DEPARTMENT OF AGRICULTURE

Email to: reports@lrl.leg.mn

September 14, 2017

Chris Steller
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RE: PT contract #90893 MN Department of Agriculture (MDA) and University of Minnesota, Office of Sponsored Projects Final Report

Project: Predictive Tools for Nitrate Modeling & Outreach

Dear Chris:

Here is complete copy of the final report submitted to the Minnesota Department of Agriculture Pesticide and Management Division. The electronic copy was emailed to you on September 14, 2017.

I am submitting only one print copy. This report was prepared by the contractor and according to the project manager is not mandated by law.

Please contact me at (651) 201-6196 if you have questions.

Sincerely,

Kam Carlson

Kam Carlson
Contracts & Grants Coordinator
Pesticide & Fertilizer Management Division
Minnesota Department of Agriculture
625 Robert Street N.
St. Paul, MN 55155-2538

Enclosures: One copy of final report for project listed above

Minnesota Department of Agriculture
Pesticide & Fertilizer Management
FINAL REPORT PHASES I&II
DATE: JUNE 30, 2017

PROJECT NUMBER:	90893
PROJECT DESCRIPTION:	Developing, Enhancing and Demonstrating Predictive Tools for Nitrate Losses from Crop Production in Minnesota
PRINCIPAL INVESTIGATOR:	David Mulla
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Abstract

Ground water is increasingly at risk for nitrate contamination in Minnesota. The most vulnerable areas are the central sands and karst regions. Objectives of this project are 1) To develop agricultural chemical best management practices that will prevent, minimize, reduce, and eliminate the source of groundwater degradation, and 2) To evaluate BMP effectiveness by: identifying, developing, enhancing and demonstrating predictive modeling tools for nitrate losses under common crop production systems, soil types and climate conditions across the state. BMPs of interest include: a) Nitrogen fertilizer practices (rate, timing, splits, spoon feeding, etc.), forms of N (anhydrous, urea, slow release, etc.), b) Irrigation management practices (checkbook method, scheduling), and c) Vegetative management practices (cover or catch crops, perennial crops, cropping systems, planting dates, etc.). Based on a review of literature, evaluation according to multiple objective criteria, testing with field data and advice from an Agency Project Review Team, the Environmental Policy Integrated Climate (EPIC) model was determined to be the best tool for assessing impacts on N BMP effectiveness in the central sands region, while the Soil Water Assessment Tool (SWAT) model was evaluated and determined to be the best tool for the karst region.

The Project Team identified a need for additional field research specifically related to nitrate leaching BMPs under corn and potato crops in the irrigated central sands region. The project review team met regularly to provide input to the project. Staff from the MDA participated in all project review team meetings. Staff from MGS, MPCA, DNR and MDH participated in some of the project meetings and discussions.

Two experimental sites in the central sands (Rosholt farm and Becker farm) were established to provide data for EPIC modeling. An additional experimental site (Field to Stream Partnership) in the Root River watershed and three watershed monitoring stations downstream of it were used to provide data for SWAT modeling in the karst region of southeastern Minnesota.

Field research at the Becker site studied the effect of conventional and adaptive management for irrigation (IRR) and nitrogen (N) strategies on tuber yield, quality, and nitrate-N leaching for irrigated potatoes grown on coarse-textured soils. Management strategies at Becker included two irrigation treatments: (1) conventional checkbook, and (2) deficit irrigation monitored by soil moisture sensors and six N-treatments. Experimental work at Becker has led to development of significantly improved methods for estimating irrigation and nitrogen requirements in potato crops. These improvements lead to significant reductions in N leaching to groundwater. N leaching losses at the Becker site were generally low to moderate, ranging between 13-18 kg N ha^{-1} for N rates ranging between 180-270 kg N ha^{-1}. Optical sensing - based split N application (247 kg N ha^{-1}) and deficit irrigation can reduce N leaching by 9% relative to a baseline 270 kg N ha^{-1} rate applied in four splits with conventional irrigation without affecting tuber yield or quality.

A study at the irrigated Rosholt commercial farm in the central sands region was established to determine the impact of N fertilizer rate and source on nitrate-N leaching in a corn-soybean, soybean-corn and corn-corn rotation. Data from this study were used to calibrate and validate the EPIC model. The model is very accurate at estimating impacts of irrigation, N rate, timing and source on N leaching under C-Sb, Sb-C and C-C rotations. N leaching losses at the Rosholt farm were relatively high, ranging between 60-80 kg N ha^{-1} for N rates ranging between 180-270 kg N ha^{-1}. N leaching losses at Rosholt are reduced 22% for the 180 kg N ha^{-1} rate (with different forms of N) relative to the 270 kg ha^{-1} rate. Crop yields are reduced 8-14% for the 180 kg N ha^{-1} rate (with different forms of N) relative to the 270 kg N ha^{-1} rate. Preliminary evaluation of cover crops with the EPIC model shows great promise for reducing N losses by up to 84% relative to baseline N management conditions without a cover crop.

The SWAT model has been calibrated and validate for the Headwaters region of the Root River in southeastern Minnesota using field and watershed data provided from 2010 to 2013 by the Field to Stream Partnership. The Headwaters watershed is an area dominated by the corn-soybean crop rotation. Soils are flat to undulating, and are fine textured. Subsurface tile drainage is common. Ten alternative BMP scenarios in the Headwaters watershed were simulated with SWAT in response to suggestions from Kevin Kuehner at MDA and the farmer where field testing is occurring. The "Baseline" scenario involved 70% of the watershed receiving spring fertilizer application rates of 170 lb N ac^{-1} and 30% receiving fall applications at a rate of 180 lb N ac^{-1}. Scenario 1 moved all fertilizer application to spring application on April 15th prior to corn planting on agricultural lands and maintained the same application rate of 170 lb N ac^{-1} over the entire watershed. Scenario 2 split the nitrogen application, applying 110 lb N ac^{-1} prior to planting and another 60 lb N ac^{-1} were applied on June 1st. This was performed throughout the entire Headwaters watershed. Scenario 3 added winter rye cover crop Scenario 1. Scenario 4 added 50 ft filter strips to Scenario 1. Scenario 5 used filter strips on only agricultural lands with slopes greater than 2%. Scenario 6 used a reduced nitrogen application rate, cutting the amount applied on April 15th down to 120 lb N ac^{-1}. Scenario 7 utilized reduced nitrogen application rates and the split application practice from Scenario 2. Scenario 8 combined the practices of Scenario 3 and Scenario 6. Scenario 9 was similar to Scenario 8, but utilized the split application method. Scenario 10 added filter strips to Scenario 9 as a means of representing the "maximum" reduction for the watershed. The most cost effective alternative practice for nitrate-N reductions is scenario 6 (120 lb N ac^{-1} in spring), which gave a 21% reduction in nitrate-N losses relative to baseline. In comparison, cover crops plus a spring N application of 170 lb N ac^{-1} (scenario 3) gave a 17% reduction relative to baseline.

Results from this project were the basis for twenty one extension and outreach talks to over 976 producers, industry reps and technical service providers. Three research publications were developed from data in these studies. Regular communication with MDA and the rest of the Project Review Team regarding effectiveness of SWAT modeled agricultural BMPs in southeastern Minnesota provides guidance for additional BMP testing and implementation on farmer fields in the Field to Stream project.

Total average annual nonpoint source N loadings to Minnesota groundwater under current agricultural practices were estimated at 14 million lb yr^{-1} (18 lb N ac^{-1}) for the Alluvium and Outwash agroecoregion, which includes the central sands. Total average annual nonpoint source N loadings to Minnesota groundwater under current practices were estimated at 19 million lb yr^{-1} (36 lb N ac^{-1}) for the Rochester Plateau agroecoregion (karst topography in southeastern Minnesota). In the remaining phase of this project, a wide range of agricultural BMPs will be evaluated with simulation models using long term climatic records at the township and coarser scales to determine how to reduce these N leaching losses to sustainable levels that protect drinking water.

Introduction

This document provides an overview and discussion of the status of the deliverables for Phases I and II of the project entitled "Develop, Enhance and Demonstrate Predictive Tools for Nitrate Losses from Crop Production in Minnesota" currently underway at the University of Minnesota.

The project uses a phased approach with the following timeframe:

- Phase I: April 15, 2015 – June 30, 2016
- Phase II: July 1, 2016 – June 30, 2017

Nitrogen pollution of ground waters is an ongoing challenge in Minnesota. Extensive monitoring of nitrate-N in nearly 900 wells by MDA and MPCA showed that 40% of groundwater wells in sand and gravel aquifers located in central Minnesota had concentrations exceeding 10 mg/L, while 10% of wells in southeastern Minnesota exceeded the drinking water standard. Sand and gravel aquifers in central Minnesota underlie areas of extensive irrigated agriculture (e.g. corn, potatoes) on sandy or alluvial soils, while bedrock aquifers in southeastern Minnesota underlie rainfed row crop and dairy agriculture on fine textured soils on top of weathered limestone (karst). Each of these sensitive regions has relatively rapid travel times for nitrate-N leaching from agricultural fields downward to groundwater. In addition, the karst region of southeastern Minnesota has close connections between ground and surface waters, so that nitrate-N entering ground water can subsequently be discharged through springs to perennial streams.

There is a pressing need to evaluate the effectiveness of practices to reduce the transport of nitrate-N to Minnesota groundwater, particularly in the central sands and karst regions. Computer models can be of great value in evaluating the effectiveness of practices to reduce transport of nitrate-N to ground water. Models are most accurate when calibrated and validated using experimental data for various BMP treatments coupled with water quality monitoring. Whereas experimental data are collected for specific climate years, models calibrated and validated to these data can be used to extrapolate BMP effectiveness using long climatic records or future climate change scenarios. They can also sometimes be used to evaluate effectiveness of BMPs that were not actually the subject of field experimentation, when the behavior of those BMPs is well understood from research at other locations.

In this project, we used a combination of field data involving experimental nitrogen treatments with corn, soybeans and potatoes and computer modeling: "develop agricultural chemical best management practices that will prevent, minimize, reduce, and eliminate the source of groundwater degradation." Our particular focus is on BMPs to reduce nitrate-N contamination of groundwater. BMPs are evaluated through a process that involves: "identifying, developing, enhancing and demonstrating predictive modeling tools for nitrate losses under common crop production systems, soil types and climate conditions across the state. The tools will incorporate the dominant physical, chemical and biological processes related to nitrogen conversion, uptake, release, turnover and transport within the soil-plant-atmosphere continuum and their responses to changing climatic conditions."

Task 1: Introduce and specify why the suggested simulation model(s) is (are) appropriate for this study.

Models are useful for several purposes, including 1) Identifying the problems and their extent, 2) Evaluating pollution sources and pathways for transport, 3) Setting water quality goals, 4) Prioritizing agroecoregions, watersheds and critical areas within them, 5) Identifying and evaluating effectiveness of BMPs to improve water quality, and 6) Evaluating progress towards goals. A comprehensive literature review of nitrogen leaching simulation models was conducted leading to selection of the most appropriate models for the project in the central sands and karst regions of Minnesota. In brief, the process involved a screening process of selected models, a literature review and model testing.

In general, models can be classified into three tiers. Tier 1 is the simplest model, exemplified by export coefficient, regression or empirical models. Its utility for evaluating the effectiveness of BMPs is limited to broad scales and average long-term climatic conditions. Tier 2 includes screening tool models that are relatively easy to use, rely on readily available input data and represent hydrologic pathways and nutrient cycling using simplistic, often non-mechanistic algorithms and simplistic representations of climate. Tier 3 includes mechanistic models that require training, extensive input data, and operate on a continuous daily time step. The latter are able to evaluate the effectiveness of BMPs for specific sites on a storm event basis as well as using dry, average or wet climatic conditions.

Tier 1 simulation models, consisting of simpler regression-based or empirical models were unable to adequately model complex systems such as those addressed in this project and such models further for the project. Tier 2 models, such as screening type tools that were relatively easy to use but typically used simplistic representations of hydrology, nitrogen dynamics, crop growth, and climate were included in the model selection process. NLEAP is an example of a

Tier II model. The highest level, Tier 3 consists of mechanistic models that were able to simulate and evaluate the effectiveness of BMPs at continuous time steps. EPIC and SWAT are examples of Tier 3 models.

Twelve Tier 2 and 3 models were evaluated for suitability of use in the Minnesota central sands and karst regions. The initial selection was based on models capable of operating at the field scale and the Project Team's extensive experience with relevant models. The twelve models were reviewed based on their ability to simulate nitrogen management, processes and transport including nitrogen fertilizer practices, nitrogen transformation and nitrogen movement, manure management, test of nitrogen BMPs, and accurately describe soil conditions, hydrology, drainage, irrigation, crop growth and management and sediment transport. Additional evaluation criteria included input data requirements, level of documentation, how widely used and accepted the models were, linkage to GIS and graphical user interface and model user experience requirements. Numerical scores were assigned to each of the twelve models based on the literature review. The highest ranked Tier 2 model (NLEAP) and the four top ranked Tier 3 models (EPIC, APEX, SWAT and DSSAT) were selected for further consideration by the Project Team.

The review included a comprehensive overview of each model's capabilities, strengths and weaknesses relative to the project. The final model selection was based on the following process:

i. Collecting input data required for each candidate model
ii. Setup and configuration of each candidate model
iii. Running candidate models and simulating field scale hydrology, nitrate-N leaching losses and crop growth
iv. Evaluation of the capacity of each candidate model with respect to the following criteria:
    a. Input data requirements
    b. Calibration and validation outputs and statistics for hydrology, nitrate-N leaching losses and crop growth simulations
    c. Effective representation and capability to simulate alternative best management practices (BMPs)
    d. Ease of use
    e. Utility of simulation outputs

After further consideration, it was determined that NLEAP lacked the capabilities needed to assess impacts of N BMP effectiveness for the purposes of this project. NLEAP has several weaknesses, including very simplified water and nitrogen balance routines, inability to simulate crop growth accurately, and no simulation of N-fixation by legumes. EPIC and DSSAT were evaluated using data from the Rosholt farm, and EPIC was determined to be the best tool for assessing impacts on N BMP effectiveness in the central sands region, while SWAT was evaluated and determined to be the best tool for the karst region.

EPIC stands for the Environmental Policy Integrated Climate model, a process based, deterministic model that operates on a daily time step. This model was developed in the early 1980's to assess the effect of erosion on productivity for use in the 1985 National RCA analysis. Since then the model has been expanded and refined to allow simulation of many processes important in agricultural management. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, and economics.

There is a comprehensive nitrogen cycle simulation routine in EPIC model. The nitrogen cycle is simulated by the processes of denitrification, mineralization, immobilization, and fixation. The concentration of nitrogen in rainfall may also be included. Nitrate that is adsorbed and in solution may leave with the runoff, through percolation or lateral subsurface flow. Loading functions for organic nitrogen are also provided. Nitrogen may be moved into the top soil layer as water in that layer evaporates and water from lower layers enters. Discharge of water below the crop rooting zone is predicted by EPIC and can be used along with soil porosity to estimate travel time of water to deep aquifers.

Strengths of EPIC include having a flexible framework that allows the simulation of a wide variety of conservation practices and other BMPs, such as fertilizer and manure application rate, source, method and timing, cover crops (perennial grasses), filter strips, conservation tillage, irrigation management, planting date, crop maturity, crop type, rotation sequence, cover crop and double cropping systems, and plant population and row spacing. EPIC can be used to simulate field scale nitrate leaching, as well as regional scale nitrate leaching. EPIC is widely used all over the world.

SWAT stands for the Soil and Water Assessment Tool (SWAT) model, a physically-based continuous-time, conceptual, long-term, distributed watershed scale hydrologic model. SWAT is designed to predict the impact of land management practices on the hydrology, sediment and nitrogen transport in large, complex catchments. It is capable of simulating surface runoff, percolation, return flow, erosion, nitrogen and phosphorus loading, irrigation, groundwater flow, field drainage, plant water use and other supporting processes from small, medium and large watersheds. There are numerous applications of SWAT model all over the world.

Strengths of SWAT include having comprehensive hydrologic, water quality, crop growth algorithms, a flexible framework that allows the simulation of a wide variety of conservation practices and other BMPs, such as fertilizer and manure application rate, source, method and timing, cover crops (perennial grasses), filter strips, conservation tillage, irrigation management, and subsurface tile flows. SWAT has detailed algorithms to represent the nitrogen cycle, including crop uptake and nitrate leaching or drainage losses.

Task 2: Assess existing field and watershed scale projects and collect data for modeling purposes.

The Project Team established a review process and provided a discussion of existing water quality research and demonstration projects undertaken or funded by the MDA. The Project Team additionally reviewed other relevant research and demonstration projects to evaluate their applicability and relevance for inclusion in the project. The Project Team focused on relevant research and demonstration projects located within the project focus areas, namely coarse textured soils in the irrigated central portion of the state and Dakota County, and the southeastern karst region. For crop production systems on irrigated coarse-textured soils the Project Team reviewed data from several locations, including the University of Minnesota Sand Plain Research Farm near Becker, the Herman Rosholt Farm by Westport and the location formerly known as the Staples Irrigation Center. For the southeastern karst region information came from project sites in Dodge County, the Whitewater paired tributary watershed study, projects by the Minnesota Geologic Survey and the St Anthony Falls Lab, and the Root River Field to Stream Partnership project.

The Project Team has provided MDA with information regarding missing chemical/physical/crop response measurements in ongoing MDA-led projects. In some cases, such as data from the Root River Field to Stream Partnership, this information was available once data release forms were signed by the participating land owners. For other project sites additional data collection was added, such as deep profile soil nitrate testing at the nitrogen rate study funded by MDA currently underway at Central Lakes College in Staples. The Project Team identified a need for additional research specifically related to nitrate leaching under corn and potato crops in the irrigated central sands region.

Becker Irrigated Potato Field Experiment

A plot-scale field experiment initiated in 2016 was continued in 2017 at the Sand Plains Research Farm in Becker, MN to evaluate the effect of conventional and adaptive management for irrigation (IRR) and nitrogen (N) strategies on tuber yield, quality, and nitrate-N leaching for irrigated potatoes grown on coarse-textured soils. Data from this study will be used for future modeling of nitrate-N leaching using the EPIC model in Phase III of this project.

Management strategies for IRR included two treatments: (1) conventional checkbook, and (2) deficit irrigation monitored by soil moisture sensors. Six N-treatments were imposed (Table 1) including (1) 40 lb N/ac control treatment, (2) split-applied urea treatments of 160 lb N/ac, and of (4) 240 lb N/ac, (3) controlled-release polymer coated urea (PCU) treatments of 160 lb N/ac, and of (5) 240 lb N/ac, and (6) split-applied urea applied at a variable-rate based on weekly remote sensing of crop nitrogen stress. Experimental work has led to development of significantly improved methods for estimating irrigation and nitrogen requirements in potato. These improvements lead to significant reductions in N leaching to groundwater.

Table 1: Rate and timing of N fertilizer treatments during 2016 in the Becker, MN potato experiment.

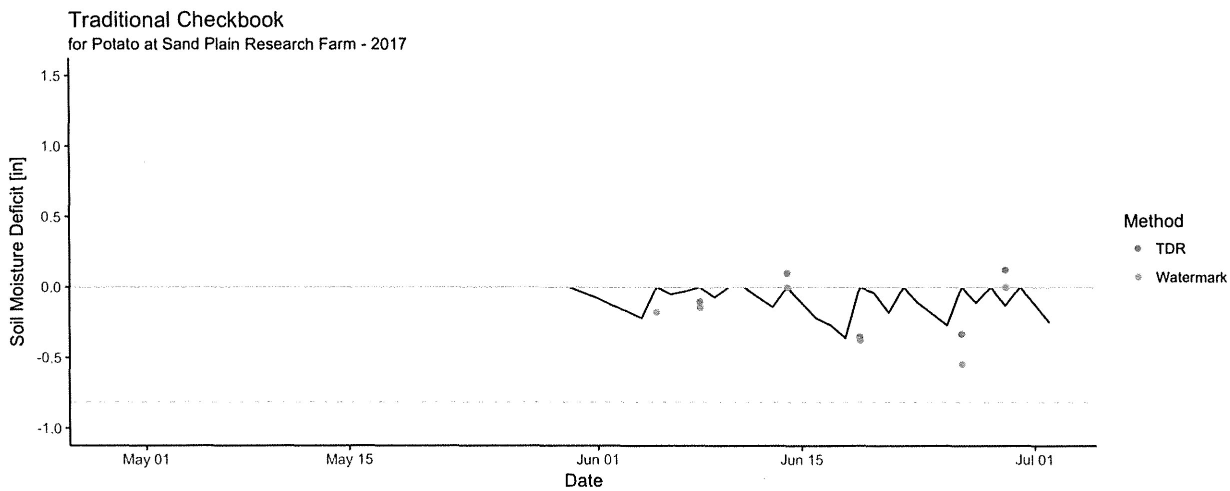
Rate and timing of N-fertilizer treatments										
			Planting 22 April	Emergence 1 June	Post-Emergence 23 June	14 July	21 July	27 July	Total‡
N-Treatment†			kg N ha^{-1}						
1	–	Control	45 DAP	–	–	–	–	–	45
2	–	Urea	45 DAP	67 Urea	17 UAN	17 UAN	17 UAN	17 UAN	180
3	–	ESN 180	45 DAP	135 ESN	–	–	–	–	180
4	–	Urea	45 DAP	135 Urea	23 UAN	23 UAN	23 UAN	23 UAN	270
5	–	ESN 270	45 DAP	225 ESN	–	–	–	–	270
6	–	Var.	45 DAP	135 Urea	–	23 UAN	23 UAN	23 UAN	247

† DAP: Diammonium Phosphate, ESN: "Environmentally Smart Nitrogen", UAN: Urea + Ammonium Nitrate
‡ N-fertilizer rates rounded, and may not sum exactly across N-treatments

Improved Water Balance Based Estimation of Irrigation Requirements

Water balance calculation procedures, more commonly known as the Checkbook method, have not been substantially improved in decades. Current implementations of the Checkbook method rely on computation by hand or using by using a semi-automated computer spreadsheet, and require significant time and effort to accurately operate. Additionally, the estimates of evapotranspiration [ET] and leaching [L] utilized in the existing computational procedure are overly simplistic. The current Checkbook method reflects historical limitations imposed by lack of available weather data with enough information to calculate reference ET or with adequate spatial and temporal coverage.

Data provided by the Central MN Ag Weather Network can be used to fully automate water balance calculations. This will decrease the time required for producers to schedule irrigation and improve the accuracy of soil moisture deficit estimates. A prototype of a full automated irrigation scheduling tool has been developed for potato at the Sand Plain Research Farm in Becker, MN. Current implementation of the tool incorporates remote sensing observations of crop canopy cover, weekly measurements from soil moisture monitoring equipment such as Spectrum TDR-300 and Irrometer Watermark sensors, and data from soil moisture characteristic curves and in-situ field capacity drainage curves for Hubbard sandy loam. Although these additional data sources are not necessary for the operation of the irrigation scheduling tool, their incorporation improves the accuracy of the water balance calculations. Using readily available data sources, this tool could potentially be extended to the entire Central Sands region, and to other areas in the North Central USA with irrigated production on sandy soils. A comparative example of the Improved Water Balance and the Traditional Checkbook using data from the field study is shown in Fig. 1. The traditional checkbook method shows more frequent and more severe soil water depletion than the improved method based on soil moisture monitoring. The primary factor leading to improvement in estimating soil water deficit is in improved estimates of ET from Central MN Ag Weather Network data, rather than assuming a constant ET as in the checkbook method.



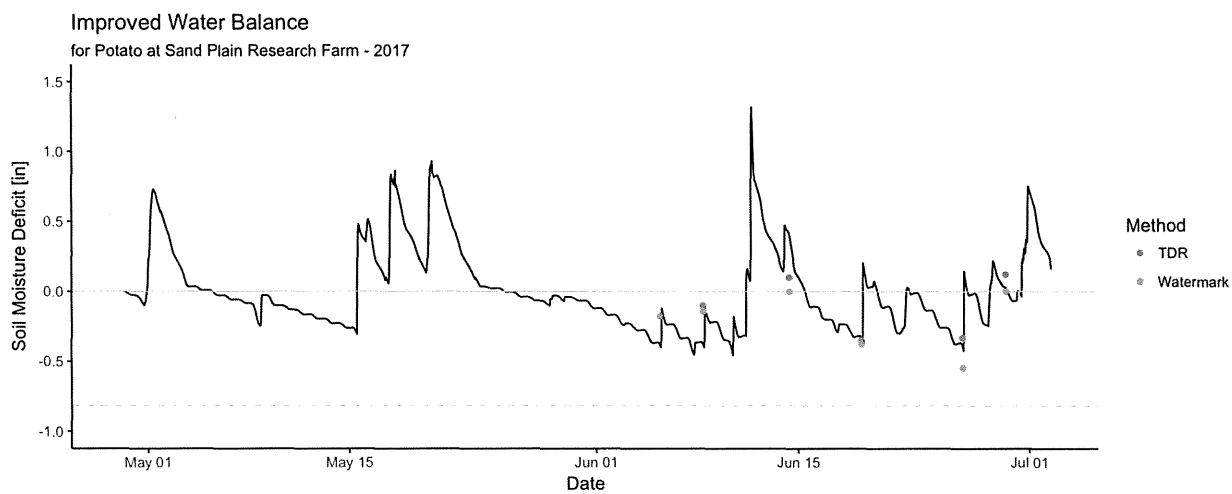


Fig. 1: Estimates of soil moisture deficit using the traditional checkbook method (top) and an improved hourly water balance approach (bottom).

Improved Estimation of N Fertilizer Requirements

Rate and timing for potato supplemental nitrogen applications are commonly determined by growers through assessment of petiole-N concentration. Although these methods are useful and widely adopted by producers, they are labor and time intensive to conduct and have poor spatial and temporal coverage of crop-N status. Ground-, UAV-, or aerial-based multispectral remote sensing is a potential strategy to improve the management of supplemental nitrogen. Data from remote sensing, however, is difficult to manage without an automated procedure to process, analyze, and interpret the data with respect to crop-N status. We have developed an applied Nitrogen Sufficiency Index [NSI] based on the Simple Ratio (SR8) index using remote sensing to determine relative crop-N status with respect to a well-fertilized reference plot (treatment 5). We have successfully managed supplement applications of N using this SR8 NSI approach (Fig. 2), and results compare closely with a more tedious approach using SPAD meters to detect N deficiency in potato leaves. This SR8 NSI method could be utilized by growers to divide entire fields into management zones having variable (customized) N application rates.

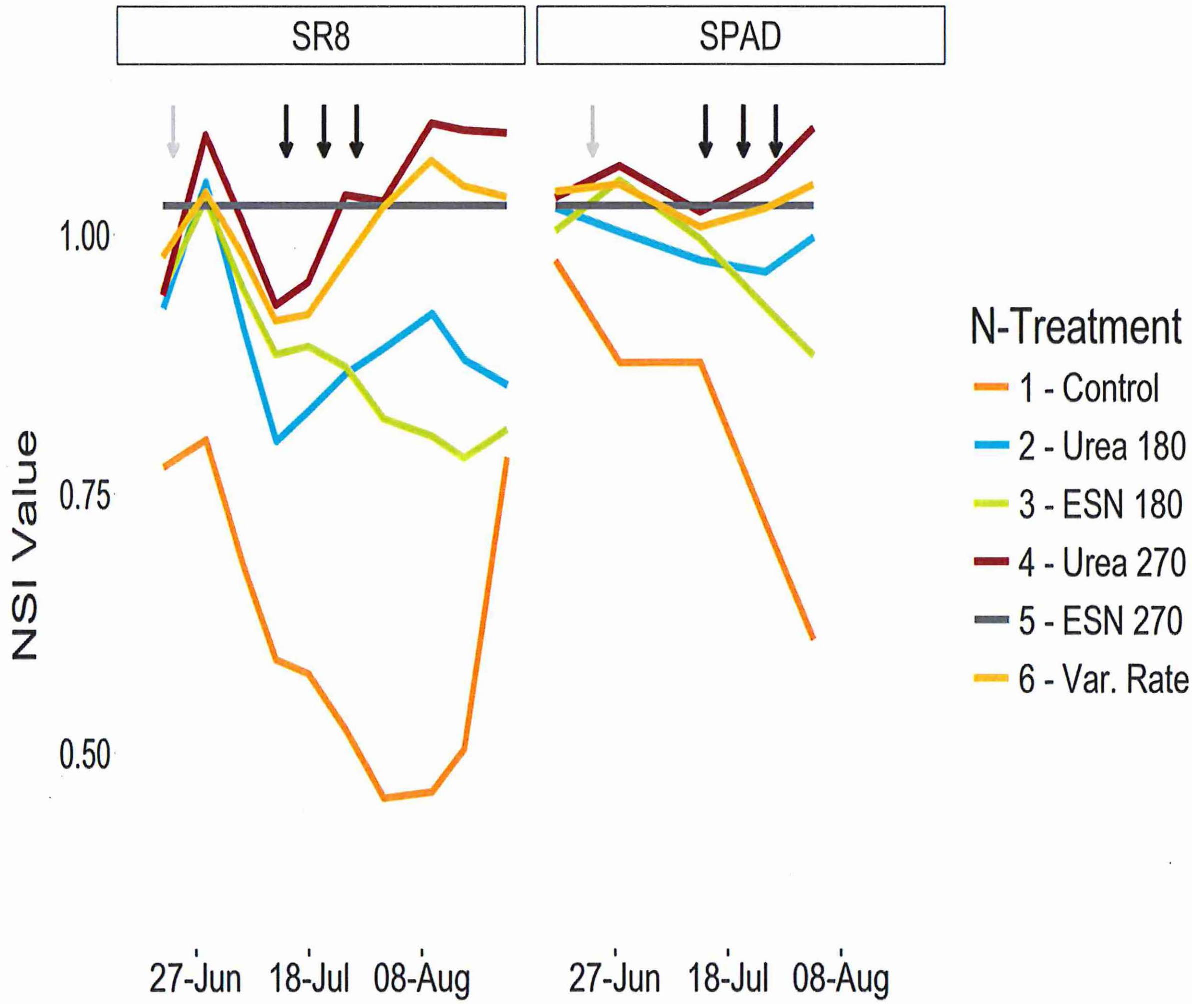


Fig. 2: Nitrogen Sufficiency Index (NSI) based on Simple Ratio 8 (SR8) or SPAD meter remote sensing readings of potato canopies or leaves during 2016 at Becker, MN. NSI values less than 0.95 indicate N deficiency in potato canopies or leaves. Black arrows indicate timing of supplemental N fertilizer applications in variable rate treatment six.

Overall, N-treatments in 2016 had a significant effect on total and marketable yield, while IRR did not. Additionally, remote spectral sensing was able to identify significant plant-N deficiencies on a timely basis; as a result, the variable rate treatment (6) received 20 lb N/ac less than the comparable split-applied urea treatment (4) in 2016 without a significant difference in tuber yield or quality.

Water quality below the root zone was measured with suction-cup lysimeters. Monitoring equipment was installed in each experimental plot and water sampling was conducted on weekly to twice-weekly basis. Samples were stored frozen and analyzed conductimetrically for nitrate-N concentrations using a Wescan N analyzer. Interpolated daily values of nitrate-N concentration were calculated for each sub-plot. EPIC modeling is underway to estimate N leaching losses (kg/ha) using these data. Results indicate that remote sensing - based (SR8 NSI) split N application (247 kg N/ha) and deficit irrigation reduced N leaching by 9% in 2016 relative to leaching losses in the 270 kg N/ha rate treatment with conventional irrigation without affecting tuber yield or quality.

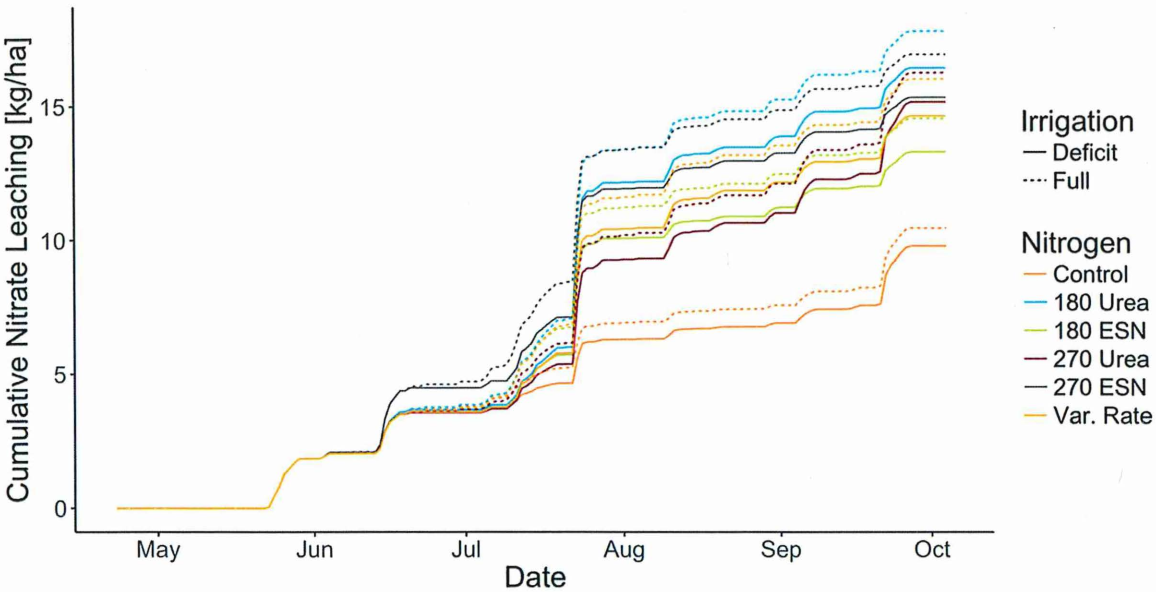


Fig. 3: Cumulative nitrate-N leaching below potato rooting zone in 2016 at Becker, MN for six N fertilizer treatments under conventional checkbook (full) versus deficit irrigation.

Task 3. Generate predictive nitrate loss estimates

Rosholt Farm EPIC Model Simulations

The major objective of this phase of the project is to test EPIC model suitability and accuracy to simulate yield, N uptake, and N leaching losses at the Rosholt farm site in the Central Sands Region of Minnesota. Model predicted outputs were compared against measured values for grain yield, nitrogen uptake and nitrogen leaching loss responses as affected by the different nitrogen fertilizer application rates.

The study was conducted at Rosholt Research Farm in Pope County (95.17° north, 45.72° west) during the years 2011 to 2014. The site has three blocks of 48 plots each, where each block has 12 treatments and four replicates arranged in a randomized, complete block design. Block I, II and III were under continuous corn (C-C), soybean-corn (Sb-C), and corn-soybean (C-Sb) rotations, respectively. Each plot has an area of 15'x40'. As shown in Table 2, the treatments were established based on the different rates of nitrogen applications (0-280 lb/ac) from four different sources (urea, super-U, ESN, and ESN/Urea). Data from years 2011 and 2012 were used for model calibration, while years 2013 and 2014 were the validation years. The model testing was focused on treatments 1, 4, 5, 6, 7, 9, 10 and 12, that received different rates of urea fertilizer as nitrogen sources.

EPIC calibration and validation work at the Rosholt farm involved eight of the twelve N fertilizer treatments in the corn-corn (C-C), soybean-corn (S-C) and corn-soybean (C-S) experimental plots. Table 2 summarizes the N fertilizer treatments. N leaching was not measured in treatments 2, 3, 8 and 11, and EPIC model simulations were not attempted in these cases.

Table 2: N Fertilizer Treatments tested at the Rosholt Farm for irrigated C-C, S-C and C-S rotations. N fertilizer was applied in two split applications.

Treatments	Product	N rate (lbs/ac)	N rate (Kg/ha)
1	-	0	0.0
2	urea	40	44.8
3	urea	80	89.6
4	urea	120	135
5	urea	160	179.2
6	urea	200	224.0
7	urea	240	268.8
8	urea	280	313.6
9	SuperU	160	179.2
10	ESN	160	179.2
11	ESN	200	224.0
12	ESN/Urea	160	179.2

Performance of the EPIC model was excellent in predicting percolation, nitrate leaching, plant nitrogen uptake, residual soil nitrogen and crop yield for the C-Sb, Sb-C and C-C rotations at the Rosholt experimental site. Comparisons between field measurements and EPIC simulated nitrate-N leaching were excellent (Fig. 4). Results of the EPIC study showed that the model responded accurately to climate, crop rotation, and fertilizer rate or source.

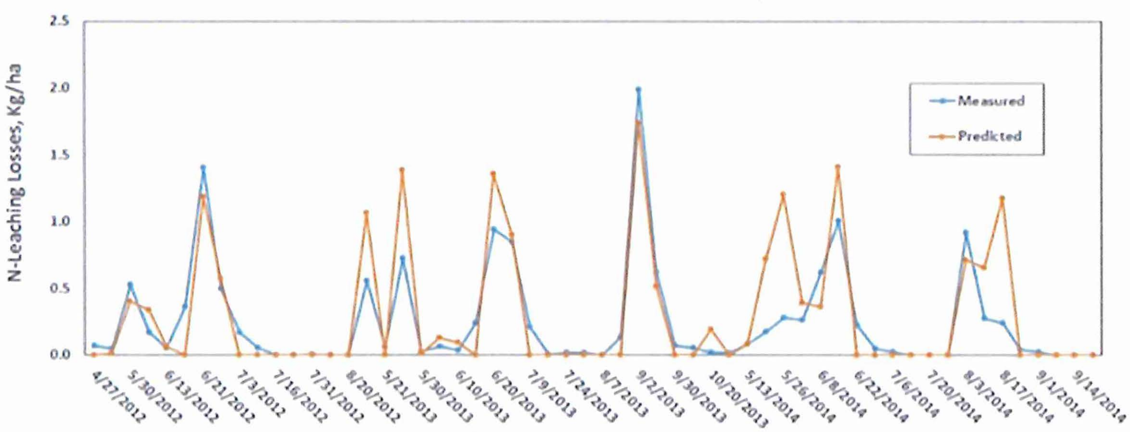


Fig. 4: Comparison between measured and EPIC predicted nitrate-N leaching at Rosholt farm for 135 kg ha^{-1} N fertilizer treatment in a corn-corn rotation.

Climate at the Rosholt study site differed distinctly from one year to the next (Fig. 5). The wettest growing season occurred during 2012, the driest during 2014. However, there were also differences in water input on a daily basis (indicated by the slope of the cumulative curves in Fig. 5 at a given point in time) that were important for understanding water percolation and nitrate-N leaching across years.

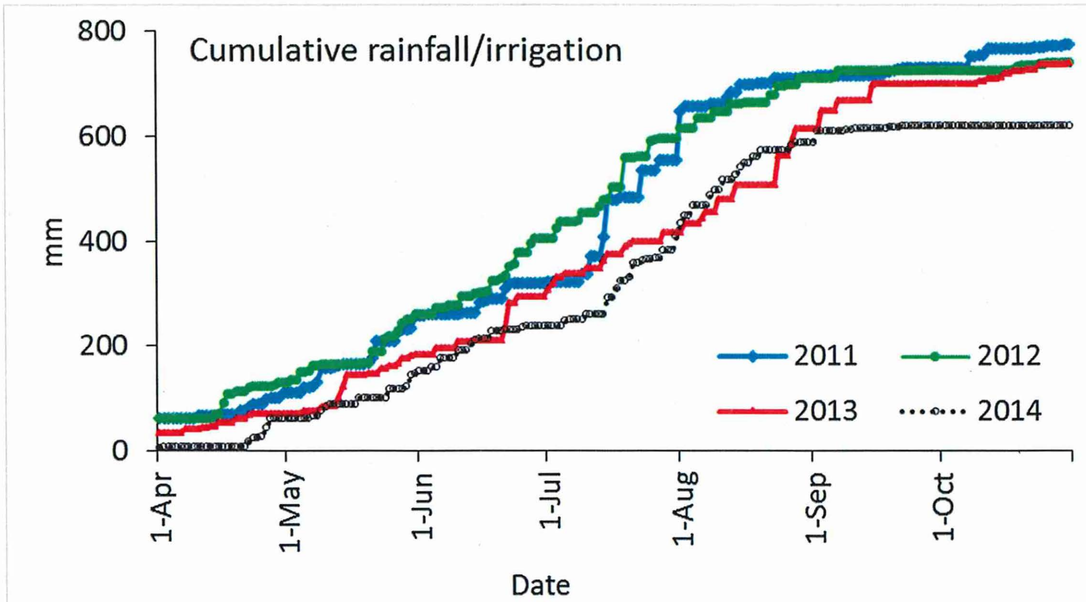


Fig. 5. Cumulative rainfall and irrigation (mm) at Rosholt during the years 2011-2014.

Soil Water Percolation

Soil water deep percolation varied significantly among the years, for different treatments. The EPIC model predicted daily and cumulative percolation reasonably well, in comparison with measured results. "Measured" percolation values were actually estimated indirectly, based on a checkbook method estimate for ET and a resulting water balance. EPIC, in contrast, uses daily estimates of ET that are more accurate than the checkbook method. Percolation was highest during the year 2011, followed by the years 2013 and 2014, while the year 2013 showed the lowest percolation values. High percolation during 2011 resulted from high rainfall events occurring during the month of July (Fig. 5). High values of percolation observed during the months of July and August in 2011 and 2014 were related to high rainfall events.

An increase in the rate of N fertilizer caused crop ET to increase, thereby causing decreases in percolation (Fig. 6). Slow release fertilizers had less crop ET (and more percolation) than ET at the 225 and 270 kg N ha^{-1} application rates.

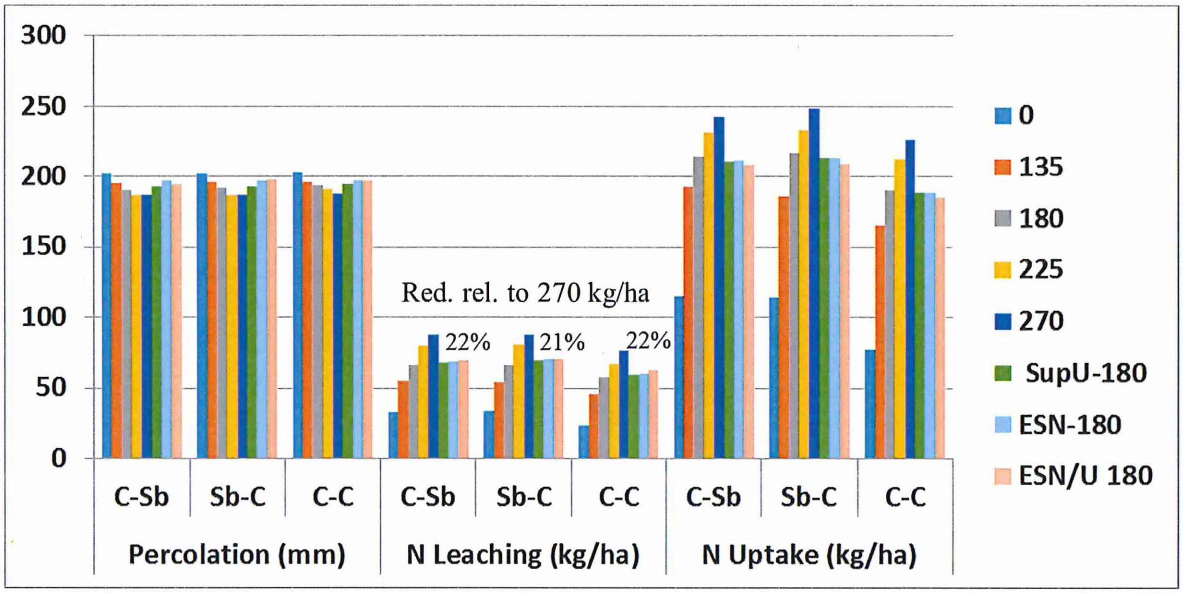


Fig. 6: EPIC simulated percolation, N leaching, and N uptake at Rosholt for three crop rotations and eight N fertilizer treatments.

Nitrate-N Leaching

Nitrate leaching was largely influenced by the rainfall intensity, crop rotation, and N rates (Fig. 6), and to a lesser degree by fertilizer source. The model predications were in close agreement with the measured values. Nitrate-N leaching was higher for soybeans than corn, and for the Sb-C/C-Sb rotations compared to the C-C rotation. Nitrate-N leaching losses were similar for the 180 kg ha^{-1} rate of either split applied urea or for pre-plant applications of ESN, Super-U or ESN/U. High rainfall during the years 2011 and 2013, accompanied by pre-plant application of slow release fertilizers at high rates caused slightly higher leaching of nitrate-N compared to the split application of urea. Nitrate leaching losses approached maximum values of 105 kg ha^{-1} and 120 kg ha^{-1}, with an application of 270 kg N ha^{-1} as urea, during 2011, under corn and soybean crops, respectively. Average annual nitrate leaching losses varied between 75-95 kg ha^{-1} with an application of 270 kg N ha^{-1} as urea. Corn harvested after soybean showed higher nitrate-N leaching, compared to leaching for corn following corn.

Crop N Uptake

Nitrogen uptake in crop following two split applications of urea and pre-plant application of slow release fertilizer was accurately predicted by the EPIC model. Nitrogen uptake by the corn crop was significantly influenced by crop rotations (Fig. 6). Corn generally showed 15-40% higher N uptake in the Sb-C rotation, compared to the C-C rotation. Soybean crops fixed a considerable amount of N, and hence showed higher N uptake, compared to the corn crop. EPIC simulations showed that increasing N fertilizer rates in the corn crop prior to soybean generally decreased N fixation in soybean.

Residual Soil N

Residual soil N observed at the harvest of crop was higher after the soybean crop, compared to corn (Fig. 7). In corn years, application of urea at 270 kg ha^{-1}, caused considerable buildup of nitrate-N in the soil rooting zone, while crops grown without N fertilizer (control), depleted the soil root zone nitrate-N. In corn years, application of 135 or 180 kg N ha^{-1}, regardless of source, generally led to small depletion in soil root zone nitrate-N. Application of 225 kg N ha^{-1} resulted in a small buildup of nitrate-N in the rooting zone.

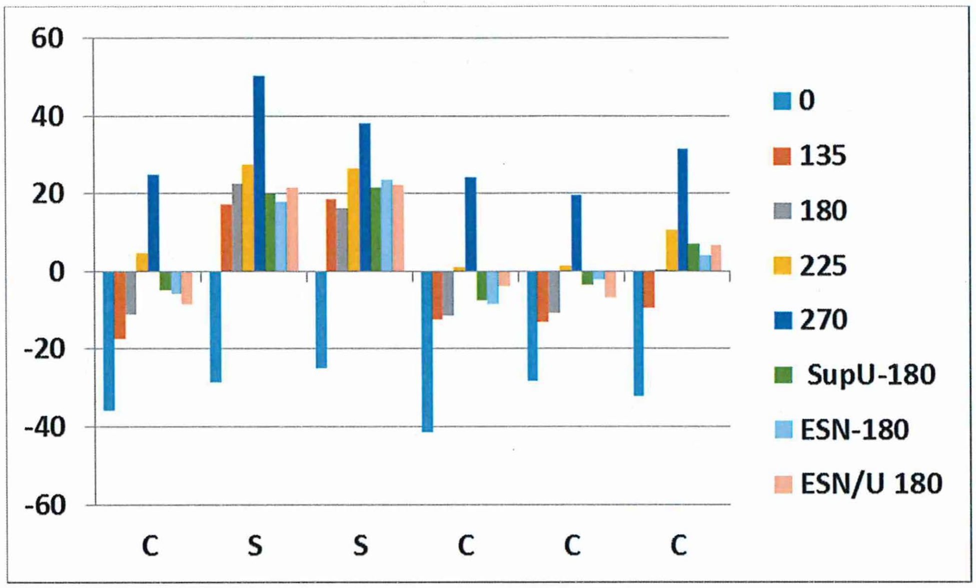


Fig. 7: EPIC simulated residual soil N for three crop rotations and eight N fertilizer treatments.

Crop Yield

Crop yield, especially for corn, was highly influenced by the crop rotation. Corn harvested after soybean showed much higher yield than corn harvested after corn (Fig. 8). Un-fertilized corn had 44% higher yield in the Sb-C rotation than in the C-C rotation. Maximum yields of corn (14 Mg ha^{-1}) were observed under the Sb-C rotation with an N fertilizer application of 270 kg ha^{-1}. Corn yields were decreased 10% with applications of 180 kg N ha^{-1} as urea or slow release relative to the highest N rate.

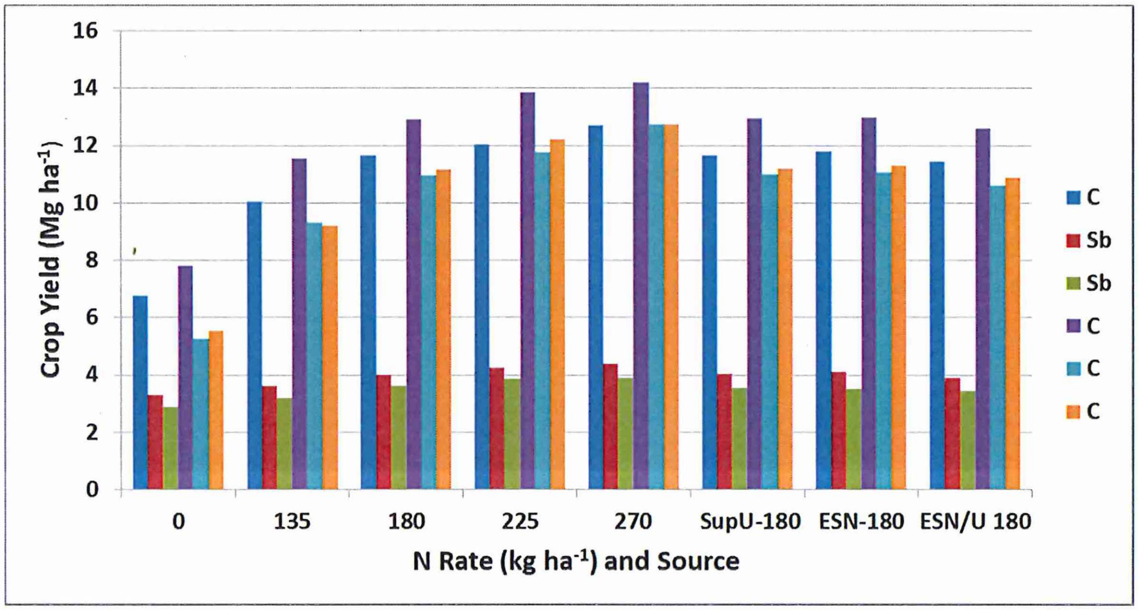


Fig. 8: EPIC simulated crop yield for three crop rotations and eight N fertilizer treatments. The ordering of results represents the C-Sb, Sb-C, and C-C rotation results averaged over four years.

Nitrate-N leaching results at Rosholt average above 50 kg ha^{-1} annually for all N fertilizer applications greater than 180 kg N ha^{-1}. These nitrate-N leaching results are clearly not low enough to provide long-term sustainable and safe groundwater nitrate-N concentrations in the central sands region. Alternative management practices involving either additional split N fertilizer applications or winter rye cover crops planted after harvest of corn in the corn-corn rotation (135 kg ha^{-1} N fertilizer application) were explored using the calibrated/validated EPIC model. Results indicate that good establishment of a winter rye cover crop provides excellent reduction in nitrate-N leaching losses (84% reduction) at the Rosholt site (Fig. 9). Nitrate-N leaching losses of 15 kg ha^{-1} or less should be sustainable.

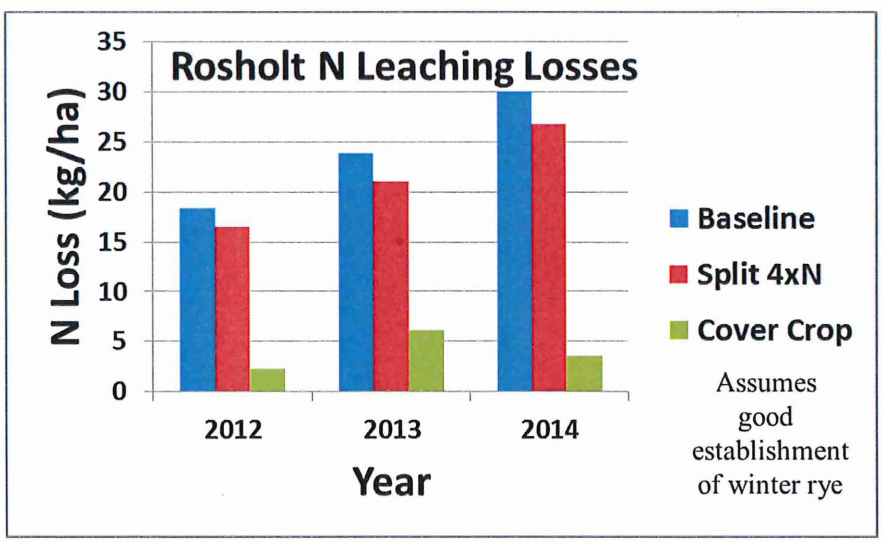


Fig. 9: EPIC simulated nitrate-N leaching losses at Rosholt in a corn-corn rotation receiving 135 kg ha^{-1} N fertilizer in two or four splits, with and without a winter rye cover crop.

Root River SWAT Predictive N Loss Estimates

The SWAT model has been calibrated for the Root River in southeastern Minnesota using measured data provided from 2010 to 2013 by Kevin Kuehner at MDA. Three watersheds are being studied in for this project (Fig. 10). The westernmost in the Root River basin is the Headwaters watershed. This watershed is roughly 11 square kilometers, or 2,700 acres. Within the Headwaters watershed is a producer's field where alternative BMPs are being implemented and evaluated for water quality protection. SWAT has been conducted at the SRF field site as well as the Headwaters watershed using measured data. The second watershed is Crystal Creek, located roughly in the middle of the Root River watershed. It contains some karst geologic features in the near subsurface. Crystal Creek is a 15 square kilometer (3,700 acres) watershed with an outlet located near Juniper road north of 150th street and 5 miles northeast of Harmony. Third is the Bridge Creek watershed, located south of Rushford and southwest of Houston. Bridge Creek is a 19 square-kilometer (4,700 acres) watershed.

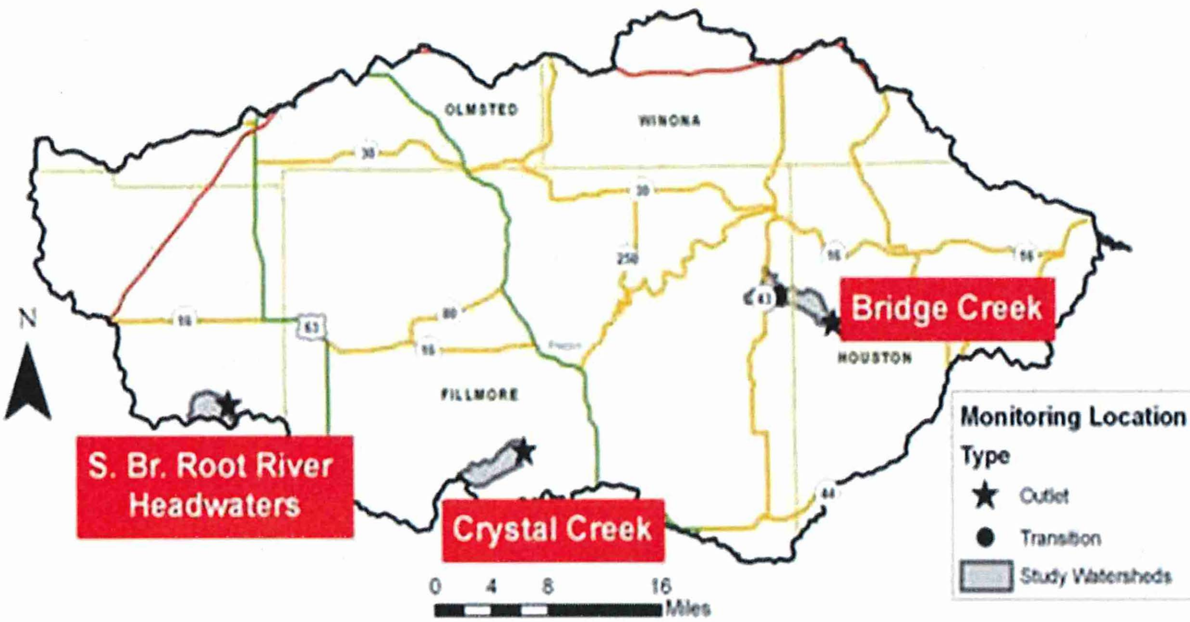


Fig. 10: Location of MDA Field to Stream project water quality monitoring data in the Root River watershed.

Headwaters BMP Simulations

The Headwaters watershed is an area dominated by the corn-soybean crop rotation. Soils are flat to undulating, and are fine textured. Subsurface tile drainage is common. Alternative scenarios in the Headwaters watershed were selected in response to suggestions from Kevin Kuehner and the farmer where field testing is occurring. Eleven different simulations have been performed on the Headwaters model with regards to nitrate-N output from the watershed (Table 3). The "Baseline" scenario was meant to simulate current fertilizer practices. Based on information provided by Kevin Kuehner, 70% of the watershed was simulated with spring fertilizer application rates of 170 lb N ac^{-1} and 30% was fall applied at a rate of 180 lb N ac^{-1}. Fall application took place on October 11th prior to the corn rotation, while spring application took place on April 15th, five days prior to corn planting. The watershed was simulated with roughly half of agricultural land growing corn and the other half growing soybeans, rotating each growing season. This 50-50 split was maintained throughout all simulations. Corn was planted on April 20th and harvested on October 20th, while soybeans were planted on May 1st and harvested on October 10th.

Table 3: Root River Headwaters SWAT Simulation Scenarios

Scenario Name	Nitrogen Application and Land Cover Adjustments	Nitrogen Applied (lbs/ac)
Baseline	30% Fall, 70% Spring	Fall: 180, Spring: 170
Scenario 1	100% Spring	Spring: 170
Scenario 2	100% Split Application	April 15: 110, June 1: 60
Scenario 3	Cover Crop, 100% Spring	Spring: 170
Scenario 4	100% Spring, Filter Strips	Spring: 170
Scenario 5	100% Spring, Filter Strips on >2%Slope	Spring: 170
Scenario 6	100% Spring, Reduced N	Spring: 120
Scenario 7	100% Split, Reduced N	April 15: 80, June 1: 40
Scenario 8	Cover Crop, 100% Spring, Reduced N	April 15: 120
Scenario 9	Cover Crop, 100% Split, Reduced N	April 15: 80, June 1: 40
Scenario 10	Cover Crop, 100% Split, Reduced N, Filters	April 15: 80, June 1: 40

Scenario 1 moved all fertilizer application to spring application on April 15th prior to corn planting on agricultural lands and maintained the same application rate of 170 lb N ac^{-1} over the entire watershed. Scenario 2 split the nitrogen application, applying 110 lb N ac^{-1} prior to planting and another 60 lb N ac^{-1} were applied on June 1st. This was performed throughout the entire Headwaters watershed. Scenario 3 added winter rye cover crop Scenario 1. Scenario 4 added 50 ft filter strips to Scenario 1. Scenario 5 used filter strips on only agricultural lands with slopes greater than 2%. Scenario 6 used a reduced nitrogen application rate, cutting the amount applied on April 15th down to 120 lb N ac^{-1}. Scenario 7 utilized reduced nitrogen application rates and the split application practice from Scenario 2. Scenario 8 combined the practices of Scenario 3 and Scenario 6. Scenario 9 was similar to Scenario 8, but utilized the split application method. Scenario 10 added filter strips to Scenario 9 as a means of representing the “maximum” reduction for the watershed.

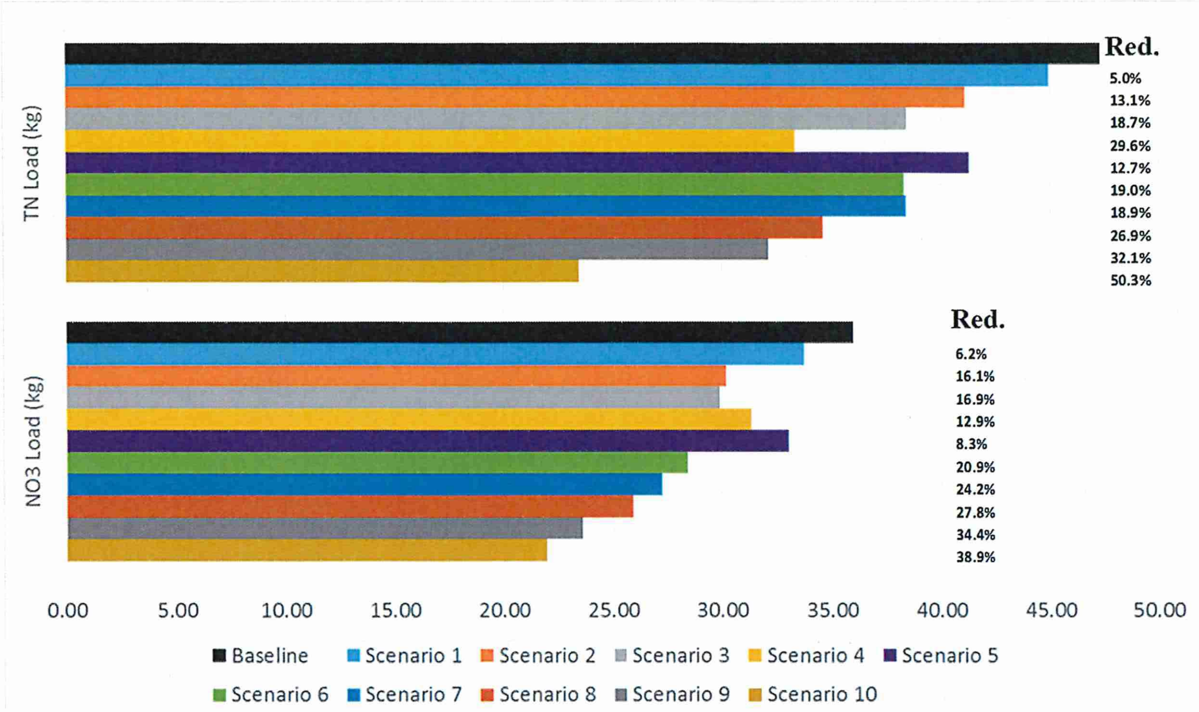


Fig. 11: SWAT simulated impacts of alternative BMPs (from Table 3) on nitrate-N losses to the mouth of the Headwaters watershed relative to existing baseline conditions in the watershed.

The largest nitrate and total nitrogen load reductions in the Headwaters watershed come from Scenario 10, as expected (Fig. 11). It is interesting to note how much impact simply reducing the nitrogen application rates can impact the total load seen at the watershed outlet. Scenarios 6 and 7 reduce the nitrogen loads by almost 20% and nitrate loads by 21-24%. Also, filter strips placed on landscapes that are more susceptible to runoff account for around half of the reduction seen from applying filter strips across the entire watershed. Only 15% of the entire watershed contains areas of slopes greater than 2%, a great portion of filter strip load reduction could be achieved in small areas of the watershed. Cover crops also provide good load reductions. However, it is important to understand that cover crops are not always feasible throughout the watershed. According to Kevin Kuehner, cover crops are not an optimal strategy for the Headwaters watershed, so the results for cover crop scenarios are not feasible for most producers. The most cost effective alternative practice for nitrate-N reductions is scenario 6 (120 lb N/ac in spring), which gave a 21% reduction in nitrate-N losses relative to baseline. In comparison, cover crops plus a spring N application of 170 lb N ac^{-1} (scenario 3) gave a 17% reduction relative to baseline.

Crystal and Bridge Creek Model Calibration

The Crystal Creek watershed is a 15 square kilometer (3,700 acres) watershed with an outlet located near Juniper road north of 150th street and 5 miles northeast of Harmony. The Crystal Creek SWAT watershed model is performing well during calibration. This watershed contains some karst features in its underlying geology. One third of the watershed area is in hay and rangeland, while the rest is in row crop agriculture. Crystal Creek is steeper than the Headwaters watershed, with slopes up to 6%. Currently, the daily Nash-Sutcliffe Efficiency (NSE) value is up to 0.63 and the Percent Bias (PBIAS) is at 10.09. This has been achieved by decreasing the amount of evapotranspiration (ET) in the watershed and attempting to increase the amount of groundwater flow. However, these attempts have increased lateral flow. Groundwater flow is still a small portion of the output, while lateral flow comprises 15% of the outlet streamflow. Based on the water balance, some of the ET and lateral flow still needs to be converted to groundwater flow before evaluating alternative BMPs. Further calibration and validation of the SWAT model in this portion of the Root River watershed is needed before evaluating alternative BMPs.

Located south of Rushford and southwest of Houston, the Bridge Creek watershed is a 19 square-kilometer (4,700 acres) watershed. The outlet is located in the southeast corner the Root River watershed. Over half of the watershed has slopes of over six percent and the entire watershed is underlain by karst features. Row-crop agriculture makes up a large portion of the land use in the uppermost portion of the watershed. Agriculture, hayfields, and forests each make up roughly one-third of the watershed, with some interspersed rangelands and minor developments.

The SWAT Bridge Creek simulation has an NSE value of 0.16 and a PBIAS of -47. The inaccuracy of the model is due in part to the inability to synchronize the low flow values of 2012. The water balance for Bridge Creek shows that too much ET is occurring in this simulation. ET should be slightly less than it is in Crystal Creek; however, the Bridge Creek output gives an ET value of 650 mm. While seasonal variability and regional differences are possible, it seems likely that this value is too large. Reduction of ET in the model will improve the correlation with measured stream discharge. Further calibration and validation of the SWAT model in this portion of the Root River watershed is needed before evaluating alternative BMPs.

SWAT modeling efforts in the Root River are continuing, with a focus on simulating BMPs in the Crystal and Bridge Creek watersheds. Once this effort is completed, the SWAT model will be used to evaluate agricultural BMP impacts on groundwater across the entire Root River watershed.

Task 4: Education and Outreach

The Project Team completed the following outreach and extension activities:

Southeastern Karst Region

Regular communication with Kevin Kuehner at MDA and the rest of the Project Review Team regarding effectiveness of SWAT modeled agricultural BMPs – provides guidance for additional BMP testing and implementation on farmer fields. The project review team met regularly to provide input to the project. Staff from the MDA participated in all project review team meetings. Staff from MGS, MPCA, DNR and MDH participated in some of the project meetings and discussions.

Central Sands

Twenty one extension and outreach talks to over 976 producers, industry reps and technical service providers. Three research publications developed

Details for these education and outreach efforts are itemized below:

Fernández, F.G. 2015. Nitrogen management with in-season applications. 2015 Summer Field Day at the University of Minnesota West Central Research and Outreach Center. July 10, 2015. Morris, MN.

Carl Rosen held a field day at Sand Plain Research Farm at Becker on July 14 for the Area II potato growers. There were about 50 growers and industry personnel that attended. He highlighted research on nitrogen management and talked about how the MDA modeling study will help develop tools for better scheduling of nitrogen applications.

Fernández, F.G. 2015. Lessons from the Rosholt Farm on nitrogen management for irrigated corn. Rosholt Farm Agronomy Day. July 16, 2015. Westport, MN.

Fernández, F.G. 2015. Local research on nitrogen management for irrigated corn. 2015 Becker Irrigated Research Field Tour at the University of Minnesota Sand Plain Research Farm. July 28, 2015. Becker, MN.

Fernández, F.G. 2015. Nitrogen management for irrigated and non-irrigated corn. Central Lakes College Ag and Energy Center Field Day. August 21, 2015. Staples, MN.

Fernández, F.G. 2015. Effect of nitrogen management on nitrate leaching and maize on highly productive irrigated sandy soils. Minnesota Department of Agriculture Fertilizer Management Section Meeting. St. Paul, MN. 14 December 2015.

Fernández, F.G. 2015. Improved nitrogen management with new guidelines for irrigated corn. Irrigator's Clinic, Glenwood, MN. 16 December 2015. (60 attendees).

Carl Rosen talked about our nitrogen management research with the RDO agronomists on December 22, 2015. They are interested in ways of improving N use efficiency.

Fernández, F.G. 2016. Are single pre-plant nitrogen applications better than split applications? Minnesota Ag EXPO, Mankato, MN. 27-28 January 2016. (53 attendees).

Fernández, F.G. 2016. Overview of University of MN nitrogen management education and promotion programs and activities. Minnesota Department of Agriculture Nitrogen Fertilizer Education and Promotion Team, St Paul, MN. 16 February 2016. (25 attendees).

Fernández, F.G. 2016. Nitrogen losses on drained and undrained soils. Minnesota Independent Consultant Winter Education Meeting, Hutchinson, MN. 19 February 2016. (75 attendees).

Fernández, F.G. 2016. Mechanisms of nutrient uptake: Is fertilization enough? 8th annual Minnesota Crop Nutrient Management Conference, Morton, MN. 9 February 2016. (113 attendees).

Struffert, A.M., Rubin, J.C., Fernández, F.G. and Lamb, J.A. 2016. Nitrogen Management for Corn and Groundwater Quality in Upper Midwest Irrigated Sands. Journal of Environmental Quality 45(5): 1557-1564.

Fernández, F.G., Rubin, J.C., Struffert, A.M. and Lamb, J.A. 2016. Maize yield and nitrogen use efficiency in Upper Midwest irrigated sandy soils. Agronomy Journal 108(4:1681-1691.

Carl Rosen gave a summary of on-farm potato N trials in Park Rapids to about 60 RDO agronomists on March 31 in Fargo. The title of the talk was: Summary of On-farm Nitrogen Trials 2012-2015.

Fernández, F.G. 2017. Can soil nitrogen testing and canopy sensing improve yield and nitrogen deficiency predictions? Minnesota Ag EXPO, Mankato, MN. 25 January 2017. (75 attendees).

Fernández, F.G. 2017. Improved nitrogen management with new guidelines for irrigated corn. 48th Annual Central Minnesota Irrigator's Clinic and Annual Meeting, Parkers Prairie, MN. 26 January 2017. (81 attendees).

Fernández, F.G. 2017. Improved productivity with in-season nitrogen management. 9th Annual Minnesota Crop Nutrient Management Conference, St Cloud, MN. 7 February 2017. (75 attendees).

Fernández, F.G. 2017. In-season split nitrogen management and the role of soil testing. 3rd Annual Nitrogen: Minnesota's Grand Challenge & Compelling Opportunity Conference, Mankato, MN. 16 February 2017. (101 attendees).

Fernández, F.G. 2017. Splitting nitrogen applications: when are they worth your time?. 11th Annual Crops Day, Farmington, MN. 15 March 2017. (90 attendees).

Fernández, F.G., J.D. Clark, and J.A. Spackman 2017. How to manage urea and other forms of nitrogen effectively in south central Minnesota. 2017 Agronomy Field Tour at the Univ. of Minnesota Southern Research and Outreach Center, Waseca, MN. 20 June 2017. (59 attendees).

59 people attended the Waseca Field day on June 20th to hear a presentation by Fabian Fernández on research findings on N leaching from Becker in contrast with N management on irrigated fine textured-soils.

Carl Rosen talked to potato growers on March 1, 2017 in Duelm, MN. The title of the presentation was: Nitrogen and Irrigation Management Strategies for Potato Production to Reduce Nitrate Leaching.

Bohman, Brian, Carl Rosen, David Mulla, and Matt McNearney. 2017. Nitrogen and irrigation management strategies for potato production to reduce nitrate leaching. Proceedings of the Northern Plains Potato Growers Association Research Conference Reports.

Task 5. Delivery of model outputs for BMP impacts on N loss to groundwater in different formats, including tables, graphs, and empirical relationships. The project team will also offer MDA staff and other stakeholders training on use of models and their outputs.

Model outputs were continuously delivered to MDA and other stakeholders in different formats. Figures, tables, relationships, trends and interpretations were provided through presentations to the project advisory team, through the quarterly progress updates, and presentations at outreach events and professional conferences.

In consultation with the MDA the model training was postponed until the model calibration/validation was completed and results were available.