability fractions should be considered when soluble phosphorus is a substantial fraction of the total phosphorus loading at edge-of-field.

## WQCT credit estimation methods for particulate forms of phosphorus and nitrogen

The SWAT model evaluation confirmed the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) nutrient enrichment approach used by the Region 5/STEPL model methods is a valid approach for WQCT.

**Region 5/STEPL Method for P and N**

The Region5/STEPL model was based on algorithm developed for the CREAMS model for particulate P or N. It has the following basic equations:

$$P_p = P_{soil} \times S \times e \qquad (1)$$

Where,

$P_p$: Particulate P (P transported with sediment: sediment P and organic P) from the field (kg/ha);
$P_{soil}$: soil P content (soluble and organic P; fraction, kg/kg soil);
S: sediment loss from the field (kg/ha); and
e: enrichment ratio.

The enrichment ratio is calculated as:

$$e = a \times S^b \qquad (2)$$

where a and b are empirical coefficients with a default value of 7.4 and -0.2, respectively, for both P and N.

Solving Equation (2), entering the results into Equation (1), applying the default values for coefficients a and b, and reducing the S coefficient, we have

$$P_p = 7.4 \times P_{soil} \times S^{0.8} \qquad (3)$$

Note that parameters in Equation (3) are in metric units. Converting metric units to commonly used U.S. units, we have

$$P_p = 3{,}164 \times P_{soil} \times S^{0.8} \qquad (4)$$

Where,

$P_p$: Particulate P (lb/ac);
$P_{soil}$: soil P content (fraction; same as Equation [1]); and
S: sediment loss from the field (t/ac);

Changing P to N, Equation (4) can be applied to calculate particulate N.

## Data inputs for equation (4)

In practice, data for the parameters in applying Equation (4) can be obtained as follows:

1. Sediment loss (soil erosion, S) in tons per acre: RUSLE2 annual soil loss estimate for the field;

2. Total P or N concentration ($P_{soil}$ or $N_{soil}$) of the soil in the field in fractions: soil samples from the eroding layer of the soil profile tested for total P or total N in a soil lab. It is important to note that in the current Region5/STEPL model application, P or N concentrations of the field are assumed to have fixed values based on soil texture. Research by this study (K&A, 2015) showed that these default values generally do not reflect the actual field condition and could result in substantial errors in results when estimating nutrient loads.

**Applicability of equation (4)**

Equation (4) calculates only the particulate portion of the total P (or N) loading from the field. In situations where sediment transported nutrients are the vast majority of the total loads, results from Equation (4) approximate the total loads. This approximation often holds for P but varies for N as soluble forms of N, mostly nitrate, can constitute a substantial portion of the total N load.

The implication of using particulate forms of nutrients to approximate the total load in a WQCT program is that management practices aimed at reducing soil erosion, and subsequently sediment attached nutrient, would be properly quantified for their effect on nutrient load reduction and hence their ability to generate WQCT credits. On the other hand, management practices that can significantly reduce the loss of soluble forms of nutrient, for example, fertilizer application rate reduction, would not be fully accounted for in their effectiveness at reducing nutrient loading and consequently their ability to generate WQCT credits would be discounted. In these cases, a separate method of quantifying the loading of soluble forms of nutrient would become necessary. Alternatively, in situations where multiple management practices are implemented, quantifying only the reduction of the particulate form of nutrients would add an implicit margin of safety to the credit calculation.

**Recommended margin of safety when applying the method for particulate nutrient forms**

Table 1 (below) shows the differences between the Region 5 mode method, as represented by Equation (4) above, and SWAT simulated particulate P and N loads based on results from K&A (2015) on the two test areas or hydrologic response units (HRUs) from the Illinois study field. Default enrichment ratio coefficients resulted in under-estimation of long-term (40-year) average particulate P and over-estimation of average particulate N. In a normal distribution 2 times the standard deviation on both sides of the average combined covers about 95 percent of the data. Therefore, the following calculation

(Average Difference ± 2 × Standard Deviation of Differences) / SWAT Average

would give the percent of time that 95 percent of the long-term average estimated by Equation (4) would fall within 2 standard deviations of the SWAT estimated (or the “true”) long-term average load. Results of the calculation are shown in Table 1. Further, because load under-estimation would still protect the environment when using WQCT, a margin of safety would be required to cover primarily the higher end of the distribution. Consequently, only the results of +2 times the Standard Deviation of Differences were included in the margin of safety consideration.

Table 1. Differences and their statistics between Region 5 model (Equation [4]) and SWAT results for the Illinois test HRUs.

| HRUs | Equation (4) Average | SWAT Average | Average Difference[1] | Standard Deviation of Differences | % of - 2×Standard Deviation from SWAT Average[2] | % of + 2×Standard Deviation from Average Differences[3] |
|---|---|---|---|---|---|---|
| | | (kg/ha) | (kg/ha) | (kg/ha) | | |
| **Particulate P** | | | | | | |
| IL 645 | 2.482 | 4.341 | -1.859 | 1.468 | -110.5% | 24.8% |
| IL 1061 | 3.010 | 3.170 | -0.161 | 1.091 | -73.9% | 63.8% |
| **Particulate N** | | | | | | |
| IL 645 | 18.091 | 16.029 | 2.062 | 5.195 | -52.0% | 77.7% |
| IL 1061 | 23.134 | 14.717 | 8.417 | 7.437 | -43.9% | 158.3% |

[1] Average of the differences between loads estimated by Equation (4) and those by SWAT
[2] (Average Difference - 2× Standard Deviation of Differences)/SWAT Average
[3] (Average Difference + 2× Standard Deviation of Differences)/SWAT Average

Based on results in the last column of Table 1, margins of safety components of a trade ratio of 1.75:1 (a margin of safety of 75 percent) for P and 2.75:1 (a margin of safety of 175 percent) for N would provide conservative load reduction estimates if Equation (4) was to be used for calculating particulate forms of nutrient loads. These margins of safety would need to be further modified after other crediting considerations, such as in-stream attenuation and load reduction equivalency, are taken into account.

## WQCT crediting equation for Nitrate (NO3) loading from corn fields

In situations where the soluble form of N, nitrate, is a substantial part of the total N load from the field, a multiple linear regression (MLR) method for estimating nitrate loading from corn fields was examined by the project team (K&A, 2015). MLR equations were developed for two very different HRUs of the Illinois study field. These equations had common independent variables and the coefficients of the independent variables were similar. The general form of the equations is:

$$\textit{Nitrate load} = a_o + a_1 \times \textit{Runoff 3mo} + a_2 \times \textit{N applied} + a_3 \times \textit{Soil nitrate at sidedress} \qquad (5)$$

Where:

*Nitrate load*: load of nitrate from the field (lb/ac);
*Runoff 3mo*: the three month surface runoff volume from one month before the planting to two months after (inches);
*N applied*: N applied from fertilizers (lb/ac); and
*Soil nitrate at sidedress*: soil nitrate level two weeks before nitrogen sidedress (lb/ac).

Because of the uniformity of the independent variables and the similarity among their coefficients in the MLR, data (observations) from these HRUs were pooled together and one single MLR equation was developed as an initial attempt at a simple nitrate load quantification method for corn fields. This equation has the following format:

$$Nitrate\ load = 5.389 + 1.624 \times Runoff\ 3mo + 0.221 \times N\ applied$$
$$+ (-0.164) \times Soil\ nitrate\ at\ sidedress \quad (6)$$

$R^2 = 0.614$, n = 62, regression standard error = 3.905 lb/ac, *nitrate load* average = 13.24 lb/ac.

It is also noted here that the constant $a_o$ in Equation (5) varied between the two test HRUs much more than the coefficients of the independent variables in the regression equations developed for the two test HRUs. However, when Equation (6) is applied to calculating the load reductions of nitrate related management practices such as N fertilizer use reduction, the constant will be cancelled out, as nitrate load calculated for the after-management action is subtracted from the before-action load.

Because not all producers apply sidedress applications or take nitrogen soil tests after canopy closure another set of MLR equations using the pre-planting soil nitrate test as the independent variable for soil nitrate level were also developed. The general form of the equations is:

$$Nitrate\ load = a_o + a_1 \times Runoff\ 3mo + a_2 \times N\ applied + a_3 \times Soil\ nitrate\ before\ planting \quad (7)$$

Where:

*Nitrate load*: load of nitrate from the field (lb/ac);
*Runoff 3mo*: the three month surface runoff volume from one month before the planting to two months after (inches);
*N applied*: N applied from fertilizers (lb/ac); and
*Soil nitrate before planting*: soil nitrate level before planting (lb/ac).

Similar to the development of Equation (8), data (observations) for HRU-specific equations were pooled together and one single MLR equation was developed as a simple nitrate load quantification method from corn fields. This equation has the following format.

$$Nitrate\ load = 8.606 + 2.098 \times Runoff\ 3mo + 0.093 \times N\ applied$$
$$+ (-0.165) \times Soil\ nitrate\ before\ planting \quad (8)$$

$R^2 = 0.550$, n = 62, regression standard error = 4.218 lb/ac; *nitrate load* average = 13.24 lb/ac.

Data Inputs for Equations (6) and (8)

In practice, data for the parameters in applying Equation (6) can be obtained as follows:

1. *Runoff 3mo*: estimation of this 3-month runoff could be made in a WQCT crediting method by using the SCS curve number method or other simple hydrological models. This can be done using either actual weather record after the 3-month period or historic average anytime. Using historic average would be suitable when long-term average loading was being estimated. As such, long-term averages of the other variables would be used as well.
2. *N applied*: values can be obtained from the farm operator.

3. *Soil nitrate at sidedress*: soil samples would need to be collected between corn planting and the sidedress application of nitrogen fertilizer at corn growth stage V6 (six leaves with collars visible).
4. *Soil nitrate before planting*: soil samples would need to be collected before the planting of corn.

<u>Margin of Safety and Proposed Trading Ratio</u>

In linear regression, approximately 95 percent of the observations fall within ±2×standard error of the regression fitted values. Comparing the average observed nitrate load 13.24 lb/ac to 2×standard error = 7.81 lb/ac shows that 2×standard error is 59.0 percent of the average. Assuming that nitrate loading from the field eventually reverts to a long-term average, a 59.0 percent margin of safety would therefore cover 95 percent of the potentially observable values. Adding other uncertainties such as uncertainties in estimating the 3-month runoff, a 100 percent margin of safety would provide a conservative estimate when using Equation (6) to quantify nitrate load reductions. This implies a trading ratio of 2:1 for nitrate load reduction credits before any other crediting consideration (e.g., in-stream attenuation and load reduction equivalency) is taken into account.

By the same reasoning, if Equation (8) was to be used, the 2×standard error would be 63.7 percent of the average. This implies a 100 percent margin of safety would be adequate to cover 95 percent of the potentially observable values, same as the margin of safety in the application of Equation (6). Therefore, the same trading ratio of 2:1 could be used to address the edge-of-field estimation.

## References

Kieser and Associates, LLC (K&A). 2015. Appendix 2- #1 - SWAT Application for Developing a Credit Estimation Method for Precision Agriculture.

EPA. 1976. Loading Functions for Assessment of Water Pollution from Nonpoint Sources, Volume 1. EPA – 600 /2-76-151. May 1976

Pennsylvania Department of Environmental Protection (PA DEP). 2008. Phosphorus and Sediment Credit Calculation Form.

USDA NRCS. 1986. Urban Hydrology for Small Watersheds, TR-55. Conservation Engineering Division Technical Release 55. June 1986.

# APPENDIX 2

## Item #3. VRT with Auto-steer Systems and Section Boom Control

# The Use of Variable Rate Technology (VRT) with Auto-steer Systems and Section Boom Control to Generate Credits in Water Quality Trading Programs
November 2015

Water Quality Credit Trading (WQCT) programs need repeatable and science-based credit estimation methodologies that provide reasonable and practical levels of precision and efficacy when assessing reductions of nutrient loads by conservation practices. Through its various components, the use of precision agriculture can help farmers more precisely apply crop nutrients and potentially reduce nutrient run-off. These components may include spatial- or geo-referenced information on crop production fields (e.g., grid soil samples, detailed soil mapping, aerial photography, topographic maps, yield maps, soil texture maps, environmentally sensitive areas), recordkeeping systems, an analysis and decision-making process, specialized implementation equipment to precisely apply variable rates of crop inputs and measure yields to understand crop response (includes Global Positioning System (GPS) guidance systems, variable rate-application equipment, yield monitors, electrical conductivity, and moisture measuring devices), and provisions for evaluation and revisions after each cropping system.

One set of VRT practices that have the potential to generate WQCT credits is the use of auto-steer and section boom control equipment during fertilizer applications. GPS linked to tractor steering and/or fertilizer implement boom sections can be used to minimize overlap of fertilizer application on the same portion of a field. Auto-steer systems reduce farmer fatigue, increase pass efficiency, minimize missed areas, and reduce acreage receiving double applications according to recent assessments.

Farmers without the benefit of guidance systems will often find ways to minimize overlaps. In Ohio, Batte and Mohammad (2006) found that operators commonly use a foam marker as a reference point for their last pass. These markers are affected by wind, crop canopy and reduced visibility at the time of application. Batte and Mohammad found field fertilizer overlaps can range from 0.6 percent to 26 percent of the field acreage when using these traditional markers. Research has also indicated that operators who averaged less than 5 percent overlapping generally have higher occurrences of application skipped areas. Overlaps and skipped application areas occur due to many reasons. For instance, applicators:

- May not time the shutdown of application correctly when turning around for the next pass,
- May fail to line up the equipment on the right row when starting the next pass,
- May not have equipment that aligns evenly with the field width, thereby an overlap on the last pass occurs at the field edge, or
- May be following irregular field edges or avoiding obstacles in the field (e.g., surface tile intakes).

Auto-steer and/or section boom controls better ensure overlaps and missed application areas do not occur. Applicators may realize several benefits by preventing overlapping fertilizer applications and missed applications. These benefits include spending fewer hours applying products per field, which reduces fatigue, and provides fuel savings and cost savings from applying less fertilizer. Conclusions from Griffin et al. (2008) suggest these benefits result in extending the producer's work day by three hours and reducing net input costs for a savings of \$1.63 per acre on representative Corn Belt farms. Similarly, Shockley et al. (2011) found that net returns increased by 1.2 percent to 2.3 percent when using auto-steer technology.

Shockley et al. (2012) went on to analyze section boom control in four, uniquely-shaped fields in Kentucky (Figure 1). Shockley et al. determined that implementing boom controls for self-propelled sprayers averaged a 9 percent reduction in overlap acres for the four fields, with smaller fields having the largest reduction in overlap areas. Shockley et al. (2012) noted that numerous studies have indicated many Midwest fields, which are typically rectangular, would not benefit as greatly as the irregular fields found in Kentucky. However, this study indicated that profitability was influenced primarily by size of field as opposed to regularity.

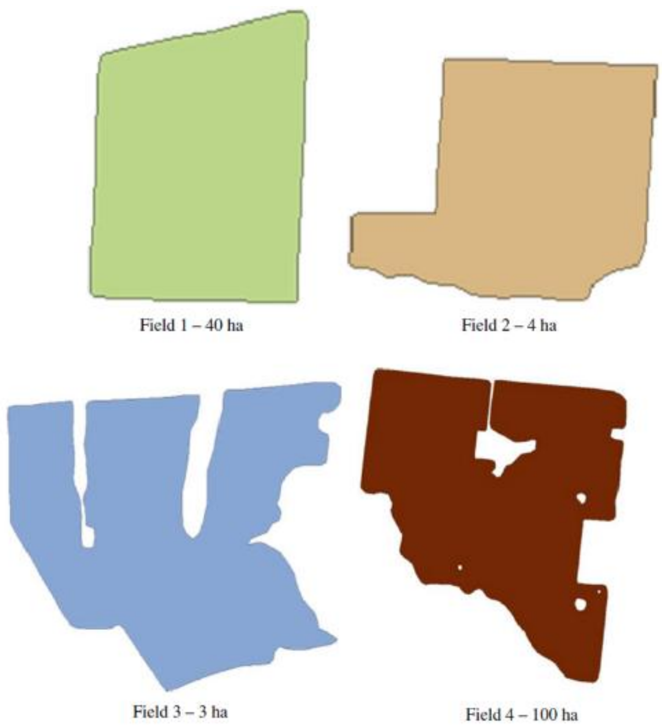



Figure 1: Irregular Fields Studied by Shockley et al. (2012)

John Deere, a project contributor, provided the following information on section boom control (personal communication). The $NH_3$ Swath Control Pro is a GPS-based applicator guidance system for section boom control which utilizes a multi-section on/off system to allow for greater control of $NH_3$ application to improve efficiency, lower costs, and minimize working hours for farmers. The Swath Control system, illustrated by Figure 2, is a 9 section, bar design that has 15 openers. The control system divides the boom into three, two-opener sections on either end and three single opener sections in the middle. These individual applicators are designed to turn on and off based on whether a particular section of farm field has already had fertilizer applied to it (as verified through GPS).

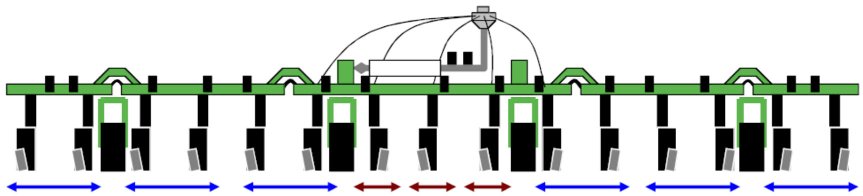


Figure 2: Swath Control Pro System Schematic

Figure 3 illustrates the potential effectiveness of the Swath Control system on an irregular, 104.36-acre parcel.

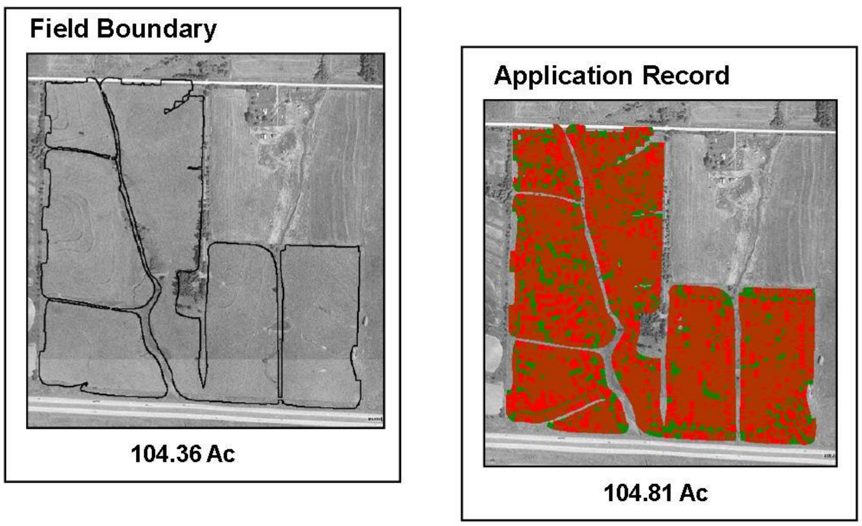



Figure 3: Application Record of Swath Control System

Application records for the field indicate fertilizer applications exceeded the necessary amount by 0.45-acres. Figures 3 and 4 illustrate the overlapped, double-applied portions of the field with green shading.

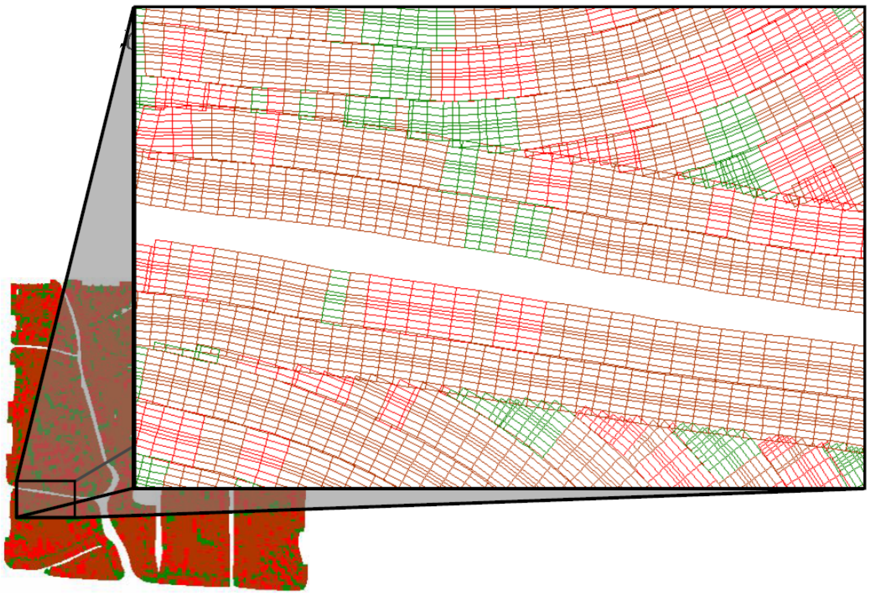


Figure 4: Application Record of Swath Control System

Over-applying fertilizer, as previously stated, is cost-inefficient even for relatively small areas of field. Take for instance, a 100 acre field that requires 201 lbs of $NH_3$ (165 units of nitrogen) at \$650/ton. Without Swath Pro, a farmer will apply enough fertilizer to cover 105.5 acres despite the total field only being 100 acres. This application rate will require 10.6 ton of $NH_3$, at a cost of \$650/ton for a total of \$6,890. Using Swath Pro, the farmer will apply enough fertilizer to cover 100.5 acres. The more efficient application will require 10.1 ton of $NH_3$ for a total cost of \$6,565. Overall Swath Pro would prevent 0.5 ton of $NH_3$ from being applied and result in a cost savings of \$325 or \$3.25/acre. Total costs for section boom control can range upwards of \$900,000 according to findings from Shockley et al. (2012). Despite this large capital investment, the increase in efficiency and subsequent cost-savings resulting from these technologies allows for a payback period of 1.3 years to 10 years (with an average payback period of 4.6 years according to Shockley et al. (2012). Of note, the payback period for Swath Pro is heavily dependent on site-specific characteristics including size of farming operation, degree of field irregularity, and overall size of field. However, a potentially short payback period, coupled with operational cost savings illustrated in previous examples, and the opportunity to generate WQCT credits, highlights the possible economic incentive for implementing Swath Pro.

From a technical perspective, WQCT protocols using Swath Pro or appropriate applicators for dry and liquid fertilizers could be easily adapted for WQCT using the phosphorus credit estimation methods. This is because a field map of actual applications can be provided. One necessary element is to determine the operation's typical overlap. Without this base case data the number of acres removed from having two fertilizer applications is unknown. A program might study their region's typical fields and resulting overlaps and develop an assumed level of overlap. This conservative estimation process would be justified if scores of fields start to generate credits. For example, a base case assumption of 5 percent (the low estimated percent of acres in the field study by (Shockley, 2012) could be adopted. Credit quantification would be based on applying a reduced application of nutrient on 5 percent minus the new overlap acre estimate. For instance, a section boom control map indicating one acre of overlap remained, would result in four acres generating credits by applying the appropriate nutrient crediting estimation method.

Programmatically, WQCT credit generation using Swath Pro or equivalent equipment may only work for a few acres on each field. Because this is likely to generate a relatively small credit sum, producers may not consider it worth their time to pursue WQCT payments. Therefore, it might improve efficiency and producer participation if WQCT program managers worked with custom applicators. Custom applicators could aggregate their new clients' activities that generate credits. (Large farms may still accrue enough acres to benefit from individually pursuing the nutrient reduction credits.) Aggregating credits is an effective method to lower transaction and administrative reporting costs. In addition, if the use of section boom control technology is accepted as an eligible BMP by many WQCT programs, manufactures of this technology could work with WQCT programs to develop in-cab software that would generate crediting reports to support trading activities.

## References


Batte, M.T., Mohammad, R.E. 2006. The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. Computers and Electronics in Agriculture. 53:28-44.

Griffin, T.L., Lambert, D.M., and J. Lownberg-DeBoer. 2008. Economics of GPS enabled navigation technologies. In: (Ed.) R. Khosla, Proceedings of the 9th International Conference on Precision Agriculture. Denver, Colorado.

Shockley, J., Dillon, C., Stombaugh, T. 2011. A Whole Farm Analysis of the Influence of Auto-steer Navigation on Net Returns, Risk, and Production Practices. J. of Agricultural and Applied Economics. (February 2011) 43, 1:57-75.

Shockley, J. Dillon, C.R., Stombaugh, T., and S. Shearer. 2012. Whole farm analysis of automatic section control for agricultural machinery. Precision Agriculture. 13:411-420.

# APPENDIX 2

## Item #4. Final Draft Report: May 2015. Viability and Potential for Stacking Greenhouse Gas (GHG) and Water Quality Credit Trading (WQCT) Credits

# FINAL DRAFT REPORT: May 2015
# Viability and Potential for Stacking Greenhouse Gas (GHG) and Water Quality Credit Trading (WQCT) Credits

**Prepared for**: American Farmland Trust by Kieser & Associates
**Funded by**: The Packard Foundation as part of USDA NRCS CIG 69-3A75-12-204
*Coupling Precision Agriculture with Water Quality Credit Trading*

## Introduction

This project effort was to determine the technical viability and potential for stacking greenhouse gas (GHG) credits with water quality credit trading (WQCT) credits. To test the viability of the Michigan State University-Electric Power Research Institute's greenhouse gas protocol (MSU-EPRI GHG protocol) approach for generating WQCT credits the project team simulated the MSU-EPRI GHG protocol for nutrient management on a field located in central Illinois using USDA's Soil and Water Assessment Tool (SWAT) Version 2009 to estimate the resulting changes in nonpoint source nitrogen loading at the edge-of-field. The flexible compliance option provided by WQCT must provide equivalent or greater environmental protection when compared to the traditional wastewater treatment facility upgrade approach in order to be viable. Existing WQCT program frameworks have numerous policies and protocols to provide assurance that equivalent or greater reductions will be provided (EPRI, 2013; MCD, 2005). The scope of work for this project was not to create a full functioning framework, but rather to test the physical and technical viability of nonpoint source loading reductions when agricultural operations apply the MSU-EPRI GHG protocol. The model estimation described here allows the project team to confirm the credit generation technique is technically viable considering several key concerns raised by the US EPA. This portion of the report will focus on evaluation of the comparison of water quality nonpoint source loading reductions on an actual cropped field in Illinois that is currently implementing variable rate technology (VRT) for nitrogen and phosphorus. Comparisons analyzed in this effort include the GHG nutrient management requirements, VRT nutrient management requirements, and traditional application methods of state-wide averages.

## Background

The EPA WQCT policy (2003) and recent guidance documents (EPA, 2004; EPA, 2007) strive to provide more details on what an effective, efficient, and appropriate trading program must consider. A few of the more salient points made are that trades must provide equivalent or better environmental protection and be structured in a manner that applies standard methods and adequate eligibility criteria.

One such criteria is that credit units (pollutant mass/time period) be contemporaneous with the National Pollutant Discharge Elimination System (NPDES) permit effluent limit averaging period. In general, this is often interpreted so that when a concentration based effluent limit is determined based on the monthly average of required sampling efforts, then the credit unit must also be based on monthly time steps. This is so that July discharges are equivalently offset by July based credit generation. Use of longer effluent averaging periods in NPDES permits allows a longer contemporaneous window to be used. Or, as in the case of Wisconsin Department of Natural Resources' trading program provisions (2013) adopted in a statewide rule, policy/guidance can also be used to justify trading credit generation that is based on annual average credit time steps for monthly average NPDES permit effluent limits. This action allows for trading programs to use annual contemporaneous periods even though NPDES permit averaging periods remain monthly.

A second criterion to be considered is that the introduced uncertainty when using trading as a flexible compliance alternative must be addressed by an adequate margin of safety. For example if there is potential for year-to-year variability in the edge-of-field loading then an adequate margin of safety must be provided to address the variability. This margin of safety can be in the form of a component of the trade ratio as an explicit margin of safety, or by use of conservative assumptions as an implicit margin of safety.

Key to nutrient management are the "4Rs," as identified by the USDA Natural Resources Conservation Service. The "4Rs" are the "right" rate and the "right" time of application, with the "right" placement, while using the "right" source. According to a GHG protocol background paper written by EPRI (2011), the "right" rate, which refers to the amount of fertilizer applied for optimal crop availability, has also been successfully linked to GHG $N_2O$ emissions. "Right" time has not been strongly linked to changes in GHGs, but applications in the spring likely contribute less to GHG than applications in the fall. There has not been research supporting any particular fertilizer placement strategy for credit generation. Studies evaluating different sources of synthetic N have been underway, however, have not yet demonstrated source as a reliably flexible credit generation source. This study focused on "right" rate, which has been implicated as the most important of the "4Rs" for reducing GHG emissions, and was examined here for technical viability and potential for stacking with GHG and WQCT credit trading.

In order to evaluate if nutrient application reductions used to generate GHG credits would simultaneously be able to generate WQCT credits, a water quality analysis of a farm field located in Illinois was completed. The field in Illinois currently applies fertilizers based on VRT map zones. A VRT zone map allows the GPS guidance system to apply different rates of nutrients based on the agronomist recommendations considering the changes in soil classifications and historic yield records.

The SWAT model was used to examine changes in nitrogen (N) loading at the edge-of-field when the operation follows the MSU-EPRI GHG protocol. In addition, equal reductions for phosphorus (P) application rate changes were added for WQCT generation purposes even though phosphorus management does not result in GHG credits. A base case (existing conditions) was compared to both the state-wide average nitrogen application rates and a 20 percent reduction of the existing rates. This evaluation considered the range of reductions achieved and the predicted variability in the reduction of edge-of-field for N and P loading across different time periods, as well as annual yield, to inform a discussion on what is needed for WQCT crediting methodologies to be technically viable.

## Methods

The methods used in the analysis considered whether or not WQCT crediting is viable based on the application of GHG credit protocols, considering the EPA policy and guidance documents (EPA, 2003, 2004 and 2007). The methods also reviewed if SWAT modeling results indicated the producer will potentially suffer a yield loss. The MSU-EPRI GHG protocol defines eligible activities as:

> Agricultural Land Management (ALM) ACR [American Carbon Registry] project activities that involve a change in fertilizer management, which may include changes in fertilizer rate (quantity), type, placement, timing, use of timed-release fertilizers, use of nitrification inhibitors, and other factors. Under this protocol, project proponents must show that project activities may not lead to a significant decrease in yields. (If yields are significantly affected, the project is determined to be ineligible.) [p. 23]

### Study Site

The study site is a 159-acre field located in north central Illinois. The field has a typical corn-soybean rotation of the region. Except for a 10-12 inch deep chisel plowing before each corn planting, the field does not have any other tillage operations. The field is tile-drained in depressions with a tile depth around four feet.

### Model Construction

Modeling of the field with VRT for nitrogen and phosphorus applications was conducted using USDA's Soil and Water Assessment Tool (SWAT) Version 2009 (Neitsch et al, 2011; Arnold et al, 2011) and its companion ArcGIS model interface ArcSWAT Version 2009.93.7b (Winchell et al, 2010). SWAT is a basin-scale computer model designed for assessing watershed-scale impacts of conservation management, particularly for agriculture dominated watersheds. It simulates the growth of agricultural crops and other vegetation in the watershed, the interaction between the crops and the soil for water, nutrient and organic matter exchanges, and losses of soil and nutrients from the watershed.

The construction of a SWAT model requires input of various data depending on the purpose of the model. For this project, four main types of input data were collected and processed: field elevation/slopes, soil characteristics, meteorological data, and agricultural field operations.

Federal agency data services provided field elevation/slope, soil, and meteorological data. Field elevation data were downloaded from USGS's National Map Viewer (http://viewer.nationalmap.gov/viewer). The elevation data had a resolution of about 10 meters. The ArcSWAT program calculated slopes of the field based on the elevation data as part of the subwatershed delineation process for the study field. Soil characteristics data were obtained through the USDA NRCS Soil Survey Geographic Database (SSURGO). These soil data were processed and incorporated into the SWAT model using the SWATioTools program developed by Dr. Aleksey Y. Sheshukov at Kansas State University. Meteorological data, including daily precipitation, daily maximum and minimum temperatures were collected from NOAA's National Climatic Data Center and processed to be incorporated into the SWAT model.

Field operations, along with field soil fertility test results and crop yields, were provided by the landowner and his crop production consultant. Field operations include the timing of plant and harvest, tillage operations, fertilizer applications, and type, amount, and method of fertilizer applied. Any missing information was estimated with general crop growth practices in Illinois and Upper Midwest, and best professional judgment.

SWAT uses the concept of hydrologic response unit (HRU) to carry out basic model calculations. Each HRU is a unique combination of soil, slope, and land use (or crop planted). The ArcSWAT model interface does not allow direct consideration of variable rate of fertilizer application during the formation of HRUs. To resolve this issue, variable rate application zones were created in the model by generating different versions of the same crop ("dummy crops") that were identified under separate names in order to be able to input different nutrient application rates. The dummy crops were created in the SWAT Land Cover/Plant Cover/Plant Growth database. These dummy crops were distributed in the study field to match the variable rate zones used by the landowner and crop consultant. These zones were then used as the land use dataset in the HRU definition phase of the SWAT model development. For this study field, the variable rate zones largely follow the USDA NRCS soil survey delineation of soil series boundaries.

Initial soil soluble phosphorus in SWAT was based on soil test phosphorus (STP) analysis conducted with soil samples from the study site in 2005, the first year of model "base case" simulation. The STP analysis used for soil samples from the field was Bray-P extraction. To convert the Bray-P values to soil soluble phosphorus, Bray-P was first converted to Mehlich III phosphorus based on studies by Sawyer and Mallarino (1999). A conversion factor of 2.5 was then used to subsequently convert from Mehlich III P (soluble phosphorus = Mehlich III phosphorus/2.5) to SWAT soil soluble phosphorus. This conversion factor was based on the SWAT definition for various mineral phosphorus components, including soluble phosphorus (Neitsch et al., 2011), and a study by White et al. (2007).

**Model Calibration**

Because the studied field was not monitored for flow or water quality, model calibration was done only for the crop yield by modifying the crop growth factors of RUE (radiation-use efficiency of the plant) and GSI (maximum leaf conductance, related to plant transpiration rate). The model setup for yield calibration was the nine-year crop rotation, started in 2005 and ended in 2013: soybean-corn-soybeans-corn-soybeans-corn-soybeans-corn-soybeans. Model output from the first year of simulation (2005) was not used in the calibration so that model parameters, especially those related to nutrient and water balances in the soil, could be stabilized. Because of incompleteness of available yield data, the final yield values used for calibration were a composite of 1) data provided by the landowner and the landowner's assistant, 2) grain delivery reports, 3) un-calibrated harvest maps, and 4) county averages from crop yield surveys reported by USDA National Agricultural Statistics Service (NASS).

**Model Scenario Evaluation**

Scenarios simulated by the SWAT model in this study were constructed to estimate the nutrient loss reduction benefits focused only upon changing the rate. As explained previously the MSU-EPRI GHG protocol focus is on changes in rate, which is only one of the “4Rs” of fertilizer management. The other 3 “Rs”, “right” time, “right” placement, and “right” fertilizer source, were not considered in this study.

In current operations at the study field, fertilizer applications are carried out three times for corn production: pre-plant application in the previous fall to the seeding after soybean harvest; “weed and feed” just before seeding in spring; and sidedress approximately one-month after the seeding. The pre-plant application includes both N and P fertilizers and the other two applications use only N. For soybean production, in most years neither N nor P fertilizers are applied. Occasionally, some pre-plant applications were made for specific variable rate zones in the previous fall to the seeding.

The application rates are determined by the landowner’s crop consultant for the field and crop using soil test results from field soil samples. Sulfate application is also recommended and made using ammonium sulfate as part of the pre-plant N application. Because SWAT does not simulate the dynamics of sulfate in the soil or for crop growth, sulfate was not considered in this study. The described operation conditions as simulated and calibrated in SWAT are referred to as the “base case” scenario.

Statewide National Agricultural Statistics Service Model

The application rates of fertilizers in the study field were evaluated against the state wide annual nutrient application rates as surveyed by National Agricultural Statistics Service (NASS) in 2005, 2006, 2010, and 2012 (NASS, 2012). As a comparison of the fertilizer application rates at the study field to those in an average farm in the state, NASS survey N and P fertilizer application rates for corn in 2010 and 2005 and for soybean in 2012 and 2006 were used to set average annual rates for N and P for the calibration period (2006-2013).

Twenty Percent Reduction Model

The application rates in the study field were also evaluated in comparison to a 20 percent reduction of overall N and P fertilizer application rates. In this case, the rate for the sidedress application was not reduced so that a sufficient supply of N could be available for corn during the most active N uptake period of corn growth (Bender et al., 2013; Neitsch et al., 2011). The “weed and feed” application rate, on the other hand, was reduced disproportionately to bring the overall N rate down to 80 percent of the base case scenario (overall 20 percent reduction).

Effect on Greenhouse Gas Nitrous Oxide ($N_2O$)

This study also examined the potential of using zoned precision fertilizer management on the reduction of an important agriculture production related greenhouse gas, $N_2O$. Having 298 times the effect of $CO_2$ on potential global warming, $N_2O$ is a potent greenhouse gas (GHG) produced in the soil predominantly by microbial activities. The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates that 60 percent of total $N_2O$ fluxes are from agricultural activities (Smith, 2007). There are several agricultural practices available for $N_2O$ reduction, such as tillage and residue management. However, nitrogen fertilizer management is probably the most effective one. In the row-crop agriculture in the Midwest, evidence suggests that fertilizer rate is the most important factor among the "4Rs" in managing $N_2O$ emission.

This study used an MSU-EPRI jointly developed relationship to convert fertilizer N rate to $N_2O$ emission. The relationship is based on field data collected in five commercially farmed fields in Michigan (Hoben et al., 2011). The MSU-EPRI study modified the relationship by Hoben et al. to

$$N_2O \text{ emissions} = 0.67 \times e^{(0.0067 \times \text{N rate})} \quad (1)$$

where $N_2O$ emissions are in kg $N_2O$-N/ha/yr and N rate is in kg N/ha/yr. The $N_2O$ emissions are then further converted to $CO_2$ equivalent using

$$CO_2 \text{ equivalent emissions} = 468.29 \times N_2O \text{ emissions} \quad (2)$$

where $CO_2$ equivalent emissions are in kg $CO_2$ equivalent /ha/yr or kg $CO_2$e/ha/yr.

Such a relationship is considered a Tier 2 emissions factor by the IPCC, in contrast to the Tier 1 emission factors that are single conversion constants such as 0.01.

The above scenario simulations were conducted for the eight-year (2006-2013) calibrated period.

**Evaluation of Potential WQCT Credits with MSU-EPRI GHG Protocol**

To evaluate the feasibility of generating WQCT credits with GHG reduction by the MSU-EPRI GHG protocol, data analysis of this study focuses on answering the three questions below:

1) How is crop yield affected with the reduction of fertilizer application rates? Here, we would like to confirm that adoption of a lower nitrogen application rate does not result in a significant yield loss.
2) Will the GHG reduction protocols consistently generate nutrient load reductions for WQCT credits in various climatic and cropping conditions? Here we evaluate the ability of the management measures to produce a persistent edge-of-field nitrogen loading reduction that can be used for credit generation, given the natural variability that occurs year-to-year from climatic factors, and differences in crop nutrient dynamics in corn and bean rotations.
3) Will the load reduction variability, monthly or annually, affect the feasibility of using the generated credits in a WQCT program based on EPA trading guidance? This is essentially an evaluation of the protocol's ability to generate water quality credits contemporaneous with the NPDES permit effluent limit averaging period.

## Model Calibration and Scenario Results

Results for model calibration and right rate, plus applications of the load reduction results to water quality credit generation for the WQCT credit estimation model are described in detail below. Also included in this discussion are results of estimates for the effect on nitrous oxide.

## Model Calibration

As noted, there was some incompleteness of available yield data, notably for the extreme drought year of 2012. Comparing the four sources of crop yield information, data provided by the landowner's assistant indicated the corn yield in the drought 2012 was exactly the same as that in 2010, a normal precipitation year. The grain delivery report and harvest map from 2012 were both incomplete. The landowner himself confirmed a substantial yield reduction in 2012. The NASS county harvest survey was deemed to be the most reliable source of yield data for 2012. The NASS 2012 county average corn yield is 64 bu/ac, very close to the SWAT simulated 63 bu/ac. In fact, SWAT simulation for corn growth showed the crop suffered on average 44 days of water stress in 2012, compared to 11~ 19 days for the other seven years simulated.

Comparison of crop yields as reported and simulated by SWAT is provided in Table 1. The average difference between simulated and actual crop yield is 0.3 percent with a maximum of 8.3 percent and minimum -8.8 percent. Excluding the extreme drought year of 2012, the average difference between simulated and actual crop yield is 0.8 percent.

Table 1 also provides the simulated sediment losses from the study field. No formal calibration was conducted in the model for sediment losses because no measured sediment data were available. However, using best professional judgment the SWAT model results were reviewed and determined to be within a reasonable range of erosion rates given the slope of the field and tillage operation practices applied. The eight-year average sediment yield of 2.3 tons per acre per year as simulated by SWAT with default model parameter values was considered reasonable.

Table 1: SWAT model input, yield output, and comparison to actual yields.

| Year | Crop | Precipitation | Nitrogen Application Rate[1] | Phosphorus Application Rate[1] | Actual Crop Yield[2] | Simulated Crop Yield | Yield Difference | Simulated Sediment Loss |
|---|---|---|---|---|---|---|---|---|
| | | (inches) | (lbs/ac) | (lbs/ac) | (bu/ac) | (bu/ac) | % | (ton/ac) |
| 2006 | Corn | 39.9 | 149.9 | 0.0 | 173 | 184 | 6.2 | 2.1 |
| 2007 | Soybean | 39.5 | 48.0 | 30.3 | 46 | 50 | 8.3 | 2.7 |
| 2008 | Corn | 47.5 | 151.3 | 1.6 | 163 | 166 | 2.1 | 3.6 |
| 2009 | Soybean | 45.3 | 48.0 | 30.3 | 52 | 54 | 3.7 | 2.5 |
| 2010 | Corn | 34.5 | 157.1 | 8.1 | 163 | 164 | 0.6 | 1.6 |
| 2011 | Soybean | 36.7 | 40.8 | 17.2 | 48 | 44 | -8.8 | 1.2 |
| 2012 | Corn | 27.0 | 189.9 | 0.0 | 64 | 63 | -1.9 | 0.8 |
| 2013 | Soybean | 32.1 | 34.6 | 28.1 | 51 | 48 | -6.7 | 2.6 |
| | Total | 302.5 | 819.5 | 115.5 | -- | -- | 8.3 | 3.8 |
| | Maximum | 47.5 | -- | -- | -- | -- | 8.3 | 3.8 |
| | Average | 37.8 | -- | -- | -- | -- | 0.3 | 2.3 |
| | Minimum | 27.0 | -- | -- | -- | -- | -8.8 | 0.8 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.
[2] Composite of 1) data provided by the landowner's assistant, 2) grain delivery reports, 3) un-calibrated harvest maps, and 4) county averages from crop yield survey reported by USDA National Agricultural Statistics Service (NASS).

Comparison of current (base case) fertilizer application rates to the statewide NASS rates

Compared to the statewide rates, the study field received about 25 percent more N on average but 35 percent fewer pounds of P application for the calibration period, as shown in Tables 1 and 2. On the other hand, simulated yields showed little change between the “base case” and the NASS case (Table 2), suggesting an over-application of N on the study field and over-application of P for an average farm in the state. Although SWAT was not specifically designed for crop production simulation, the lack of any significant change of yield with the substantial change of nutrient input indicates the amount of P fertilizer used on our study field was appropriate and there was potential for substantially reducing the use of N fertilizers.

Table 2 shows that with the reduced N application and increased P application, the study field would on average lose 6.18 percent less total N but 17.10 percent more total P. In addition, loss difference of total P shows a general trend of acceleration over the eight years of simulation, suggesting a build-up of excess P in the soil. The loss of a bushel or two per acre would likely not meet the MSU-EPRI GHG protocol definition of a significant decrease of yield which is used to determine the application ineligible. As SWAT is not a strong agronomic model, this reduction should be interpreted cautiously as a yield response indicator. The impact of the 20 percent rate reduction on the four corn-growing years of the model was examined in more detail. The results were very similar when compared to the evaluation for application reduction comparison of NASS and base case rates. For data related to N availability, most relevant to GHG reduction, 75 percent of corn years typically show two to five days of N stress for the even years between 2006 and 2012 in most HRU's. More influential for water quality credits, P availability was limited to a lesser extent, with 57 percent of corn and soybean years typically showing one day of P stress in less than half the HRU's.

Table 2: SWAT modeled nutrient losses from the study field: NASS surveyed Illinois statewide rates of N and P fertilizers

| Year | Crop | Base Case Simulated Yield | NASS Simulated Yield | Nitrogen Application Rate-NASS[1] | Total N Loss - Base Case | Total N Loss - NASS Case | Total N Loss Difference | Phosphorus Application Rate-NASS[1] | Total P Loss - Base Case | Total P Loss - NASS | Total P Loss Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | % | (lbs/ac) | (lbs/ac) | (lbs/ac) | % |
| 2006 | Corn | 184 | 181 | 123.9 | 32.0 | 30.5 | -4.54 | 0.0 | 6.5 | 6.9 | 7.05 |
| 2007 | Soybean | 50 | 50 | 32.9 | 37.6 | 35.5 | -5.67 | 36.9 | 8.0 | 8.5 | 5.87 |
| 2008 | Corn | 166 | 165 | 123.9 | 53.4 | 50.4 | -5.60 | 0.0 | 11.7 | 12.6 | 7.94 |
| 2009 | Soybean | 54 | 54 | 32.9 | 48.3 | 43.4 | -10.12 | 36.9 | 7.2 | 7.6 | 4.97 |
| 2010 | Corn | 164 | 162 | 150.9 | 31.4 | 29.4 | -6.60 | 30.3 | 5.6 | 6.4 | 13.27 |
| 2011 | Soybean | 44 | 44 | 32.9 | 18.7 | 17.7 | -5.12 | 36.9 | 4.5 | 6.1 | 36.65 |
| 2012 | Corn | 63 | 63 | 123.9 | 19.4 | 17.9 | -7.86 | 0.0 | 2.9 | 4.0 | 36.49 |
| 2013 | Soybean | 48 | 48 | 32.9 | 40.4 | 38.8 | -3.94 | 36.9 | 7.7 | 9.5 | 24.59 |
| Total | | -- | -- | 654.5 | 281.2 | 263.6 | -6.26 | 178.1 | 54.1 | 61.6 | 13.95 |
| Maximum | | -- | -- | -- | 53.4 | 50.4 | -3.94 | -- | 11.7 | 12.6 | 36.65 |
| Average | | -- | -- | -- | 35.2 | 33.0 | -6.18 | -- | 6.8 | 7.7 | 17.10 |
| Minimum | | -- | -- | -- | 18.7 | 17.7 | -10.12 | -- | 2.9 | 4.0 | 4.97 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.
See Table 1 for base case application rates.

Comparison of current (base case) fertilizer application rates to a 20 percent targeted reduction

The previous comparison between "base case" fertilizer rates and NASS survey rates showed that with the reduced N application and increased P application, crop yields were not negatively affected while nutrient losses from the field decreased or increased respectively. In this second rate change test, a 20 percent rate reduction for both nutrients was made to examine the effect. Table 3 shows that crop yields exhibited little change while N and P losses from the field decreased on average by 5.72 percent and 7.26 percent, respectively. These much smaller percent reductions of nutrient losses compared to those of fertilizer application rates (-20 percent), along with the nearly constant crop yields, suggested that there was nutrient build-up in the soil and/or nutrient losses from the field via pathways other than soil and water erosion.

The 20 percent rate reduction did result in a nominal yield reduction for corn, as seen in Table 3. The loss of a bushel or two per acre would likely not meet the MSU-EPRI GHG protocol definition of a significant decrease of yield which is used to determine the application ineligible. As SWAT is not a strong agronomic model, this reduction should be interpreted cautiously as a yield response indicator. The impact of the 20 percent rate reduction on the four corn-growing years of the model was examined in more detail. The results were very similar when compared to the evaluation for application reduction comparison of NASS and "base case" rates. For data related to N availability, most relevant to GHG reduction, 75 percent of corn years typically show two to five days of N stress for the even years between 2006 and 2012 in most HRU's. More influential for water quality credits, P availability was limited to a lesser extent, with 57 percent of corn and soybean years typically showing one day of P stress in less than half the HRU's.

Table 3: SWAT modeled nutrient losses from the study field: base case and 20 percent reduction of applied N and P fertilizers

| Year | Crop | Base Case Simulated Yield | Simulated Yield with 20% Reduction | Nitrogen Application Rate after 20% Reduction [1] | Total N Loss with 20% Reduction | % Total N Loss Difference from Base Case[1] | Phosphorus Application Rate after 20% Reduction [1] | Total P Loss with 20% Reduction | %Total P Loss Difference from Base Case[1] |
|---|---|---|---|---|---|---|---|---|---|
| | | (bu/ac) | (bu/ac) | (lbs/ac) | (lbs/ac) | % | (lbs/ac) | (lbs/ac) | % |
| 2006 | Corn | 184 | 182 | 120.2 | 30.3 | -5.28 | 0.0 | 6.0 | -6.62 |
| 2007 | Soybean | 50 | 50 | 38.4 | 35.6 | -5.30 | 24.2 | 7.5 | -5.87 |
| 2008 | Corn | 166 | 165 | 121.3 | 50.5 | -5.44 | 1.2 | 10.7 | -8.18 |
| 2009 | Soybean | 54 | 54 | 38.4 | 44.2 | -8.37 | 24.2 | 6.8 | -6.31 |
| 2010 | Corn | 164 | 163 | 126.0 | 29.0 | -7.79 | 6.5 | 5.1 | -8.85 |
| 2011 | Soybean | 44 | 44 | 32.6 | 17.6 | -5.71 | 13.7 | 4.1 | -8.70 |
| 2012 | Corn | 63 | 63 | 152.2 | 18.4 | -4.86 | 0.0 | 2.7 | -7.58 |
| 2013 | Soybean | 48 | 48 | 27.6 | 39.2 | -2.98 | 22.5 | 7.2 | -5.97 |
| Total | | -- | -- | 656.7 | 264.9 | -5.79 | 92.2 | 50.2 | -7.17 |
| Maximum | | -- | -- | -- | 50.5 | -2.98 | -- | 10.7 | -5.87 |
| Average | | -- | -- | -- | 33.1 | -5.72 | -- | 6.3 | -7.26 |
| Minimum | | -- | -- | -- | 17.6 | -8.37 | -- | 2.7 | -8.85 |

[1] Part of N and all P fertilizers were applied in the previous fall of the seeding of the target crop.

See Table 1 for base case application rates.

See Table 2 for base case N and P losses.

Load reduction and water quality credit generation

With nutrient edge-of-field loading estimates from the "base case" and the two different alternative fertilizer application rates, we can evaluate the consistency and predictability of the change of total N (TN) and total P (TP) losses when reducing fertilizer usage. Table 4 shows the load reductions for TN. Because the NASS rates were similar to the 20 percent reduction rates for N, load reductions from the two lower rates compared to the base case were also similar (Columns 6 and 7 in Table 4). The NASS rates showed slightly more reduction over the eight years of simulation. As a result, in the following analysis, we will focus on the more conservative load reductions from the 20 percent rate reduction case.

In nonpoint-point source water quality trading, a component of the trading ratio is generally used to account for year-to-year variation of nonpoint source available credits, uncertainties in nonpoint source load reduction calculations, attenuation of nutrients in streams from the credit generating site to the credit using site, and other potential factors unrelated to load reduction quantification. As noted above, uncertainty can be accounted for through explicit trade ratios or through implicit aspects of the model development.

An essential component of trade ratios is a margin of safety to address introduced uncertainty from credit calculations. It is common to find a margin of safety of 2:1 (EPRI, 2011; MCD, 2005) meaning for every two units of load reduction generated by a nonpoint source, buyers get one unit of the load reduction as their water quality trading credit. Using this ratio, Table 4 (Column 8) calculated available TN credits from the study field would potentially not be adequate if the WQCT program managers wanted to address extreme droughts. Among the eight years of simulation, the minimum credit is 0.47 lbs/ac (per year) in 2012, when a severe drought took place. The average credit of 1.02 lbs/ac is 2.17 times this minimum value. It is assumed the average credit value could be the actual trading credit assigned to our study field in a trading program. Comparing the eight-year average edge-of-field N reduction and the lowest yielding year (2012), which occurred during a substantial drought, indicates periods of low rainfall generate less than 50 percent of the average of loading years evaluated. This suggests that a 2:1 margin of safety built into the model is not fully adequate to account for climactic variability particularly in a record drought year.

This finding indicates that selection of an appropriate trade ratio should be completed based on evaluation of many more sites and several long-term weather records. A trade ratio can account for uncertainties as discussed above but also includes attenuation losses, bioavailable equivalence and other policy factors. An adequate trade ratio may need to be greater than the margin of safety ratio of 2:1 to ensure an equal or greater offset depending on the selection of the approved credit value. In the above example, selection of the average credit potential value would need to have a margin of safety that is greater than two to one. If a lower percentile value based credit value were selected, such as the 35th percentile instead of the 50th percentile, the applied conservative step would allow for a trade ratio that could be substantially less.

Table 4: Summary of SWAT modeled total N losses from the study field

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Year | Crop | Total N Loss - Base Case | Total N Loss - NASS | Total N Loss with 20% Fertilizer Reduction | Total N loss difference between NASS and base case | Total N loss difference between 20% reduction and base case | Potential N Credit with 20% Fertilizer Reduction and 2:1 Trading Ratio |
| | | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) |
| 2006 | Corn | 32.0 | 30.5 | 30.3 | -1.5 | -1.7 | 0.84 |
| 2007 | Soybean | 37.6 | 35.5 | 35.6 | -2.1 | -2.0 | 1.00 |
| 2008 | Corn | 53.4 | 50.4 | 50.5 | -3.0 | -2.9 | 1.45 |
| 2009 | Soybean | 48.3 | 43.4 | 44.2 | -4.9 | -4.0 | 2.02 |
| 2010 | Corn | 31.4 | 29.4 | 29.0 | -2.1 | -2.5 | 1.23 |
| 2011 | Soybean | 18.7 | 17.7 | 17.6 | -1.0 | -1.1 | 0.53 |
| 2012 | Corn | 19.4 | 17.9 | 18.4 | -1.5 | -0.9 | 0.47 |
| 2013 | Soybean | 40.4 | 38.8 | 39.2 | -1.6 | -1.2 | 0.60 |
| | Total | 281.2 | 263.6 | 264.9 | -17.6 | -16.3 | 8.15 |
| | Maximum | 53.4 | 50.4 | 50.5 | -1.0 | -0.9 | 2.02 |
| | Average | 35.2 | 33.0 | 33.1 | -2.2 | -2.0 | 1.02 |
| | Minimum | 18.7 | 17.7 | 17.6 | -4.9 | -4.0 | 0.47 |

The corresponding TP load changes and credit calculations are shown in Table 5. Because the NASS phosphorus rates were actually higher than the base case rates, only the 20 percent reduction case generated TP load reductions and subsequent water quality trading credits.

Table 5: Summary of SWAT modeled total phosphorus (P) losses from the study field

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Year | Crop | Total P Loss - Base Case | Total P Loss - NASS | Total P Loss with 20% Reduction | Total P loss difference between NASS and base case | Total P loss difference between 20% reduction and base case | Potential P Credit with 20% Fertilizer Reduction and 2:1 Trading Ratio |
| | | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) | (lbs/ac) |
| 2006 | Corn | 6.5 | 6.9 | 6.0 | 0.5 | -0.4 | 0.21 |
| 2007 | Soybean | 8.0 | 8.5 | 7.5 | 0.5 | -0.5 | 0.24 |
| 2008 | Corn | 11.7 | 12.6 | 10.7 | 0.9 | -1.0 | 0.48 |
| 2009 | Soybean | 7.2 | 7.6 | 6.8 | 0.4 | -0.5 | 0.23 |
| 2010 | Corn | 5.6 | 6.4 | 5.1 | 0.7 | -0.5 | 0.25 |
| 2011 | Soybean | 4.5 | 6.1 | 4.1 | 1.6 | -0.4 | 0.19 |
| 2012 | Corn | 2.9 | 4.0 | 2.7 | 1.1 | -0.2 | 0.11 |
| 2013 | Soybean | 7.7 | 9.5 | 7.2 | 1.9 | -0.5 | 0.23 |
| | Total | 54.1 | 61.6 | 50.2 | 7.5 | -3.9 | 1.94 |
| | Maximum | 11.7 | 12.6 | 10.7 | 1.9 | -0.2 | 0.48 |
| | Average | 6.8 | 7.7 | 6.3 | 0.9 | -0.5 | 0.24 |
| | Minimum | 2.9 | 4.0 | 2.7 | 0.4 | -1.0 | 0.11 |

Monthly variation of nutrient loading from the study field

In nonpoint-point source water quality credit trading, because most of the point sources have a monthly compliance schedule, an ideal trade between a nonpoint and a point source would have a time period of one month for load reduction quantification and credit exchange. However, while most of the point sources have relatively stable discharge volume and pollutant concentrations from month-to-month, load reductions generated from agricultural row crop fields vary widely depending primarily on precipitation, crop growth, and field management activities.

The variation of nutrient load reductions in each of the 12 months over the eight-year simulation period (Table 6) showed that from year-to-year the majority of months the coefficient of variation (CV) exceeded 100 percent for both nutrients. In other words, the consistency of credit generation in each month across different years is very poor. For example, total nitrogen load reduction in the month of May has the lowest CV at 70 percent among all months and both nutrients. Nevertheless, the minimum load reduction value of 0.122 lbs for May is about only one-fourth of the average value of 0.450 for the month. If the average value were to be used as the load reduction for trading in May, a trading ratio of 4:1 would be needed to fully compensate for this variation in a monthly time period based trading program. With the highest CV of 204 percent, the September total phosphorus trading would need a trading ratio of nearly 300:1. Such high a trading ratio would limit any potential cost benefits of a water quality trading program even if sufficient load reduction could be generated. This indicates that an annual credit generation time period would need to be applied.

Table 6: Monthly variation in load reductions over the “base case” with 20 percent reduction of fertilizer application across the eight-year simulation period

| | Total Nitrogen | | | | Total Phosphorus | | | |
|---|---|---|---|---|---|---|---|---|
| Month | Average | Minimum | Maximum | CV[1] | Average | Minimum | Maximum | CV[1] |
| | (lbs) | (lbs) | (lbs) | % | (lbs) | (lbs) | (lbs) | % |
| Jan | 0.083 | 0.003 | 0.201 | 88 | 0.061 | 0.000 | 0.261 | 138 |
| Feb | 0.110 | -0.004 | 0.319 | 103 | 0.043 | 0.002 | 0.155 | 116 |
| Mar | 0.133 | 0.003 | 0.488 | 149 | 0.034 | 0.005 | 0.074 | 73 |
| Apr | 0.406 | 0.021 | 1.364 | 108 | 0.058 | 0.013 | 0.185 | 102 |
| May | 0.450 | 0.122 | 0.849 | 70 | 0.066 | 0.005 | 0.137 | 81 |
| Jun | 0.186 | 0.012 | 0.607 | 110 | 0.040 | 0.001 | 0.142 | 115 |
| Jul | 0.033 | -0.006 | 0.159 | 166 | 0.036 | 0.000 | 0.145 | 137 |
| Aug | 0.029 | 0.000 | 0.093 | 138 | 0.014 | 0.000 | 0.034 | 117 |
| Sep | 0.017 | 0.000 | 0.048 | 109 | 0.017 | 0.000[2] | 0.100 | 204 |
| Oct | 0.028 | -0.001 | 0.122 | 143 | 0.019 | 0.001 | 0.059 | 110 |
| Nov | 0.243 | 0.003 | 1.077 | 147 | 0.011 | 0.001 | 0.030 | 105 |
| Dec | 0.322 | 0.009 | 1.044 | 108 | 0.086 | 0.014 | 0.220 | 79 |

[1] Coefficient of variation; [2] rounding result, actual value is 0.000057.

## $N_2O$ emissions from various N fertilizer rates

Table 7 provides calculated $N_2O$ emission rates from the “base case,” the NASS rate case, and the 20 percent reduction scenario, using Equations (1) and (2). Because the MSU-EPRI developed relationship for $N_2O$ emissions calculation [Equation (1)] is a single variable function of the N fertilizer application rate, it is not surprising that the N application rate alone determines the final GHG emissions from the field. As the two non-base case scenarios had a similar total N application over the eight-year period, the total GHG emissions were similar as well. Overall in both cases, with lower N application rates, there were total reductions of GHG emissions of 1,033 kg/ha, an average of 129 kg/ha per year.

Table 7: $CO_2$ equivalent emissions of $N_2O$ from three N fertilizer application rates

| Year | Crop | Base case N application[1] | Base case $N_2O$ emissions | NASS rate N application[1] | NASS rate $N_2O$ emissions | 20% reduction N application[1] | 20% reduction $N_2O$ emissions |
|---|---|---|---|---|---|---|---|
| | | (kg/ha/yr) | (kg $CO_2$e/ha/yr) | (kg/ha/yr) | (kg $CO_2$e/ha/yr) | (kg/ha/yr) | (kg $CO_2$e/ha/yr) |
| 2006 | Corn | 167.9 | 966 | 138.8 | 795 | 134.6 | 773 |
| 2007 | Soybean | 53.7 | 450 | 36.9 | 402 | 43.0 | 418 |
| 2008 | Corn | 169.4 | 976 | 138.8 | 795 | 135.9 | 780 |
| 2009 | Soybean | 53.7 | 450 | 36.9 | 402 | 43.0 | 418 |
| 2010 | Corn | 176.0 | 1,020 | 169.0 | 974 | 141.1 | 807 |
| 2011 | Soybean | 45.7 | 426 | 36.9 | 402 | 36.6 | 401 |
| 2012 | Corn | 212.7 | 1,304 | 138.8 | 795 | 170.5 | 983 |
| 2013 | Soybean | 38.8 | 407 | 36.9 | 402 | 31.0 | 386 |
| Total (kg/ha) | | 917.8 | 5,999 | 732.9 | 4,966 | 735.5 | 4,967 |
| Average(kg/ha/yr) | | 114.7 | 750 | 91.6 | 621 | 91.9 | 621 |

[1] These application rates are equivalent to those in Tables 2 and 3, but have been converted to metric units for use in Equations (1) and (2).

## Conclusions

The evaluation of the MSU-EPRI GHG protocol's ability to generate WQCT program credits for nitrogen focused on answering three questions. Each of these three questions is discussed here.

1) <u>How is crop yield affected with the reduction of fertilizer application rates?</u>

Based on the SWAT model yield output for the field in central Illinois, only a bushel or two per acre yield loss was evident when adopting a rather high 20 percent nitrogen and phosphorus reductions. This would likely meet the MSU-EPRI GHG protocol requiring no significant decrease of yield to result from generating GHG emission reductions. The 20 percent reduction rates used in this study suggests that even a lower rate reduction could be applied and still generate credits for both trading programs. However, it is cautioned here that SWAT was not designed to be a strong agronomic model. It is important for agricultural producers to determine their own potential for reduced yield when considering adoption of the MSU-EPRI GHG protocol approach to generate either GHG or WQCT credits.

2) <u>Will the GHG reduction protocols generate nutrient load reductions for WQCT credits in various climatic and cropping conditions?</u>

The answer to this question is a strong affirmative. Model evaluation indicated that edge-of-field nitrogen load reduction persisted even during the severe drought year of 2012, although the reduction was less than half of the eight-year average. On the other hand, the fact that the drought year load reduction was small indicates that to appropriately provide assurances that nonpoint sources consistently provide equal or greater environmental protection than point sources can achieve, trading ratios providing a margin of safety need to be designed based on longer-term weather records. In addition, low load reduction per acre rate under extreme weather conditions points to the need to include and aggregate larger blocks of acres, working with more farmland parcels in order to generate a sizable, stable source of credits to be used in a trading program.

3) Will the load reduction variability, monthly or annual, affect the feasibility of using the generated credits in a WQCT program based on EPA trading guidance?

The evaluation found the use of a monthly time step to generate WQCT credits would require some extraordinary trading ratios (in the hundreds) to ensure a margin of safety to compensate for monthly variation in load reduction. Therefore, monthly average credit generation is not a viable time step. However, when using an annual time step for credit generation, trading ratios required would fall within the commonly used value range (2~3:1). Annual time step credits can be set by either adjusting the NPDES permit effluent averaging periods or through Clean Water Act delegated authority WQCT rule, policy or guidance that allows for long-term credit generation periods to offset monthly averaged effluent limits.

## Summary and Recommendations

To evaluate the WQCT generation viability when applying the MSU-EPRI GHG protocol, the USDA SWAT model was used to simulate edge-of-field nutrient load reductions from a 160-acre commercially farmed field in central Illinois under three different scenarios of fertilizer application rates. This limited study found the three salient conditions of GHG and WQCT credit stacking viability to be met: protection against yield loss, load reduction temporal persistence, and annual contemporaneous credit change. These combined to present very strong indicators that it is technically viable to generate WQCT credits when using the same nutrient management techniques required under the MSU-EPRI GHG protocol.

The SWAT model was selected because of its robust blend of agricultural operational practice inputs and capability of simulating nutrient dynamics in both the environment (soil and water) and crop growth physiology. However, it is important to note that the SWAT model is not considered a strong agronomic model and agricultural producers should use their own agronomic determination methods when considering a change in nutrient application rates.

This study has completed the first steps toward development of a credit estimation method for nutrient management. The following recommendations are presented for next steps for the development of water quality credit trading components in the MSU-EPRI GHG protocol.

- Further development of the credit estimation method for nutrient management; this could include
    - Exploring the potential of combining the USEPA Region V load estimate model (http://it.tetratech-ffx.com/steplweb/) with SWAT output to improve load reduction estimation accuracy; and
    - Comparing findings from this study with similar evaluations from fields with different physical settings and/or agricultural operations (for example, in the current study, only commercial fertilizer was used, and no manure applications were considered).
- Developing a life-cycle economic analysis. This economic analysis is intended to inform decision makers regarding long-term average costs and the related break point where stacking credits provides a reasonable profit to compensate for occasional slight yield loses incurred due to nitrogen rate reductions.

- Developing field nutrient measurement protocols for determining TP and TN concentrations in soils; and
- Soliciting peer review of findings.

In addition, the technical analysis in and of itself will not be sufficient for stacking of ecosystem credit payments to be eligible in some programs. It will be important to integrate the technical discussions, like this one, into the ecosystem service stacking policy discussions. Technical evaluations are best used to inform the policy discussion by identifying the potential range of credits that can be generated. The benefit of knowing the reasonable potential credit values is that it can adjust the discussion points from being based on hypothetical "what ifs" to a more credible range to evaluate the monetary outcome of staying the course or adopting the GHG and WQCT stacking approach.

## References

Arnold, J., J.R. Kiniry, J.R. Williams, E.B. Haney, and S.L. Neitsch, 2011, *Soil and Water Assessment Tool Input/Output File Documentation – Version 2009*, Texas Water Resources Institute Technical Report No. 365, Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, and Blackland Research Center, Texas AgriLife Research, September 2011.

Bender, R. R., J. W. Haegele, M. L. Ruffo, and F. E. Below, 2013, Nutrient Uptake, Partitioning, and Remobilization in Modern, Transgenic Insect-Protected Maize Hybrids, *Agronomy Journal* 105(1):161-170.

EPRI. 2011. Creating Nitrous Oxide ($N_2O$) Emissions Offsets in Agricultural Crop Production in the United States (aka "Nutrient Management").

EPRI. 2013. Pilot Trading Plan 1.0 for the Ohio River Basin Interstate Water Quality Trading Project. Accessed April 17, 2015 online at http://wqt.epri.com/pdf/Full-Trading-Plan-as-amended.pdf

EPA, 2007. Water Quality Trading Toolkit for Permit Writers, EPA 833-R-07-004.

EPA, 2004. Water Quality Trading Assessment Handbook. EPA 841-B-04-001.

EPA, 2003. Water Quality Trading Policy. Accessed April 20, 2015 on line at: http://water.epa.gov/type/watersheds/trading/tradingpolicy.cfm

Hoben, J . P., R. J. Gehlw, N. Millarz, P. R. Grace and G. P. Robertson, 2011, Nonlinear nitrous oxide ($N_2O$) response to nitrogen fertilizer in on-farm corn crops of the US Midwest, *Global Change Biology* 17: 1140–1152.

MCD (Miami Conservancy District). 2005 Great Miami River Watershed Water Quality Credit Trading Program Operations Manual. Accessed April 17, 2015 on line at: https://www.miamiconservancy.org/water/documents/TradingProgramOperationManualFeb8b2005secondversion.pdf

National Agricultural Statistics Service (NASS), 2012, *Agricultural Chemical Usage Reports*: *2010 Upland Cotton, Fall Potatoes* and *2012 Soybeans and Wheat*, United States Department of Agriculture, http://www.nass.usda.gov/Statistics_by_Subject/Environmental/index.asp (last verified March 6, 2015).

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, 2011, *Soil and Water Assessment Tool Theoretical Documentation – Version 2009*, Texas Water Resources Institute Technical Report No. 406, Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, and Blackland Research Center, Texas AgriLife Research, September 2011.

Sawyer, J.E. and A. P. Mallarino, 1999, *Differentiating and Understanding the Mehlich III, Bray, and Olsen Soil Phosphorus Tests*, presented at the 19th Annual Crop Pest Management Short Course, University of Minnesota, St. Paul, MN, November 22, 1999. Available at http://www.agronext.iastate.edu/soilfertility/presentations/mbotest.pdf (last verified March 3, 2015)

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, and O. Sirotenko, 2007, *Agriculture*. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

USGS's National Map Viewer, http://viewer.nationalmap.gov/viewer (last visited March 3, 2015)

White, M., D. Storm, H. Zhang, C. Penn, P. Busteed, G. Fox, and M. Smolen, 2007, *Proposed Updates to the Soil and Water Assessment Tool (SWAT) Phosphorus Model*, Poster, Southern Extension and Research Activity (SERA) - 17 Annual Meeting, Fayetteville, AR, June 11-13, 2007.

Winchell, M., R. Srinivasan, M. Di Luzio, and J. Arnold, 2010, *ArcSWAT Interface for SWAT2009*, Blackland Research and Extension Center, Texas AgriLife Research, and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, August 2010.

Wisconsin DNR, 2013. *Guidance for Implementing Water Quality Trading in Permits*, Guidance Number: 3400-2013-04, August 21, 2013.