Pay-For-Performance Conservation Using SWAT Highlights Need for Field-Level Agricultural Conservation

Supplemental Information

R.L. Muenich, M.M. Kalcic, J. Winsten, K. Fisher, M. Day, G. O'Neil, Y.-C. Wang, D. Scavia

---

Supplemental Information **Pg. #**

Farmer number:___________________________________ **Technician name:______________________________________**

The comments in italics are notes for the interviewer.

Please start off the interview by asking the following general farm operation questions:

1. **If you have any of the following documents handy, they will be helpful for the interview**:
    a. Soil test results for your fields
    b. Maps of the locations of your farm fields
    c. Whole-farm or Michigan Farm Nutrient Balance
    d. Other Nutrient Management Plan documents

    Encourage the farmer to assemble documents ahead of time, so that field-level information on soil tests and fertilization are readily accessible.

2. **Please provide the spatial location of each of your farm fields by <u>one or more</u> of the following methods**: (a) digitizing polygons in the River Raisin PFP Tool, (b) marking on a plat map, and/or (c) drawing a picture with sufficient landmarks that we can identify the location.

    Alternatively, if you already have maps of this farmer's fields and brought them with you then you may mark up those for the interview.

3. **Please fill out the field-level survey for each farm field.**

    Go through the Farm-level survey in detail, and feel free to add any additional comments you think could be helpful in the margins.

Farmer number:___________________________________ **Technician name:**______________________________________

4. **Do you have any livestock on your farm?** *If not, skip question 5.*

5. **What livestock do you have, and how many head?**

	Dairy Cows				**Beef Cattle**				**Swine**			
	Mature Cows	Yearlings	Calves	Bulls	Mature Cows	Yearlings	Calves	Bulls	Sows	Market Hogs	Feeder Pigs/Gilts	Others
Avg. # Head through Year												

Other Livestock (List type and average # head through year)

We are asking about livestock to better understand the nutrient balance on their farm, and to open up the conversation to potential farm-level actions related to manure use.

6. **Are there additional whole-farm actions you would like us to look into and you would consider doing to reduce farm phosphorus runoff?**

- ☐ Example: Changing livestock feed to reduce phosphorus application rates
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:
- ☐ Other:

This space is for the farmer to be innovative about farm-level changes they'd be interested in making. Take note of everything they mention, and if possible we will model these changes.

Farmer number: _______________ Rotation: _____________ Field name: ____________________

A. For each crop in the rotation please select the management that best represents your operation.

CROP:________________

Planted acres:_________

Yield:_________(☐ Tons or ☐ Bushels)

Planting date:________

Harvest date:________

COVER CROPs: ☐ None used

Species: _________

Planting date:________

Harvest date:_________

TILLAGE OPERATIONS

Fall tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐ Other

Spring tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐Other

NUTRIENT MANAGEMENT

Fall/winter phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Spring/summer phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Fall/winter manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Spring/summer manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Fall/winter nitrogen application

Total rate: ________ lbs/acre

CROP:________________

Planted acres:_________

Yield:_________(☐ Tons or ☐ Bushels)

Planting date:________

Harvest date:________

COVER CROPs: ☐ None used

Species: _________

Planting date:________

Harvest date:_________

TILLAGE OPERATIONS

Fall tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐ Other

Spring tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐Other

NUTRIENT MANAGEMENT

Fall/winter phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Spring/summer phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Fall/winter manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Spring/summer manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Fall/winter nitrogen application

Total rate: ________ lbs/acre

CROP:________________

Planted acres:_________

Yield:_________(☐ Tons or ☐ Bushels)

Planting date:________

Harvest date:________

COVER CROPs: ☐ None used

Species: _________

Planting date:________

Harvest date:_________

TILLAGE OPERATIONS

Fall tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐ Other

Spring tillage: ☐ None ☐ Disk ☐ Chisel

☐ Strip ☐ Deep ☐ Vertical ☐Other

NUTRIENT MANAGEMENT

Fall/winter phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Spring/summer phosphorus application

Total rate: ________ lbs/acre

☐ Broadcast ☐ Incorporated ☐ Subsurface

Fall/winter manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Spring/summer manure/compost application

Solid_____ tons/acre Liquid_____ gal/acre

☐ Broadcast ☐ Incorporated ☐ Injected

Fall/winter nitrogen application

Total rate: ________ lbs/acre

Farmer number: _______________ Rotation: _____________ Field name: ___________________

B. Please tell us a little more about this farm field.

TILE DRAINAGE

☐ No drainage ☐ Unknown ☐ Random ☐ Systematic ☐ Controlled

Drain depth: _______ inches Drain spacing: ______ feet

STRUCTURAL PRACTICES → ***Please note locations and names on map.***

☐ Two-stage ditch (name on map: _______)

☐ Wildlife habitat (name on map: _______)

☐ Buffer strip (name on map: _______; ☐ good or ☐ poor condition; width: ___ feet; length: ____ feet)

☐ Grassed waterway (name on map: _______; ☐ good or ☐ poor condition; width: ___ feet; length: ____ feet)

SOIL TEST PHOSPHORUS VALUES → ***taken in the last 4 years***

All results for this field, or an average value	Grid size	Method	Year	Lab that processed samples
	________ acres, or_____samples	☐ Bray ☐ Mehlich ☐ Other: _______		

Please make note of the location of all structural practices on the map.

C. Please select new options you would like us to look at for this field.

☐ Reducing phosphorus application rates on this field by:__________

☐ Contour plowing and planting

☐ Incorporating phosphorus fertilizers and manure with tillage

☐ Subsurface-application of phosphorus fertilizers and manures

☐ Growing winter cover crops. Species: ______________________

☐ Installing filter strips on this field. Location:__________________

☐ Installing grassed waterways on this field. Location:____________

☐ Adding periodic conservation tillage: ☐ No-till ☐ Mulch till

☐ Using continuous conservation tillage: ☐ No-till ☐ Mulch till

☐ Others: ____

This space is for the farmer to be innovative about field-level changes they'd be interested in making. Take note of everything they mention, and if possible we will model these changes.

SWAT Set-Up Details

Table S1. Data sources used to develop the SWAT model

Management assumptions	Data source	Details
Crop rotations	NASS Cropland Data Layer (CDL) (http://www.nass.usda.gov/research/Cropland/SARS1a.htm)	We studied 6 years of pixel-level rotations developed in ArcGIS as a combination of 6 CDL layers. We used the frequency of corn (C), soybean (S), and wheat (W), along with the most common order they appear in rotation, to design 2 realistic rotations of CS and CSW.
Fertilization rates – state-level trends	Fertilizer use dataset (http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx)	We looked at the trends in fertilization of corn, soybeans, and wheat to determine if there were any trends to apply in the study period (1981-2010).
Fertilization rates – county-level nutrient balance	County-Level Estimates of Nutrient Inputs to the Land Surface of the Conterminous United States, 1982–2001 (http://pubs.usgs.gov/sir/2006/5012/)	County level estimates of on-farm fertilizer applications were used and area-weighted to watershed area.
Manure application rates and types	NASS Ag. Census data (http://www.nass.usda.gov/Quick_Stats/) and manure nutrient content calculations (http://pubs.usgs.gov/sir/2006/5012/pdf/sir2006_5012.pdf)	USDA NASS animal counts were used along with methods form Ruddy et al. (2006) to determine the total amount of manure generated per county. This was area-weighted to the RRW area and then CAFO locations were used to determine distribution of manure.
Tillage by crop type	Conservation Technology Innovation Center (CTIC) database (http://www.ctic.purdue.edu/)	We used the previously-purchased CTIC data for most Maumee counties for the period around 2005 to estimate the percent of corn, soybeans, and wheat managed with conventional tillage and no-tillage. Then we applied these portions of crop tillage to the management files for each crop rotation so that, across the watershed and across rotations, tillage would be similar to what farmers are really doing in their fields. We also chose to incorporate phosphorus applications soon after tillage in each rotation to assume farmers are doing fairly 'good' practices whenever possible. We also randomly simulated subsurface application of some P across HRUs.
Tile Drains	Estimated based on SSURGO drainage class definitions.	Tile drains were simulated using the new tile drainage routines based on DRAINMOD equations on all cropland acres with very poorly, poorly, and somewhat poorly drained soils.
Existing BMPs		Conservation tillage was estimated from the CTIC (see above) and it was assumed that (%) of P fertilizer applications were incorporated. Other BMPs including

		filter/buffer strips and cover crops were not included in the baseline model due to lack of access to data. Recent surveys in the Western Basin of Lake Erie suggest that 6% of acres have cover crops and 12% of fields have a filter/buffer strip (USDA 2016).
Impoundments & Reservoirs	NHD dataset	Waterbodies intersecting streamlines were designated as reservoirs, and others were simulated as ponds. Only impoundments greater than 50ha were included in final model.

<u>Distribution of subsurface drainage (from Kalcic et al. 2016 supplemental information)</u>

All cropland that was characterized by poor soil drainage by the U.S. SSURGO soils data was assumed to have subsurface drainage. Figure S1 shows the distribution of this estimate across the Maumee watershed and several nearby tributaries to Lake Erie.

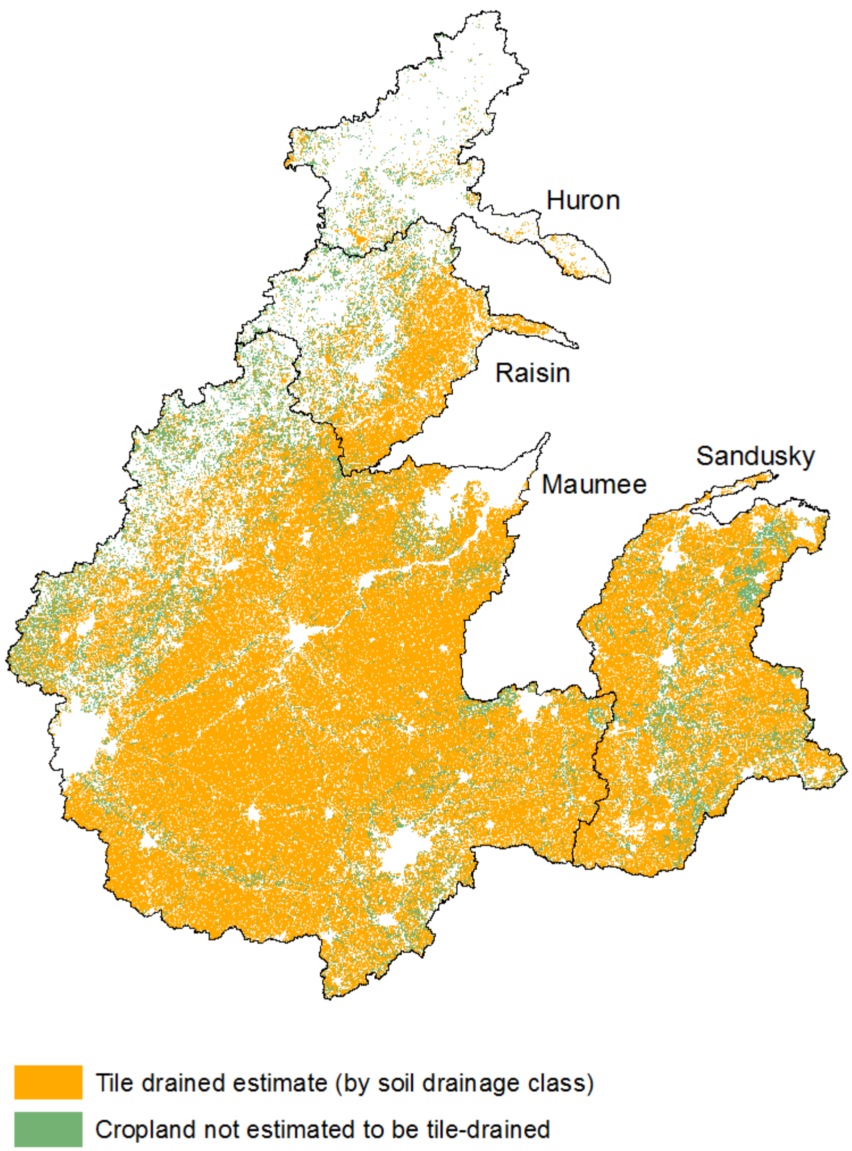


Figure S1. Result of the estimate of tile drained land for several watersheds draining to Lake Erie. Cropland with predominantly poorly, very poorly, or somewhat poorly drained soils was estimated to be drained with subsurface drains.

Distribution of impoundments (reservoirs and ponds) in the final RRW model

Impoundments configuration added based on NHD dataset - waterbody, those intersecting streamline designated as reservoirs, others simulated as ponds.

- Calculated volume of reservoir and ponds as (where V=volume and SA=surface area):
    - Reservoir: $V = 10^{-2.9244} SA^{0.9035}$
    - Pond: $V = 10^{-4.1334} SA^{1.2732}$
- This initial method resulted in 16 impoundments in the RRW model. However, only reservoirs greater than 50 ha (n=5) were included in the final model.

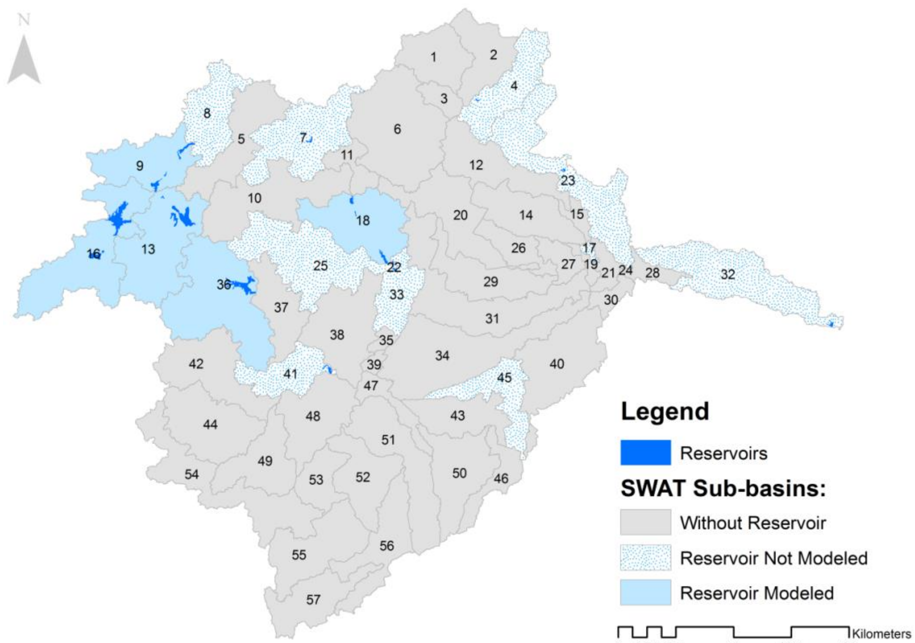


Figure S2. Location of reservoirs in RRW, highlighting which reservoirs were included in the final SWAT model.

Distribution of crop rotations

Recent estimates of crop rotations were derived from overlaying datasets for the available years (2007-2012) of the National Agricultural Statistics Service Cropland Data Layer (CDL). First the rasters were reclassified so that corn, soybean, and wheat were given the values 1, 2, and 3, respectively. Then the rasters were added so that the digit for year 2007 was in the front, followed by the digits for 2008, 2009, etc.:

CDL_summed = 100000*CDL2007 + 10000*CDL2008 + 1000*CDL2009 + 100*CDL2010 + 10*CDL2011 + 1*CDL2012

All rotations that covered at least 0.1% of all the watershed area were labeled with their crop rotation names 'C' for corn, 'S' for soybean, and 'W' for winter wheat. Next, crop rotations that were the same were combined into one category (i.e., CSCSCS and SCSCSC were combined into a "Corn-Soybean" rotation category). Finally, for each we determined the number of years in corn, soybean, and wheat, and calculated a percentage of the time a given ratio each crop is in all rotations.

The most common rotations in the watershed were simple corn-soybean rotations, followed by combinations of soybean, corn, and wheat. The top three rotations were used in subsequent calculations, however the constraints (e.g., maintaining % wheat in watershed, % rotations wheat) were met easily using only the top two most common rotations. Therefore, only the top two rotations were utilized for characterizing the management in the RRW. Using those two rotations, and two constraints, we calculated the extent of each of the rotations (Table S2).

Table S2. Calculations of the extent of each crop rotations, along with constraints by observed data we were trying to match. The numbers highlighted in the same colors were values we were trying to match.

	From previous calculation of percentage of each crop in the CDL in the watershed:	Checking calculation by crop fractions:		
Common rotations:	Coverage of cropland in the watershed:	Corn	Soy	Wheat
CORN-3, SOYB-3	*55 %*	*28%*	*28%*	*0%*
WHT-2,SOYB-2,C-2	*45%*	*15%*	*15%*	*15%*
	Totals : 1.00	**42.5%**	**42.5%**	**15.0%**
Constraints:				
	1. What we know from NASS CDL:	**41%**	**44%**	**15%**
	2. Total percent of land that should have wheat in rotation:			**45%**

Application of fertilizers and manures

Inorganic fertilizer estimations

We estimated county-level farm fertilizer applications based on Ruddy et al. (2006). Additionally, for comparative purposes we extracted the USDA ERS application rates per crop (Table S3).

Table S3. Fertilizer application rates for the entire state of Michigan from the USDA ERS by crop.

Year	*Corn* Nitrogen (lb/acre)	*Corn* Phosphorus (lb/acre)	*Soybeans* Nitrogen (lb/acre)	*Soybeans* Phosphorus (lb/acre)	*Wheat* Nitrogen (lb/acre)	*Wheat* Phosphorus (lb/acre)
1997	119	21.5	--	23.2	115[b]	25.4[b]
2002	121[a]	21.3[a]	--	19.8	115[b]	25.4[b]
2007	128[c]	19.4[c]	--	15[d]	89[d]	19.8[d]

[a]value derived by averaging year before and year after; [b]value from 2004; [c] value from 2005; [d]value from 2006

Manure estimations

The National Agricultural Statistics Service (NASS) provides estimates of the number and types of animals that exist in a county. This data was retrieved for all counties within the RRW: Hillsdale, Jackson, Lenawee, Monroe, and Washtenaw counties in Michigan, and Fulton county in Ohio (NASS 2002; NASS 2007). The data retrieved included the amount of county acres in farmland, as well as the numbers of livestock and poultry. Next, these data were used along with the methods outlined in Ruddy et al. (2006) to estimate the amount of nitrogen and phosphorus produced from the manure of animals within each county. The values for 1997 were compared with output published from Rudy et al. 2006 for each of the counties to ensure correct calculations. The biggest change seen in these counties is the decline in the number of hogs and pigs between the 1997 and 2007 censuses. Some counties have seen increases in the total number of cattle and some have seen decreases. The number of poultry, sheep and lambs, and horses and ponies has remained relatively consistent between the three censuses.

Determining amounts applied per crop

The total amounts of manure generated and fertilizer sold in each county were apportioned to the total acres of corn, soybeans, and wheat in the watershed to determine rates of application (Table S4).

Table S4. Estimated application rates of nitrogen and phosphorus for corn, soybeans, and wheat assuming they are the only three crops in the RRW based on total amounts of manure and fertilizer nutrients. Numbers in parenthesis are in lb/acre.

Year	**Corn** Nitrogen (kg/ha)	**Soybeans** Nitrogen (kg/ha)	**Wheat** Nitrogen (kg/ha)	**Corn** Phosphorus (kg/ha)	**Soybeans** Phosphorus (kg/ha)	**Wheat** Phosphorus (kg/ha)
1997	197 (176)	0 (0)	92 (82)	22 (20)	16 (14)	18 (16)
2002	224 (200)	0 (0)	105 (95)	21 (19)	15 (13)	18 (16)

Determining which sub-basins receive manure

There are 14 confined animal feeding operations (CAFOs) near the River Raisin Watershed (Figure S3). Because all but one of these CAFOs are swine and dairy which produce liquid manure, it was assumed that manure applications were concentrated around the CAFOS. Hatfield and Stewart (2002) indicate that a majority of manure, especially non-poultry manure, is applied within a few miles of where it is produced, therefore we chose to apply manure only to sub-basins that were within 5 miles of a CAFO. Therefore, in sub-basins within five miles of a CAFO, a portion of the applied N and P came from manure, though the application rates were maintained at the levels in Table S4 in order to conserve the mass balance of N and P in the watershed.

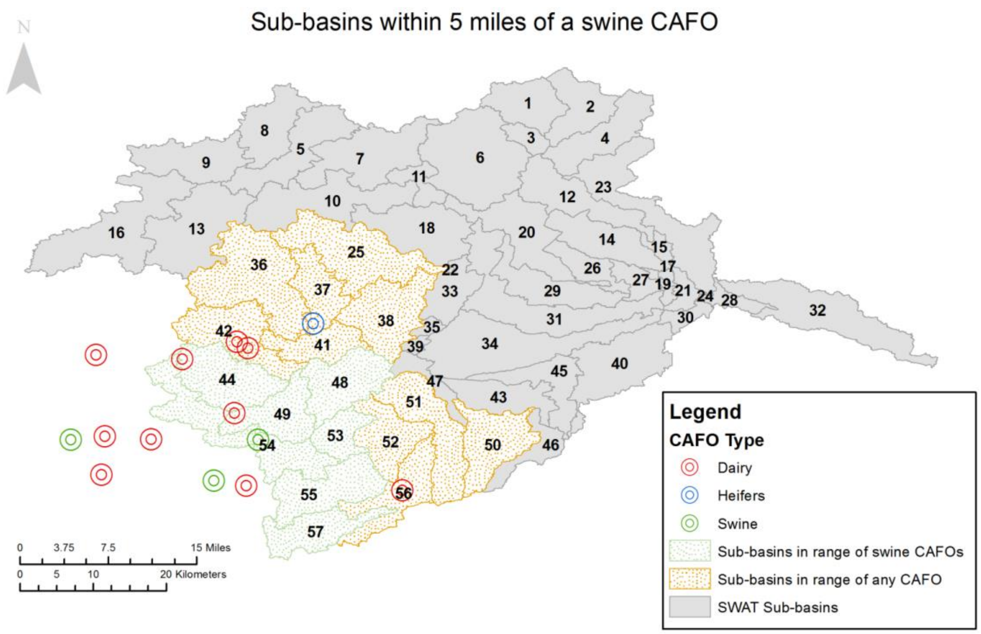


Figure S3. RRW sub-basins that are within a 5-mile radius of any CAFO or swine CAFO. Sub-basins within the distance of swine and dairy/heifer received both kinds of manure and those within range of only dairy CAFOs only received dairy manure.

Comparing nutrient input estimates with published values

In order to check the validity of the application rates, the numbers generated here were compared to Han et al. (2012) reported phosphorus numbers. They estimated that in the 2000s (around the time period of our model setup), between 500-750 kg-P/km^2-yr were applied to the land in RRW as fertilizer, and 100-200 kg-P/km^2-yr were applied to RRW as manure. To see how these numbers compare to estimates derived in this report, we took the average P application rate estimated (18kg/ha) and multiplied that number by the total amount of agricultural lands in RRW. Then, we divided by the total area of RRW to match Han et al. (2012). This calculation gave an estimate of 8.8 kg/ha-yr (880 kg/km^2-yr) of phosphorus added to the RRW from both fertilizer and manure. We used the average percent of phosphorus applied as manure in RRW counties (22.5%) to separate into fertilizer and manure, which gave an estimate of 6.9 kg/ha-yr of P from fertilizer (690 kg/km^2-yr) and 1.9 kg/ha-yr of P from manure (190 kg/km^2-yr). Both of these values are within the range estimated by Han et al. (2012), demonstrating the validity of the phosphorus estimates used in the model.

Summary of Crop Rotation Details

Table S5 shows a summary of the number, area, and percent of agricultural lands that had specific rotations, manure applied, and subsurface P applications. All management was randomly applied to HRUs except the targeted application of manure to areas near CAFOs:

Table S5. Variations of crop rotations across the watershed.

	HRUs (#)	*Area (ha)*	*Ag Area %*
Rotations			
S-C	38	26403.36	19.1926
C-S	42	42278.76	30.73243
S-W-C	42	26011.38	18.90767
C-S-W	38	29503.56	21.44613
W-C-S	18	13373.47	9.721174
Manure Application			
None	103	102314.5	74.37242
Dairy	14	19681.03	14.30614
Dairy+Swine	13	15574.97	11.32144
Subsurface P Applications			
None	92	99605.07	72.40291
Yes	38	37965.46	27.59709

Model Parameterization

Forty model parameters were updated during calibration to improve model performance (Table S6). Rows highlighted in red indicate a sub-model choice, not a calibrated parameter; * indicates that the value was changed only on tile-drained lands; † indicates that the value was changed using a percent change and is therefore not an absolute value.

Table S6. List of parameter values that were changed along with final value.

Parameter	File	Spatial Level	Description	Range	Calibrated Value
ALPHA_BF	.gw	HRU	Baseflow recession constant	0.1-0.99	0.5
ANION_EXCL	.sol	HRU	Fraction of soil pore space from which anions are excluded	0-1	0.01
BC1	.swq	Subbasin	Biological oxidation rate of NH4 to NO2 in the reach at 20° (1/day)	0.1-1	0.3
BC3	.swq	Subbasin	Rate constant for hydrolysis of organic N to NH4 in the reach at 20º C [day-1]	0.02-0.4	0.02
BC4	.swq	Subbasin	Mineralization rate of organic P to DRP in the reach at 20° (1/day)	0.01-0.7	0.01
BIOMIX	.mgt	HRU	Biological mixing efficiency; similar to a tillage operation on December 31	NA	0.5
CH_COV1	.rte	Subbasin	Channel cover factor 1; value means a fairly erodible channel	0-1	0.5
CH_COV2	.rte	Subbasin	Channel cover factor 2; value means a fairly erodible channel	0-1	0.3
CH_N1	.sub	Subbasin	Manning's roughness for tributary channels	0-0.15	0.025
CH_N2	.rte	Subbasin	Manning's roughness for the main channel	0-0.15	0.1
CMN	.bsn	Watershed	Rate coefficient for mineralization of the humus active organic nutrients	0.0001-0.003	0.0001
CN2	.mgt	HRU	Initial SCS moisture condition II curve number	0.75-1.25	-0.04
DEP_IMP	.hru	HRU	Depth to the impervious layer in the soil (mm)	0-6000	3500*
DRAIN_CO	.sdr	HRU	Daily drainage coefficient (mm/day); tile drainage is set to drain a maximum of 1 inch per day	10-51	10
EPCO	.bsn	Watershed	Plant uptake compensation factor.	0.01-1.0	0.2†
ESCO	.bsn	Watershed	Soil evaporation compensation factor; value limits evaporation in lower soil layers	0.01-1	0.89
ITDRN	.bsn	Watershed	Tile drainage equations flag	0/1	1
IWQ	.bsn	Watershed	In-stream water quality model: 0-do not simulate nutrient transformations in stream; 1-activate simulation fo in-stream nutrient transformations	0/1	1
IWTDN	.bsn	Watershed	Water table depth algorithms flag	0/1	1
LATKSATF	.sdr	HRU	Lateral soil hydraulic conductivity in tile-drained fields as multiple of original soil conductivity value	0.01-4	2

N_UPDIS	.bsn	Watershed	Nitrogen uptake distribution parameter	1-20	20
NPERCO	.bsn	Watershed	Nitrate percolation coefficient; higher value permits greater nitrate loading in surface runoff.	0.01-1	0.9
PHOSKD	.bsn	Watershed	Phosphorus soil partitioning coefficient (m^3/Mg)	80-350	165
PPERCO	.bsn	Watershed	Phosphorus soil partitioning coefficient (m^3/Mg)	NA	10
PPERCO_S	.chm	HRU	Phosphorus percolation coefficient (m3/Mg)	10-17.5	10
RCHRG_DP	.gw	HRU	Deep aquifer percolation fraction	0-1	0.7
R2ADJ	.hru	HRU	Curve number adjustment for increasing infiltration in non-draining soils	NA	10*
RS3	.swq	Subbasin	Benthic source rate for ammonium in the reach at 20° (mgNH4-N/m2/d)	0.3-1	0.3
RS4	.swq	Subbasin	Organic N settling rate in the reach at 20° (1/day)	0.001-0.1	0.001
RS5	.swq	Subbasin	Local settling rate for organic phosphorus mineralization at 20° (day^{-1})	0.001-0.1	0.1
SFTMP	.bsn	Watershed	Mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain (°C)	-5-5	-2
SMFMN	.bsn	Watershed	Minimum snow melt factor (mm H_2O/day-°C)	1.4-6.9	2.5
SMFMX	.bsn	Watershed	Maximum snow melt factor (mm H_2O/day-°C)	1.4-6.9	2.2
SMTMP	.bsn	Watershed	Threshold temperature for snowmelt (°C)	-5-5	-2.1
SOL_CRK	.sol	HRU	Potential crack volume for soil profile	0-1	0.2
SOL_P_Model	.bsn	Watershed	Soil phosphorus sub-routine: 0=new model; 1=old model	0/1	0
SOL_SOLP	.chm	HRU	Initial labile P in the soil layer (mg labile P/kg soil)	0-100	1
SPCON	.bsn	Watershed	Parameter drives the maximum concentration of sediment the river can route	0.0001-0.01	0.001
SPEXP	.bsn	Watershed	Exponent parameter in Bagnold sediment model	1-2	1
SURLAG	.hru	HRU	Surface runoff lag coefficient	NA	1.25
TIMP	.bsn	Watershed	Snow pack temperature lag	0.01-1	0.05
VCRIT	.bsn	Watershed	Critical velocity at which a river will resuspend sediments	NA	0.15

Calibration Period (2001-2005) Plots

Figure S4. Daily streamflow time series (top), flow-duration curve (middle), and cumulative plot (bottom) for calibration time period (2001-2005).

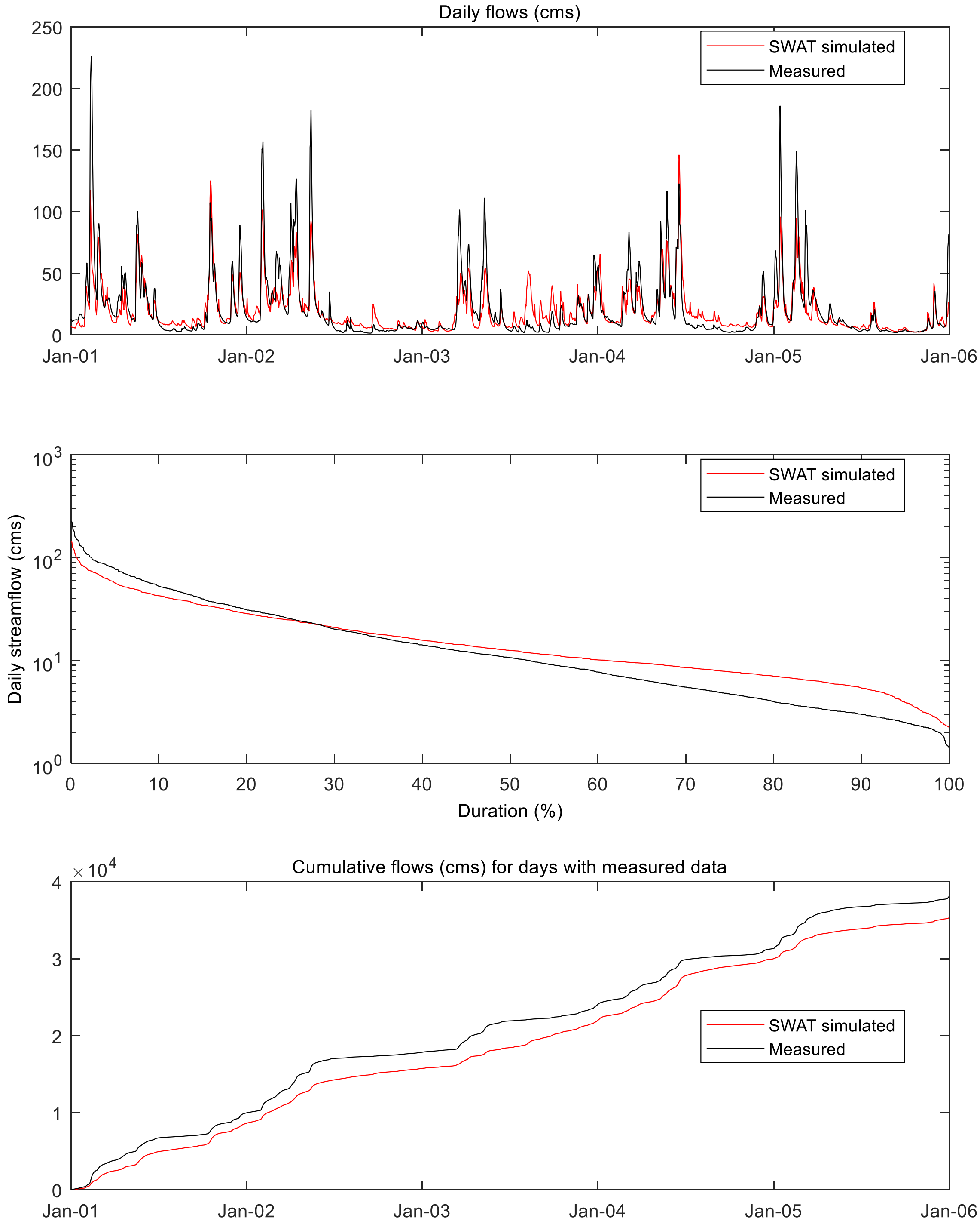


Figure S5. Total phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for calibration period (2001-2005).

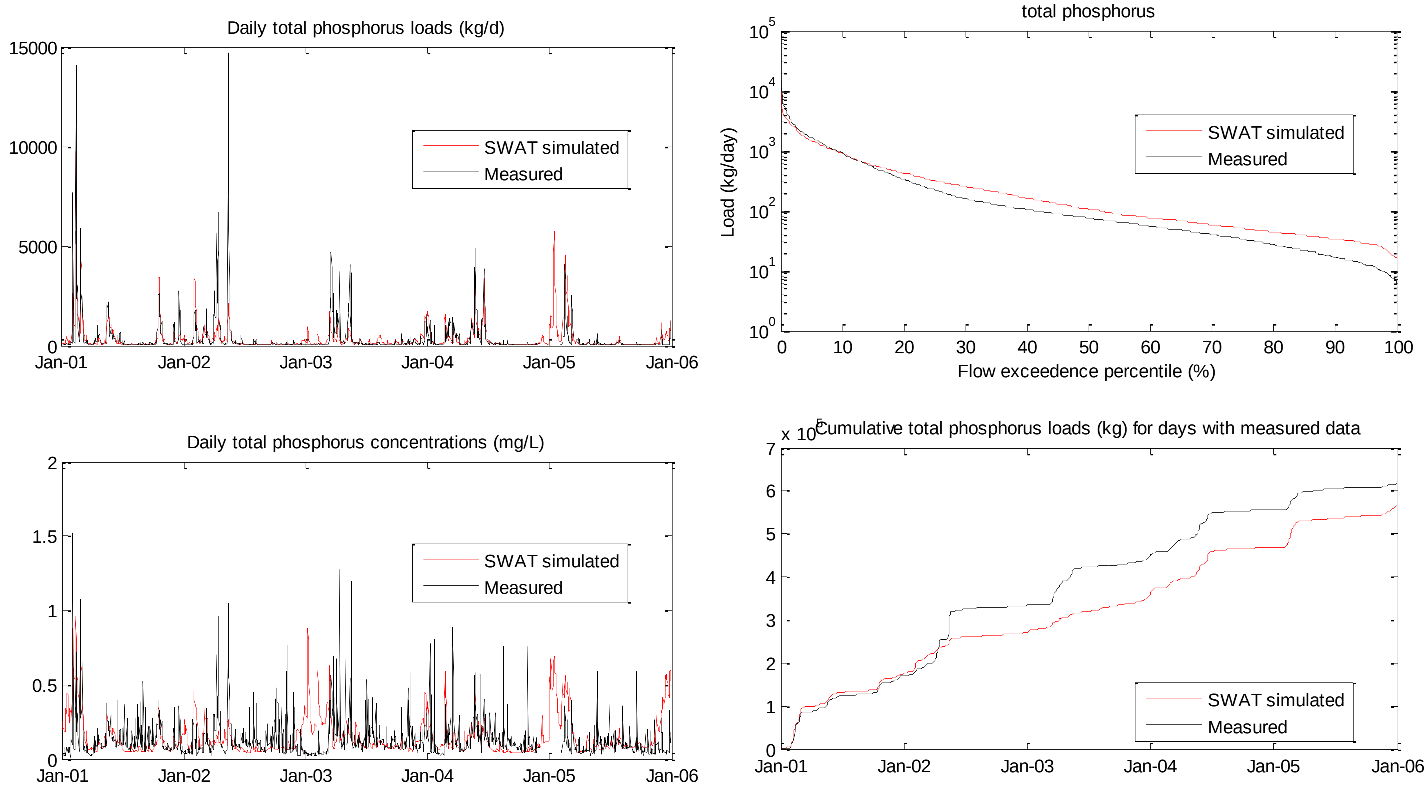


Figure S6. Dissolved reactive phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for calibration period (2001-2005).

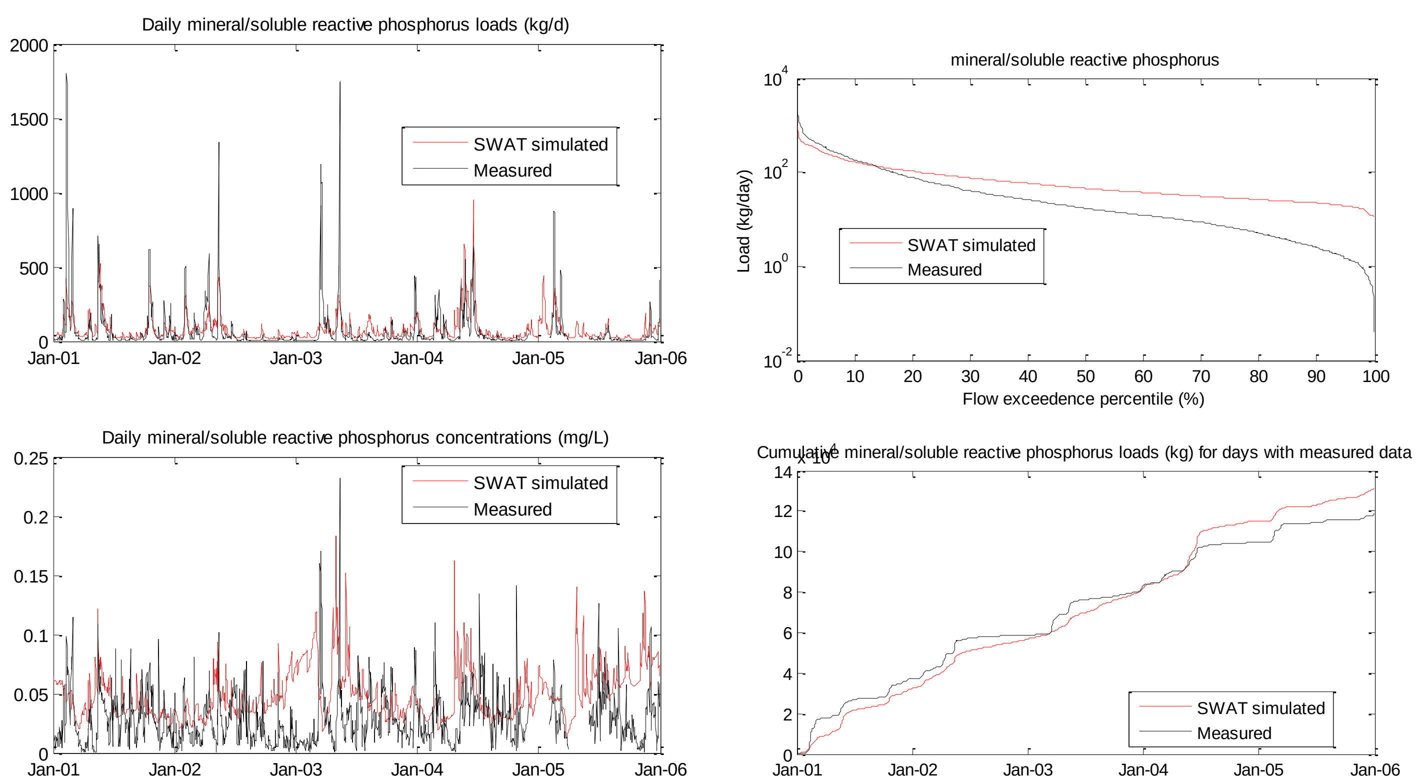


Figure S7. Total nitrogen daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for calibration period (2001-2005).

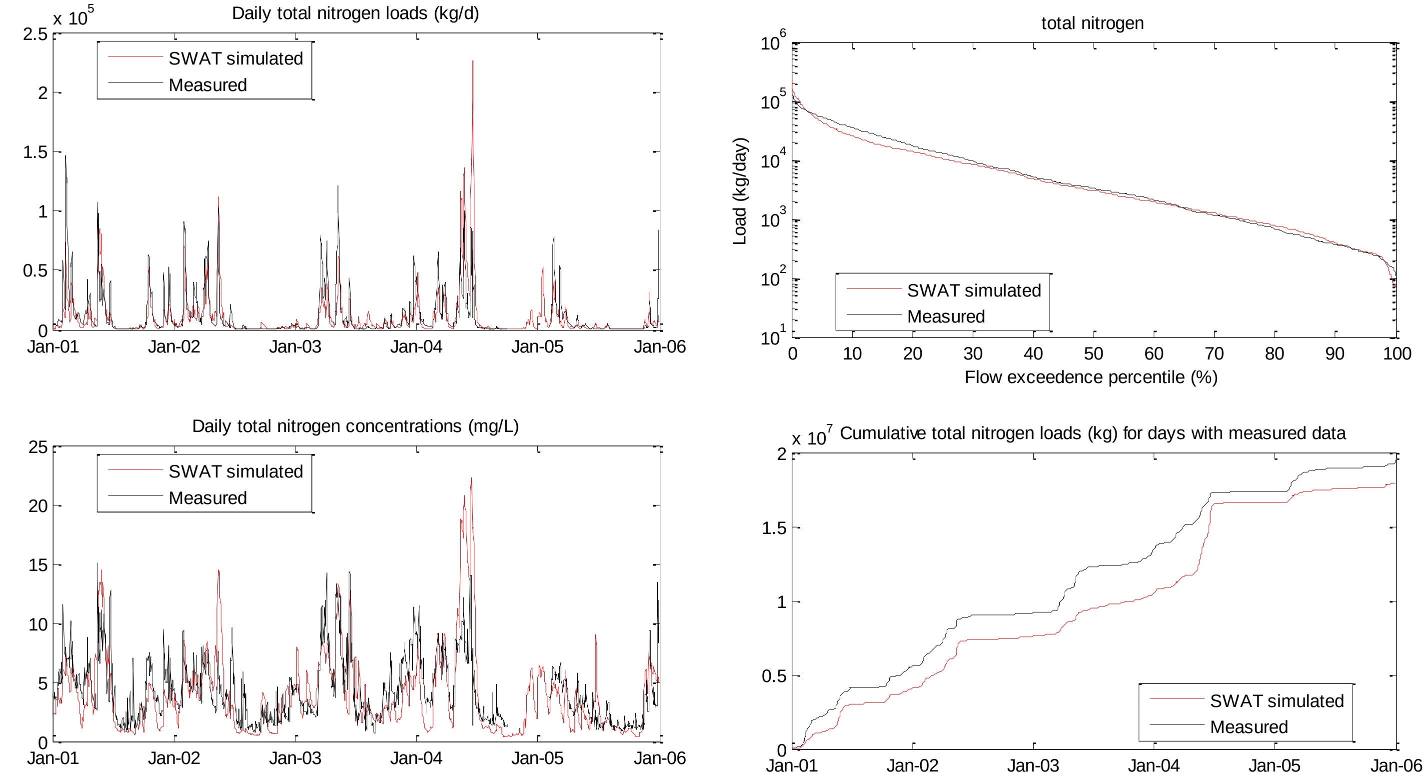
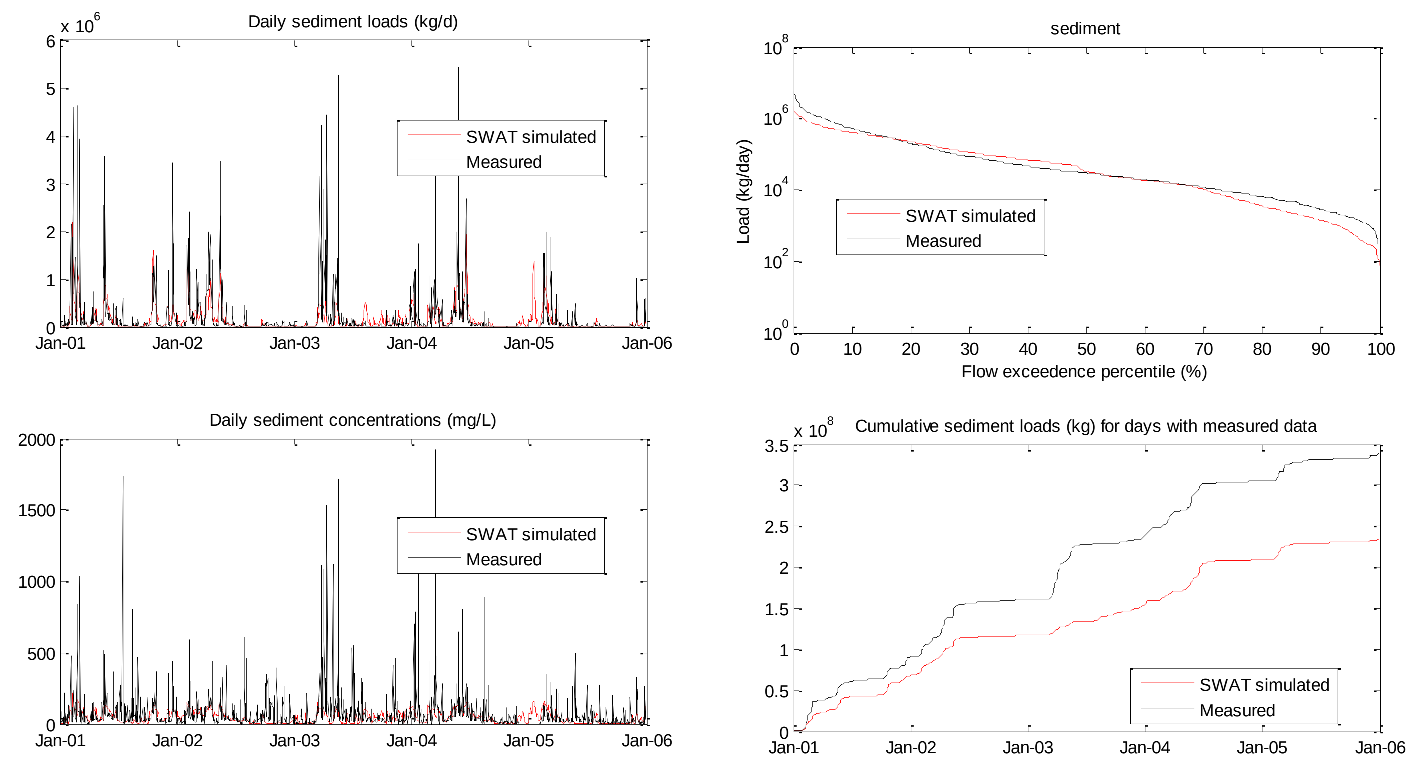


Figure S8. Sediment daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for calibration period (2001-2005).



Validation Period (2006-2010) Plots

Figure S9. Daily streamflow time series (top), flow-duration curve (middle), and cumulative plot (bottom) for validation time period (2006-2010).

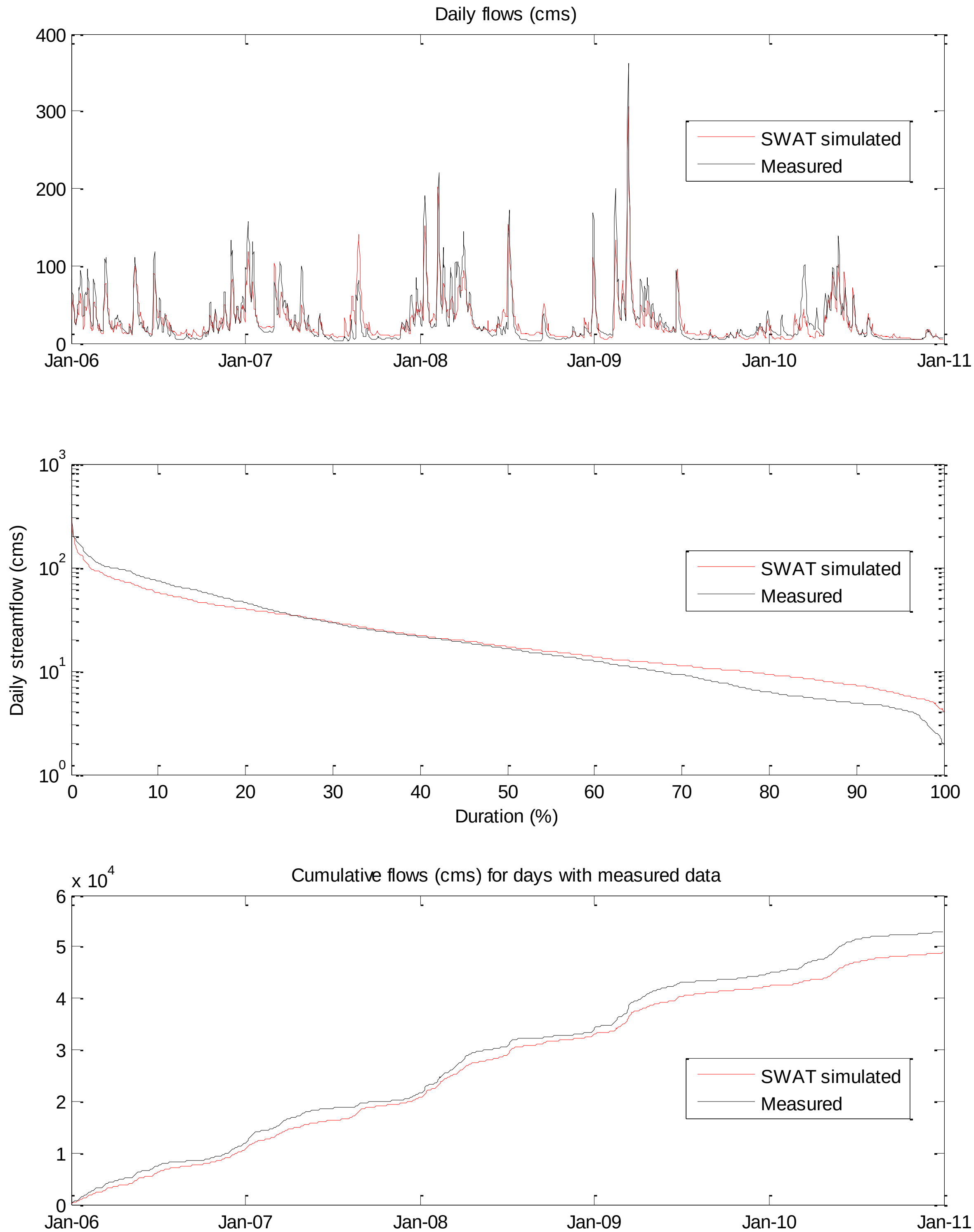


Figure S10. Total phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for validation period (2006-2010).

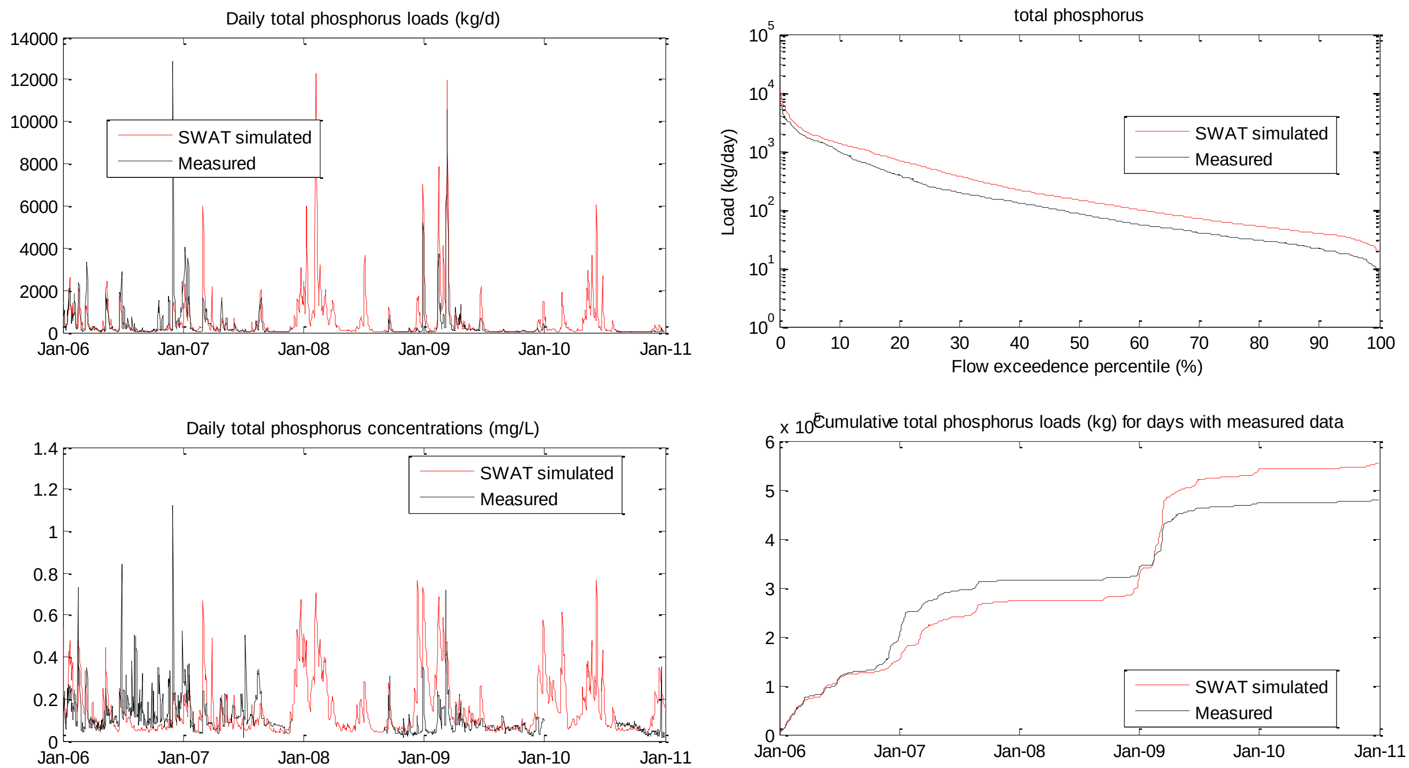


Figure S11. Dissolved reactive phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for validation period (2006-2010).

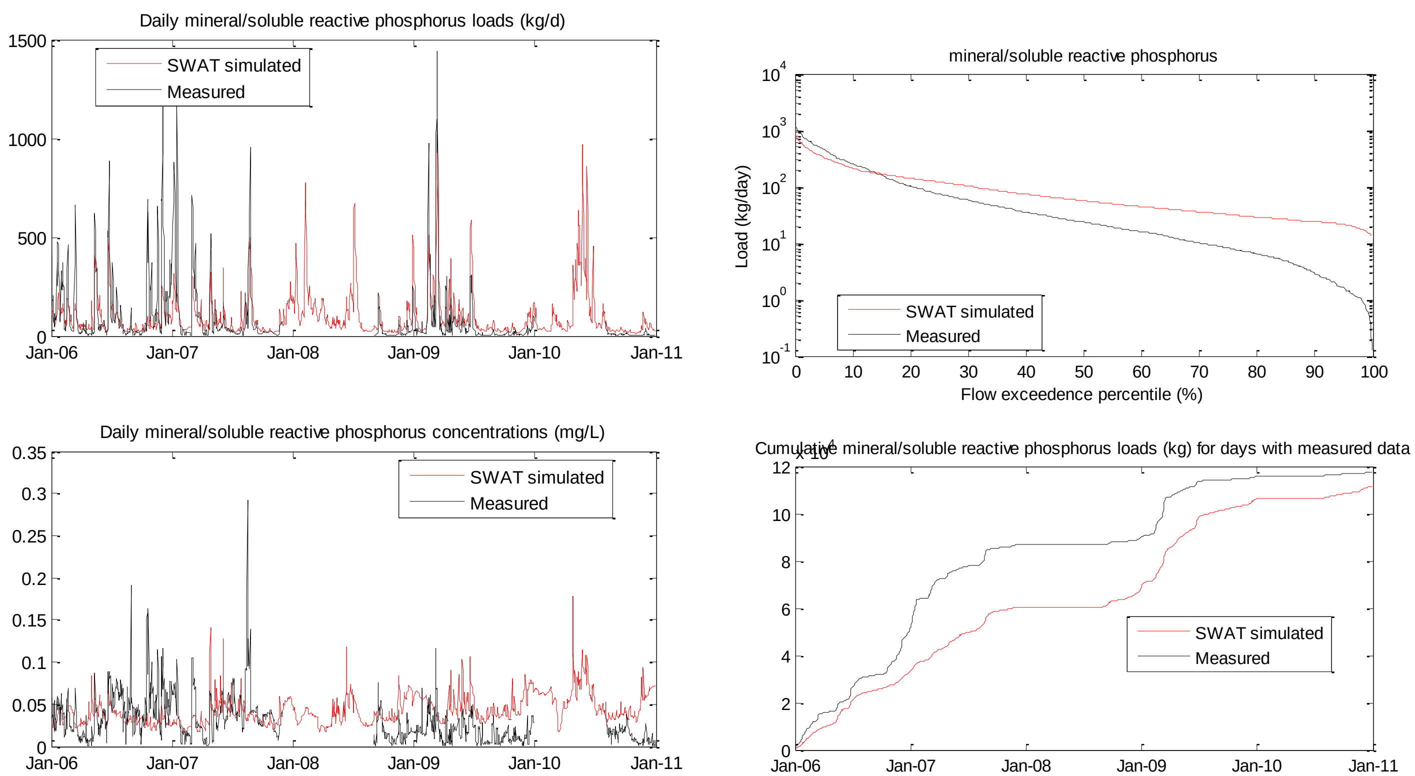


Figure S12. Total nitrogen daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for validation period (2006-2010).

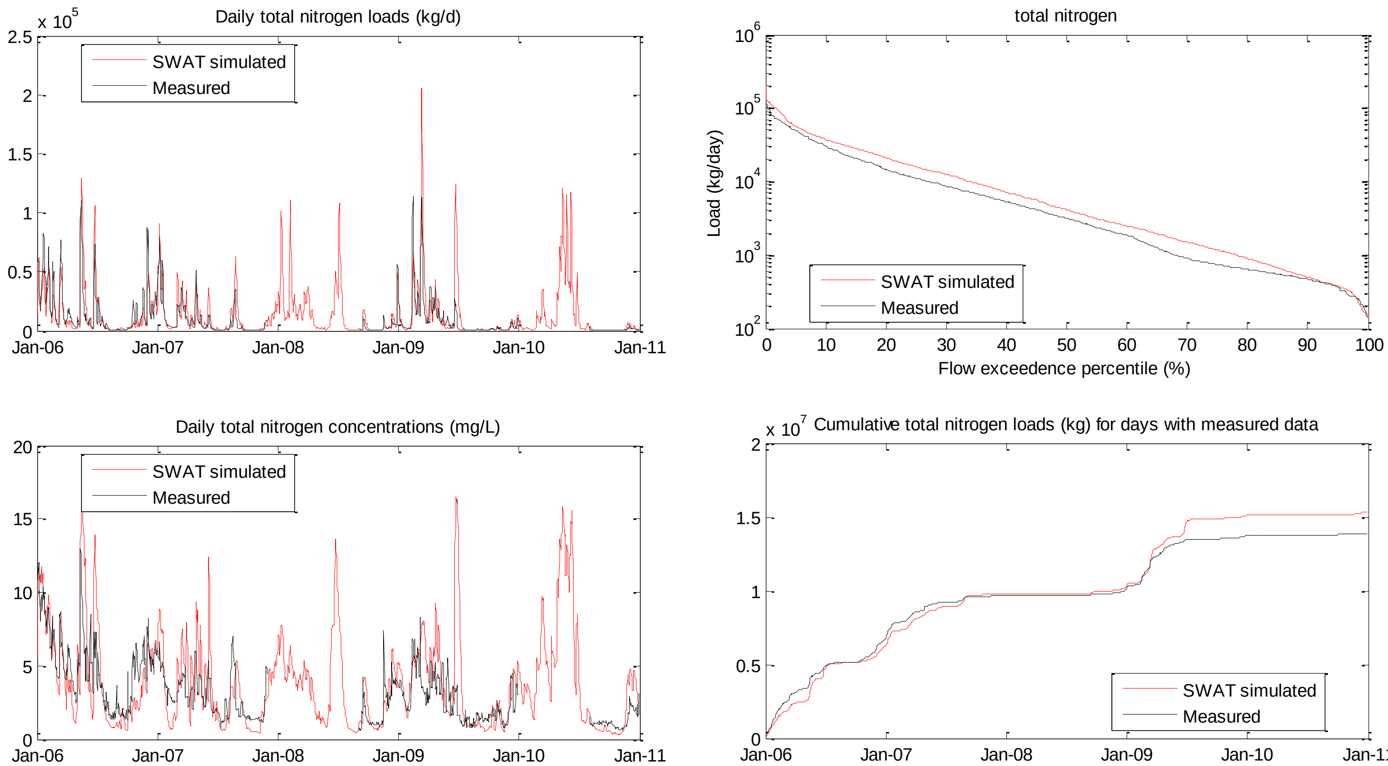
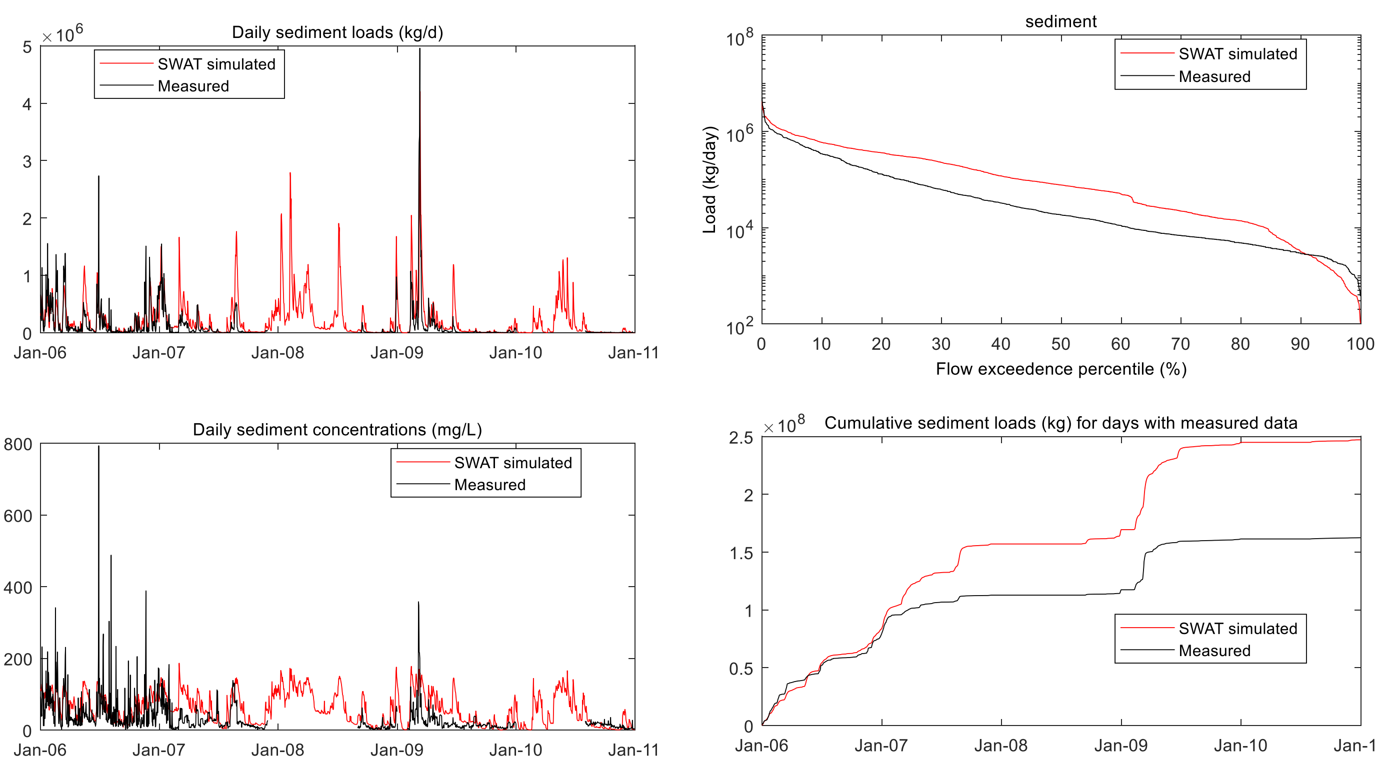


Figure S13. Sediment daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for validation period (2006-2010).



Pay-for-Performance Modeling Period (2001-2010) Plots

Figure S14. Daily streamflow time series (top), flow-duration curve (middle), and cumulative plot (bottom) pay-for-performance modeling period (2001-2010).

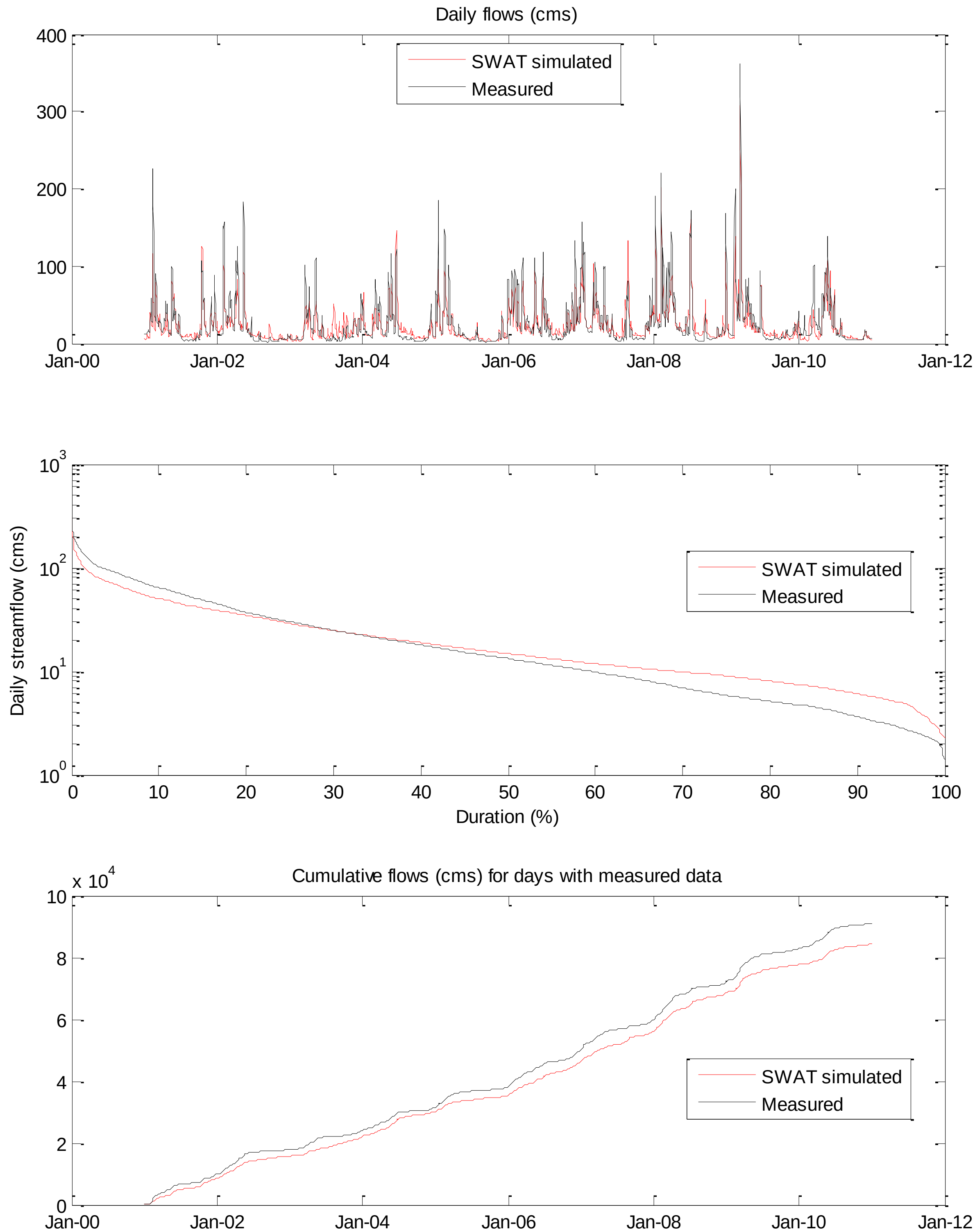


Figure S15. Total phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for pay-for-performance modeling period (2001-2010).

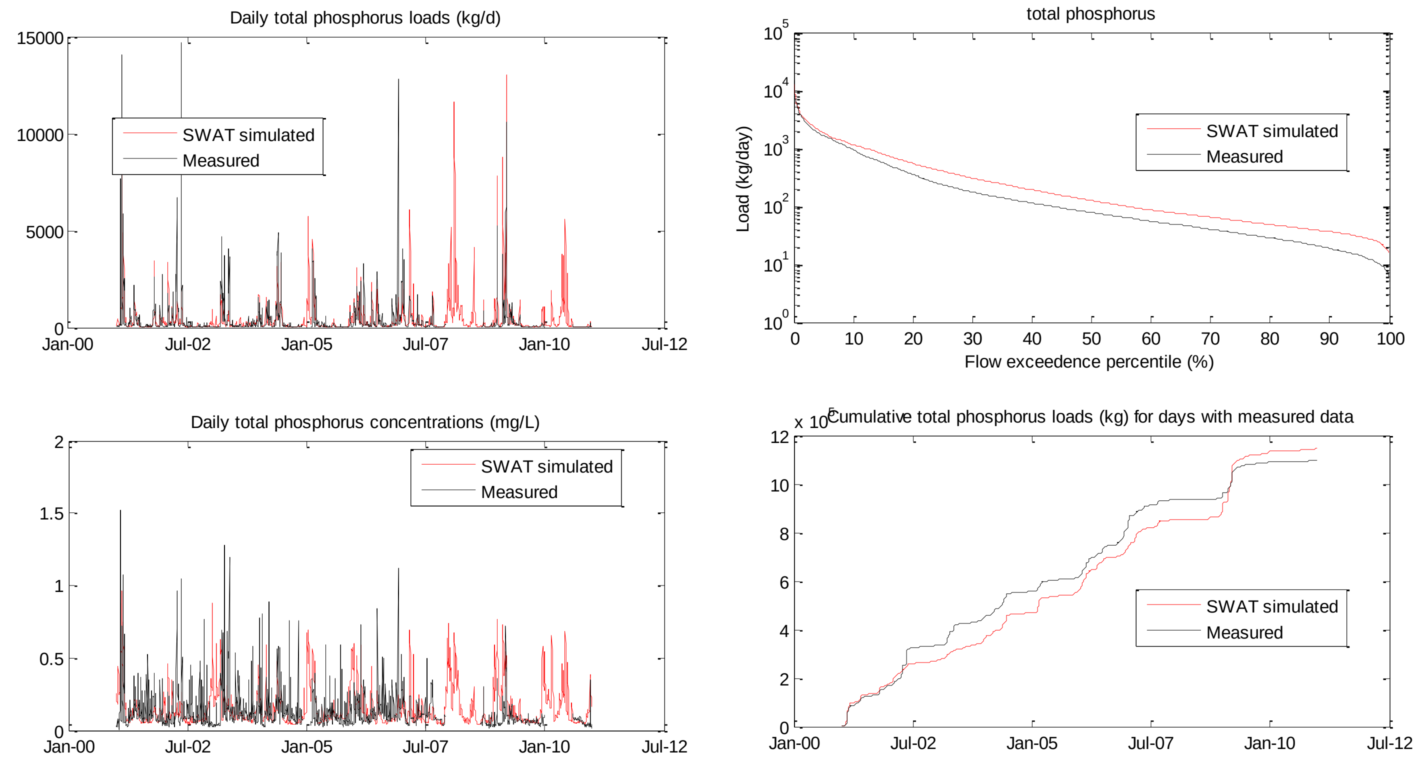


Figure S16. Dissolved reactive phosphorus daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for pay-for-performance modeling period (2001-2010).

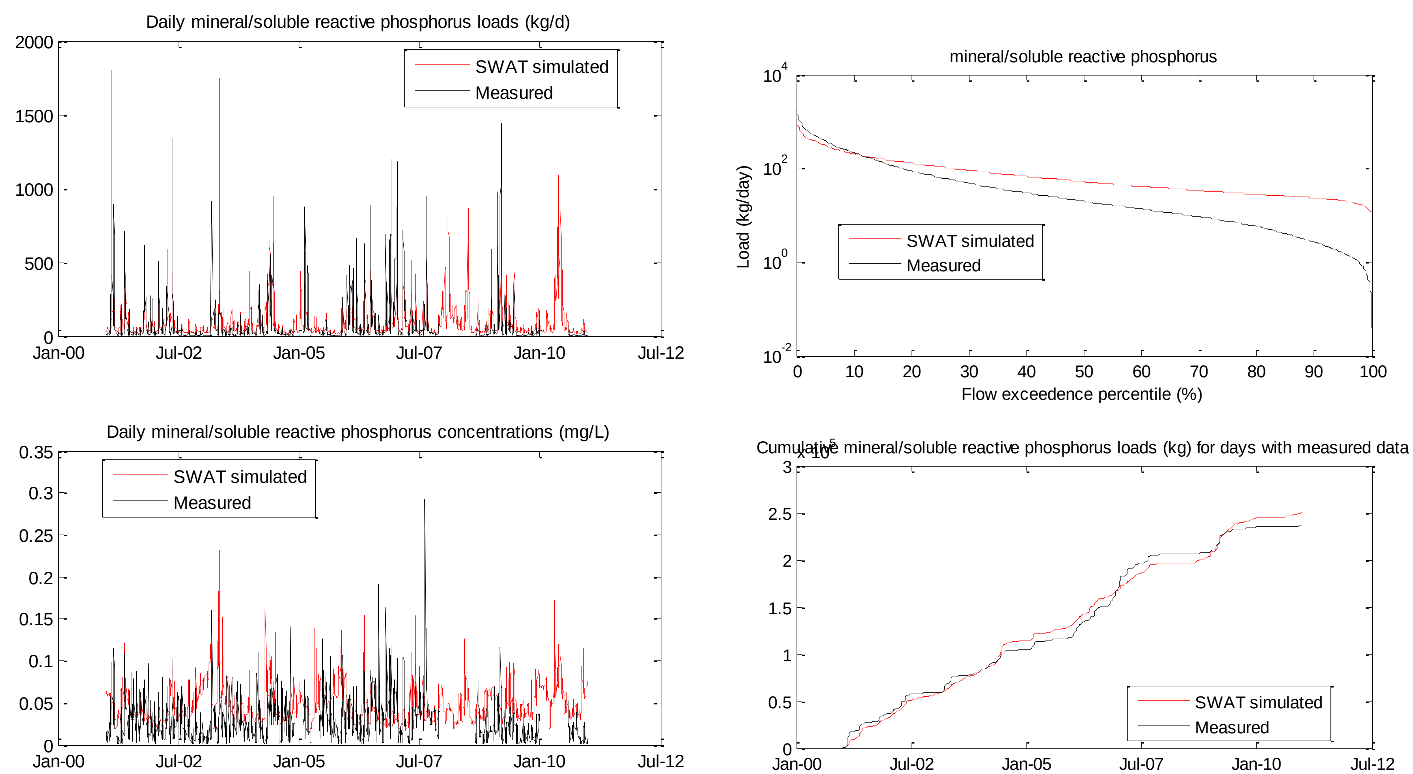


Figure S17. Total nitrogen daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for pay-for-performance modeling period (2001-2010).

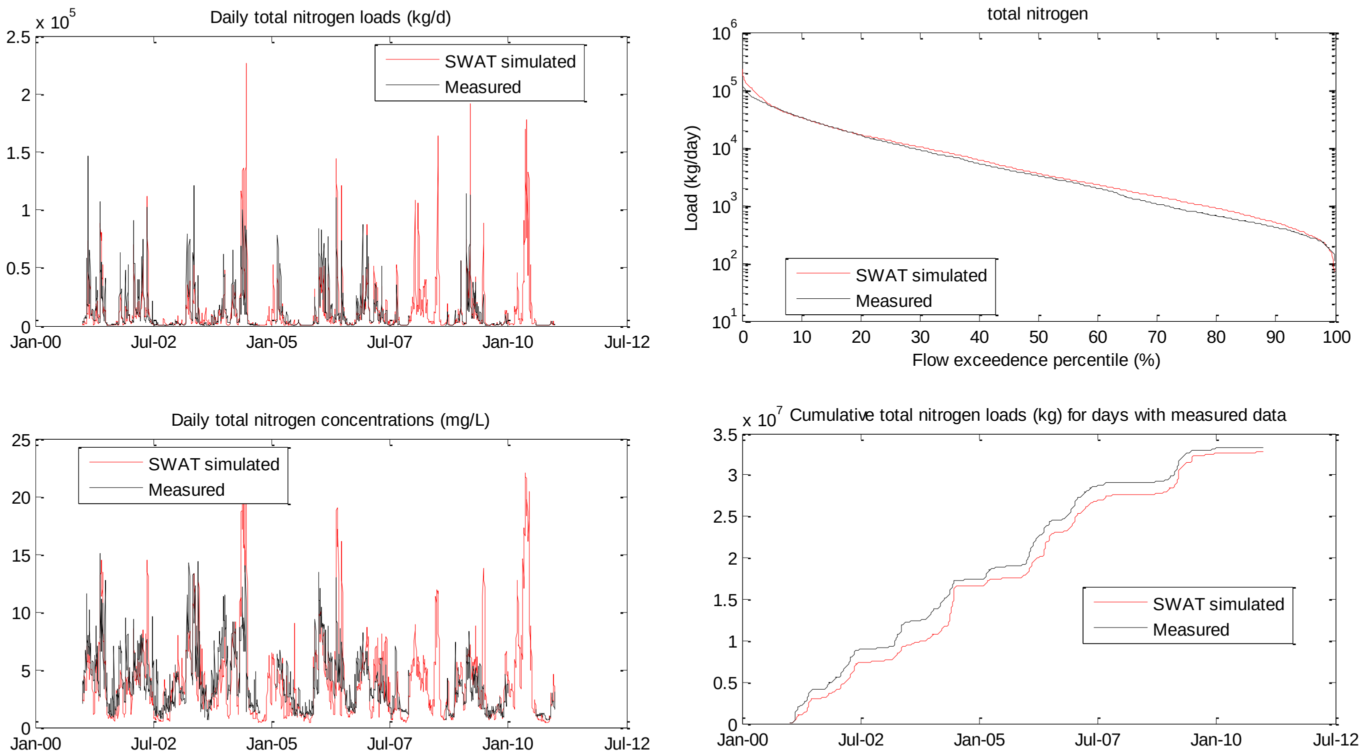
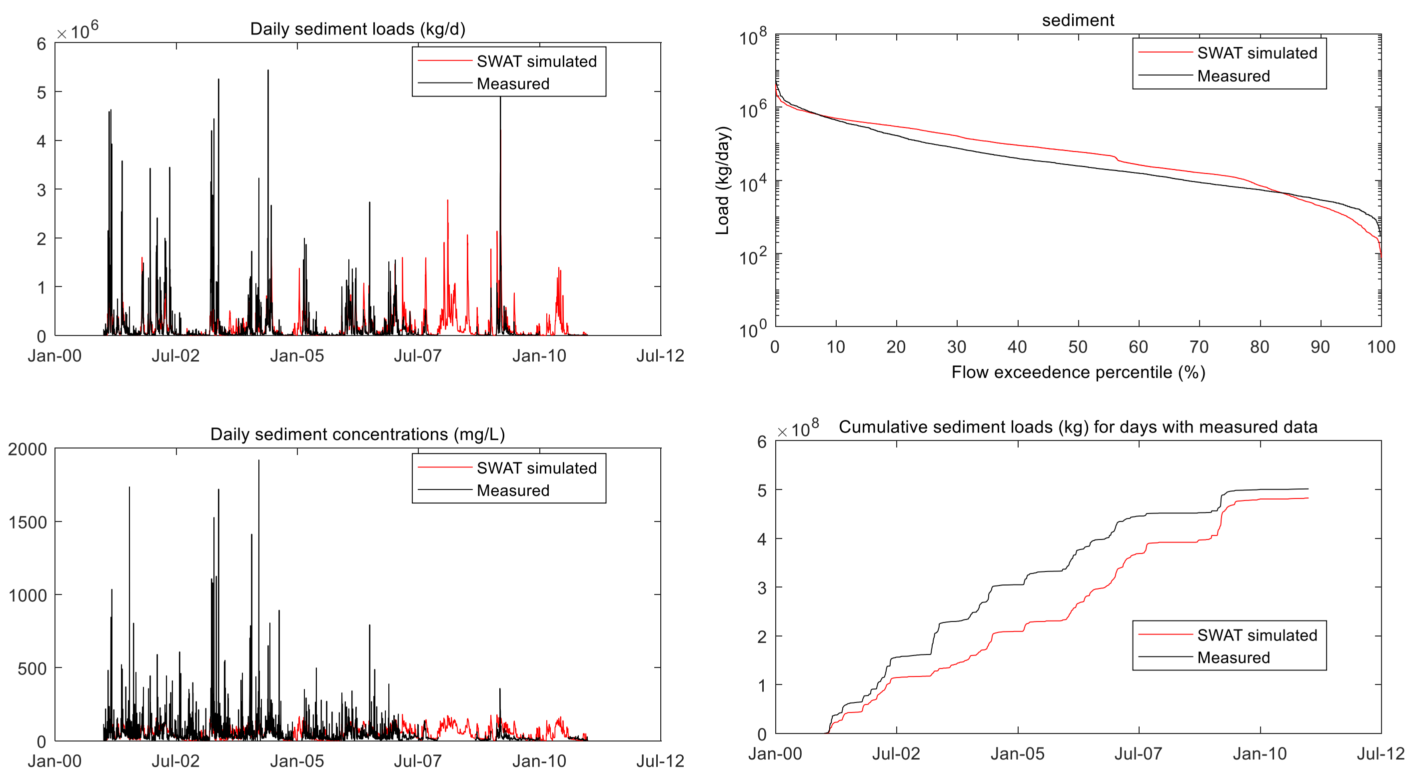


Figure S18. Sediment daily load time series (top left), daily concentrations (bottom left), load duration curve (top right), and cumulative plot (bottom right) for pay-for-performance modeling period (2001-2010).



Additional Calibration & Validation Statistics

Manual calibration was performed at the daily scale by comparing observed data at the outlet from the National Center for Water Quality Research (https://www.heidelberg.edu/academics/research-and-centers/national-center-for-water-quality-research) to simulated data from the model. Daily, monthly, and annual statistics for streamflow (Table S7) and daily and monthly statistics for sediments and nutrients (Table S8 & Table S9) are provided below.

Table S7. Daily, monthly, and annual statistics for streamflow at the outlet.

	Calibration *2001-2005*	Validation *2006-2010*	PFP Model Period *2001-2010*
R2 daily	0.71	0.81	0.78
NS daily	0.68	0.80	0.76
PBIAS daily	-7.26	-7.70	-7.39
R2 monthly	0.80	0.85	0.83
NS monthly	0.75	0.82	0.81
PBIAS monthly	-7.57	-7.75	-7.55
R2 yearly	0.61	0.86	0.86
NS yearly	0.41	0.51	0.75
PBIAS yearly	-7.25	-7.84	-7.51

Table S8. Daily statistics for sediment and nutrients at the outlet.

	Calibration *2001-2005*	Validation *2006-2010*	PFP Model Period *2001-2010*
R2 Sed	0.30	0.50	0.32
NS Sed	0.28	0.34	0.31
PBIAS Sed	-31.18	52.16	-3.92
R2 TP	0.36	0.55	0.42
NS TP	0.35	0.43	0.36
PBIAS TP	-8.59	15.68	4.63
R2 MinP	0.40	0.51	0.46
NS MinP	0.39	0.48	0.45
PBIAS MinP	10.26	-4.90	5.82
R2 TN	0.48	0.63	0.55
NS TN	0.30	0.49	0.41
PBIAS TN	-7.77	10.32	-1.57

Table S9. Monthly statistics for sediment and nutrients at the outlet.

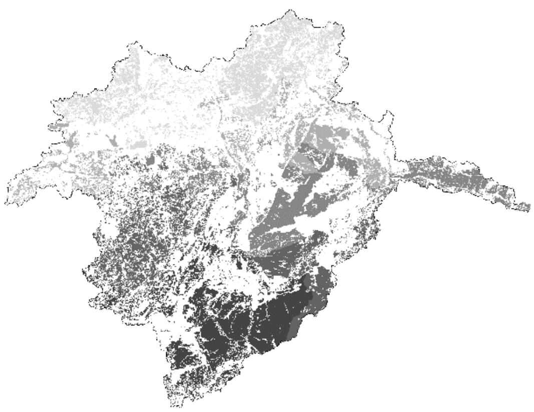
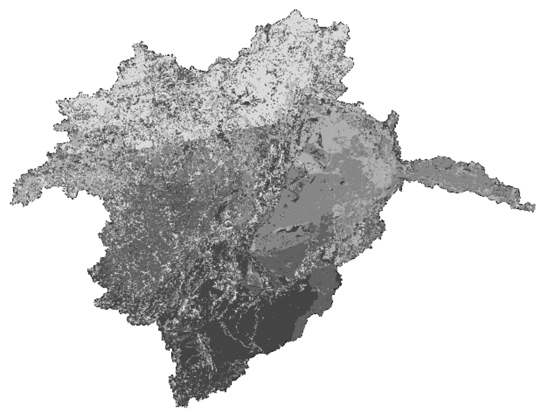
	Calibration *2001-2005*	Validation *2006-2010*	PFP Model Period *2001-2010*
R2 Sed	0.65	0.76	0.57
NS Sed	0.56	0.48	0.56
PBIAS Sed	-31.11	52.10	-4.07
R2 TP	0.60	0.66	0.59
NS TP	0.59	0.47	0.50
PBIAS TP	-7.83	16.15	5.25
R2 MinP	0.52	0.53	0.54
NS MinP	0.51	0.51	0.54
PBIAS MinP	9.50	-4.77	5.53
R2 TN	0.52	0.73	0.59
NS TN	0.25	0.66	0.43
PBIAS TN	-8.15	9.86	-1.98

HRU Filling Process

The steps used to "fill-in" the lumped HRU shapefile with the most similar HRU ID was as follows:

1. Overlay the land use, soil slope and original HRU shapfile from ArcSWAT output.
2. Use the following criteria to select the best HRU ID from all original HRUs:
    a. If the area of land is already explicitly modeled by a SWAT HRU (e.g., has the same soil, slope, and land use), use the same HRU as originally used by SWAT.
    b. If an HRU with the same combination of land use and soils cannot be found in SWAT HRU shapefile within the same subbasin, but it can be found within the watershed, the HRU with the closest mean slope (based on absolute difference), and same land use and soils will be assigned.
    c. If an HRU with the same combination of land use and soil could not be found in the watershed at all, the HRU with the same land use and closest slope was assigned.
    d. If there was no original soils data available, the HRU with the same land use and closest slope was assigned.

Figure S19. The HRU shapefile before (left) and after filling (right).

Before:	After:
	

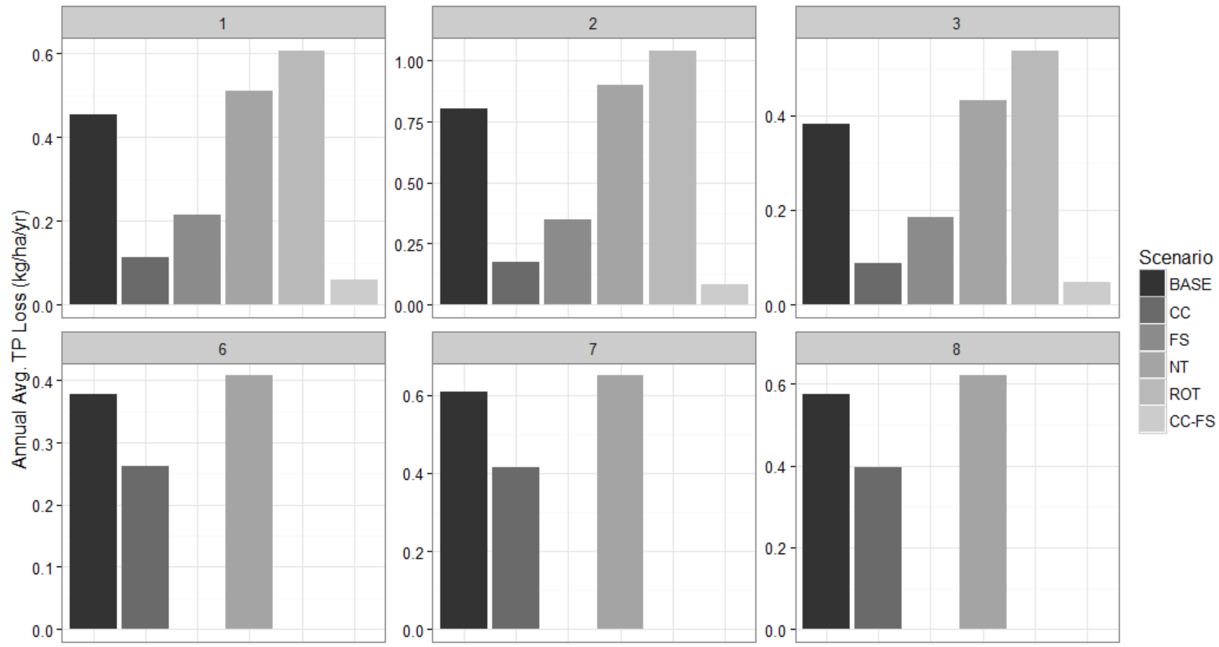
Individual Farm Details & Results

The tables below provide physical characteristics, management details, and field-level results for each farm included in the pilot phase. For practice abbreviation references, see Table 1 in the manuscript.

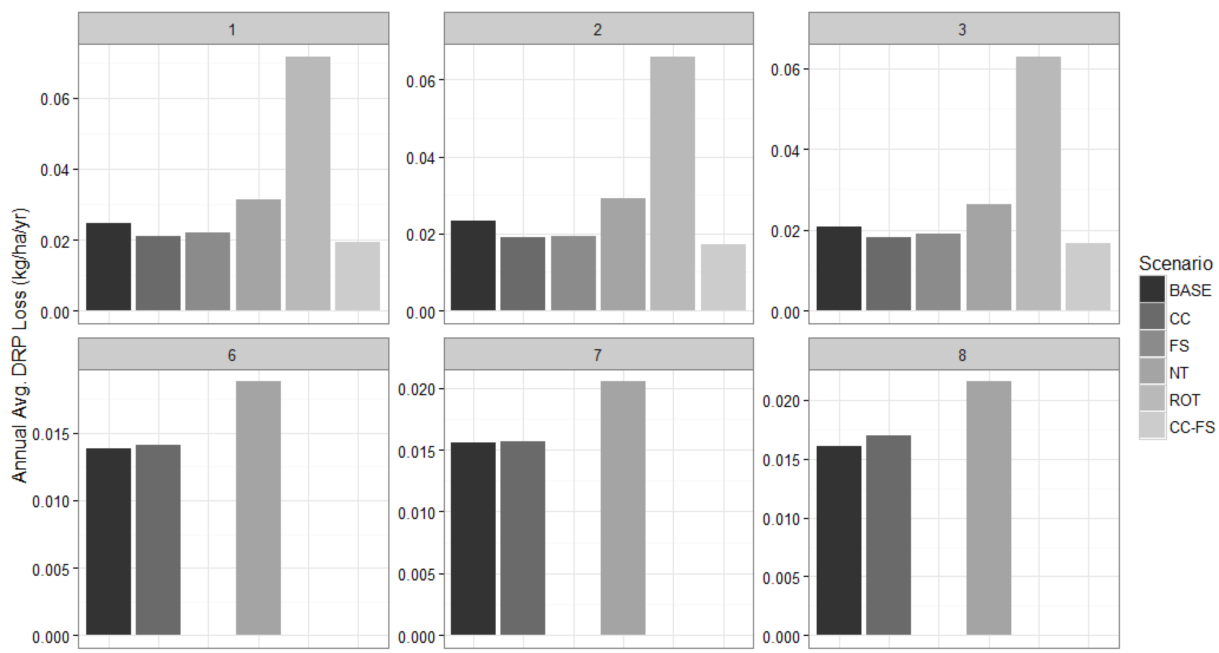
Farm ID	A
Total Acres	156
# Fields	6
Generalized Management	> Rotations: CS, CSW > Average P applied: 42 kg/ha only before corn > P timing: spring > P application method: subsurface > Tillage system: conservation tillage > Existing BMPs: cover crop after wheat harvest
Physical Characteristics	> Average slope: 1.6%; Range: [0.03% - 6.6%] > Tile drains: on all fields > Soil orders: alfisols (50%) and mollisols (50%) > Soil drainage classes: well drained (3%), moderately drained (15%), poorly drained (50%), somewhat poorly drained (32%) > Soil particle size: mostly fines
Scenarios of Interest	> cover crops (cereal rye) > filter strip around stream that runs between fields > combination of filter strip and cover crops > completely no-tillage system > change CS rotation to CSW as well

Farmer A Results

Results by Field: TP



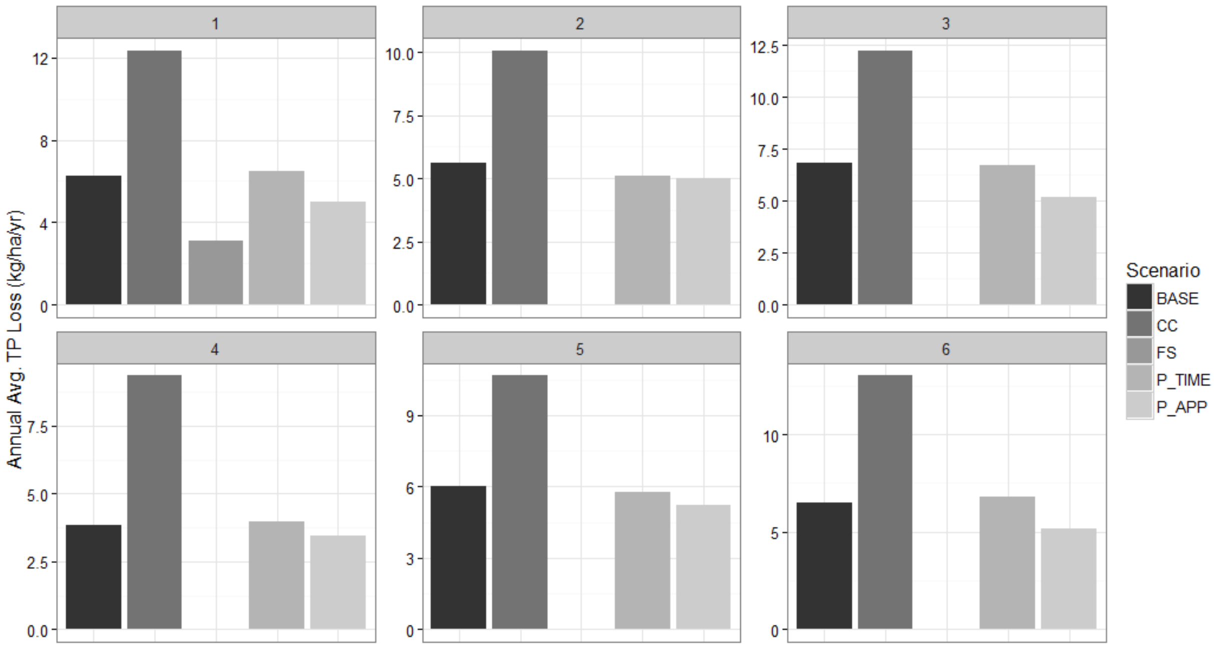
Results by Field: DRP



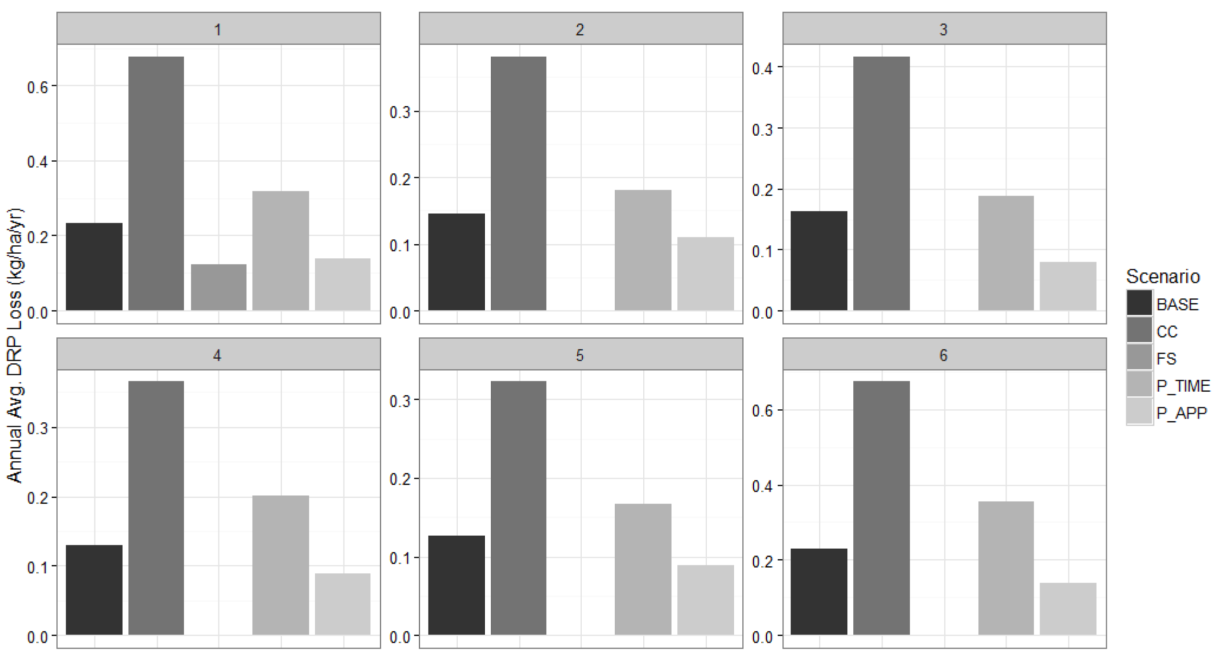
Farm ID	B
Total Acres	115
# Fields	6
Generalized Management	> Rotations: CSS, SRS, SWS > Average P applied: 24 kg/ha > P timing: mix of fall and spring > P application method: broadcast, with and without incorporation > Tillage system: conservation tillage > Existing BMPs: No additional
Physical Characteristics	> Average slope: 2.3%; Range: [0.14% - 9.7%] > Tile drains: none > Soil orders: alfisols (93%), mollisols (3%), inceptisols (3%) > Soil drainage classes: well drained (55%), somewhat poorly drained (41%), very poorly drained (3%) > Soil particle size: mostly fines
Scenarios of Interest	> cover crops (cereal rye, oats, radish) > move fall P applications to spring > all broadcast P applications without incorporation changed to subsurface applications > filter strip around surface inlet on one field

Farmer B Results

Results by Field: TP



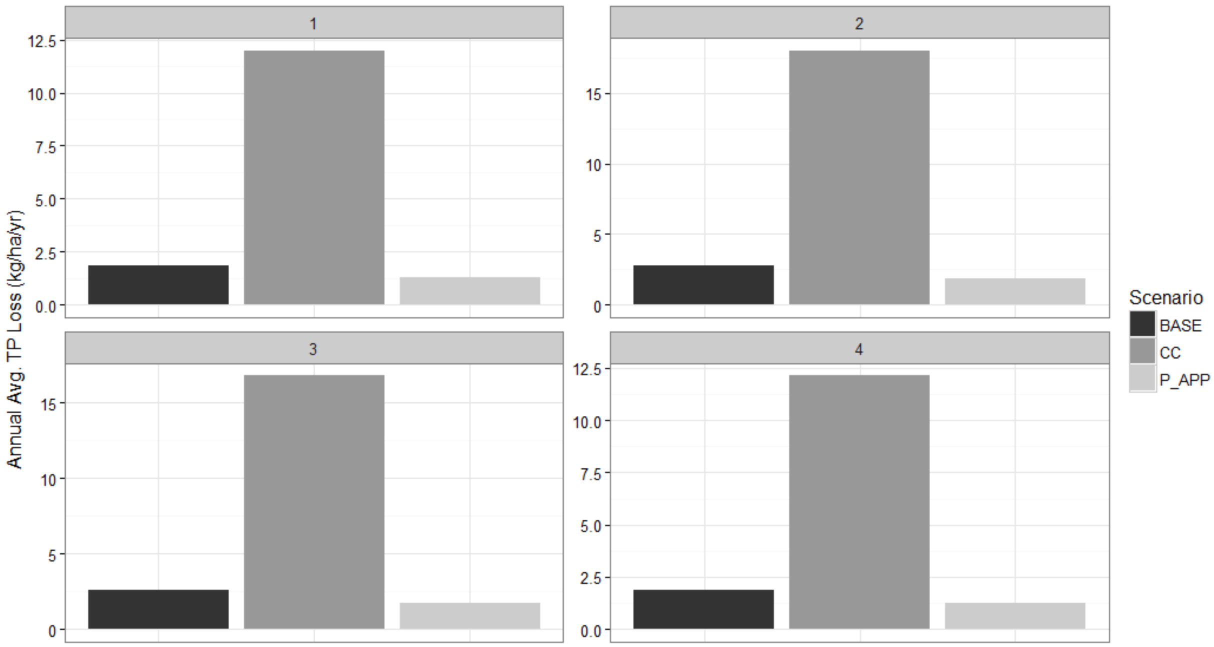
Results by Field: DRP



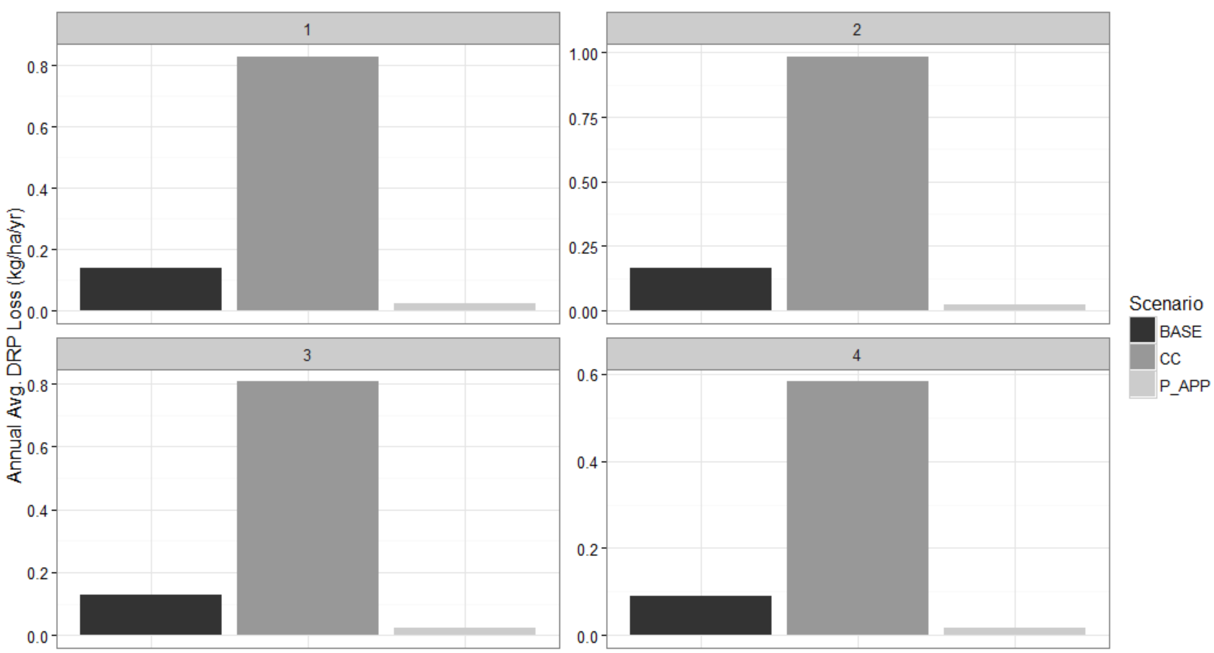
Farm ID	C
Total Acres	323
# Fields	4
Generalized Management	> Rotation: CSW > Average P applied: 30 kg/ha > P timing: mix of fall and spring > P application method: broadcast without incorporation > Tillage system: conventional till > Existing BMPs: filter strip on some of fields
Physical Characteristics	> Average slope: 0.8%; Range: [0.02% - 4.3%] > Tile drains: no tile drains > Soil orders: alfisols (100%) > Soil drainage classes: well drained (1%), moderately drained (30%), somewhat poorly drained (58%), very poorly drained (11%) > Soil particle size: mix of fines, fine-loamy, and coarse-loamy
Scenarios of Interest	> cover crops (cereal rye, oats) > subsurface application of P > using wheat in rotation as cover crop

Farmer C Results

Results by Field: TP



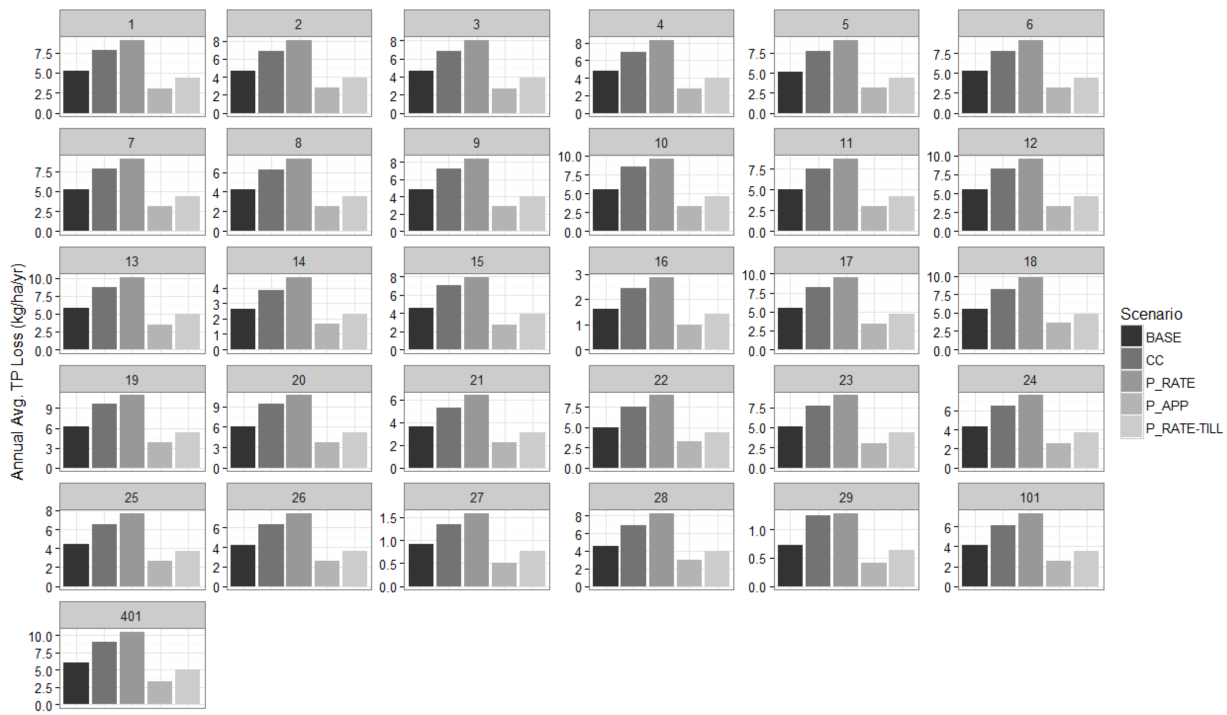
Results by Field: DRP



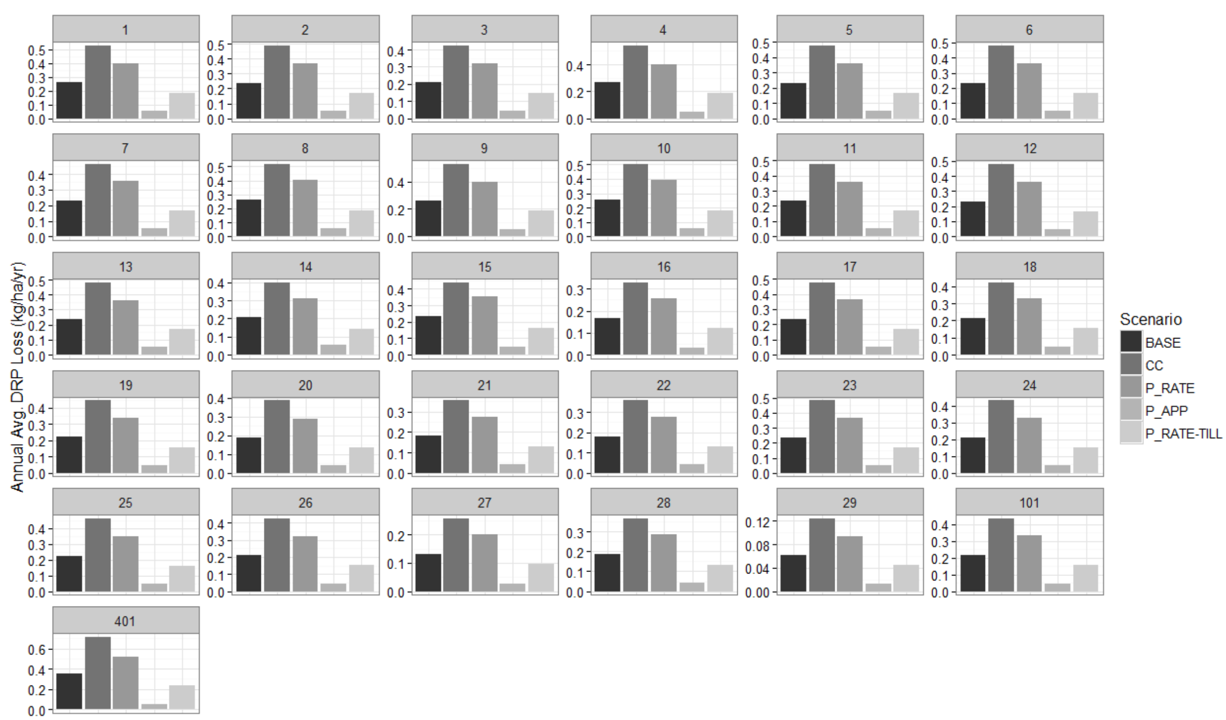
Farm ID	D
Total Acres	1250
# Fields	31
Generalized Management	> Rotations: CSW > Average P applied: 30 kg/ha > P timing: mix of fall and spring > P application method: primarily broadcast without incorporation > Tillage system: conservation tillage > Existing BMPs: cereal rye cover crop after corn
Physical Characteristics	> Average slope: 1.6%; Range: [0.01% - 11.4%] > Tile drains: none > Soil orders: alfisols (94%), mollisols (3%), inceptisols (1%), entisols (2%) > Soil drainage classes: well drained (4%), moderately drained (12%), poorly drained (2%), somewhat poorly drained (74%), very poorly drained (7%) > Soil particle size: mostly fines and fine-loamy
Scenarios of Interest	> Reduce P application > Changing from strip tillage to vertical tillage > cover crops (oats, rye) > subsurface applications of P

Farmer D Results

Results by Field: TP



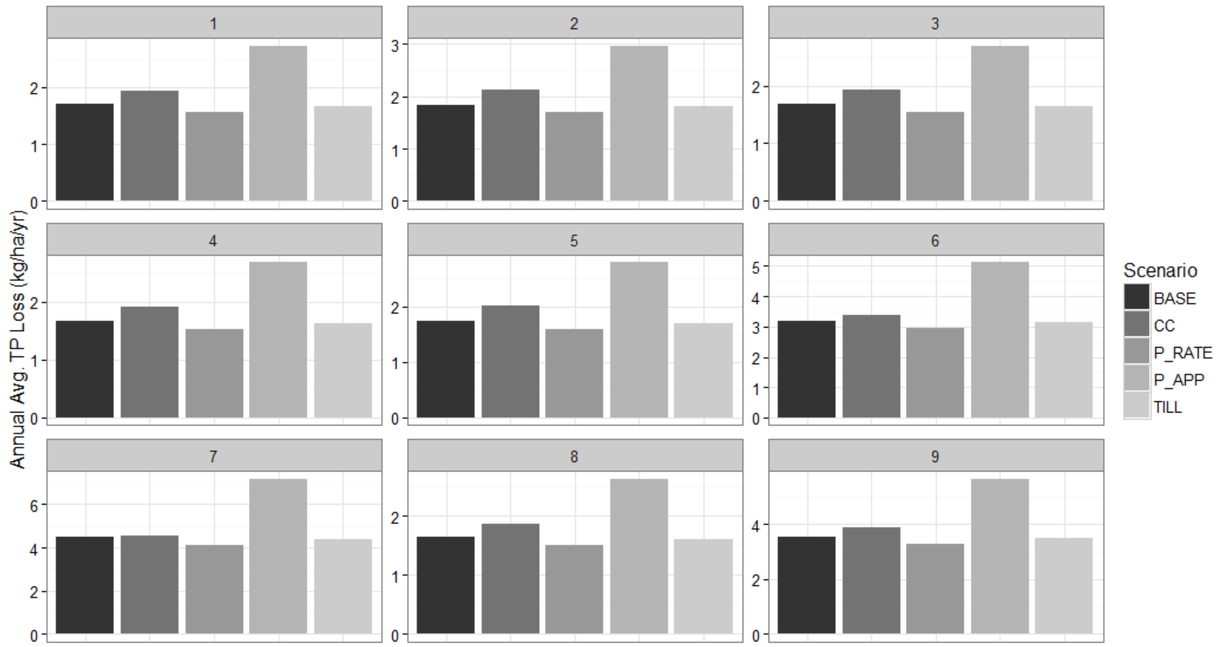
Results by Field: DRP



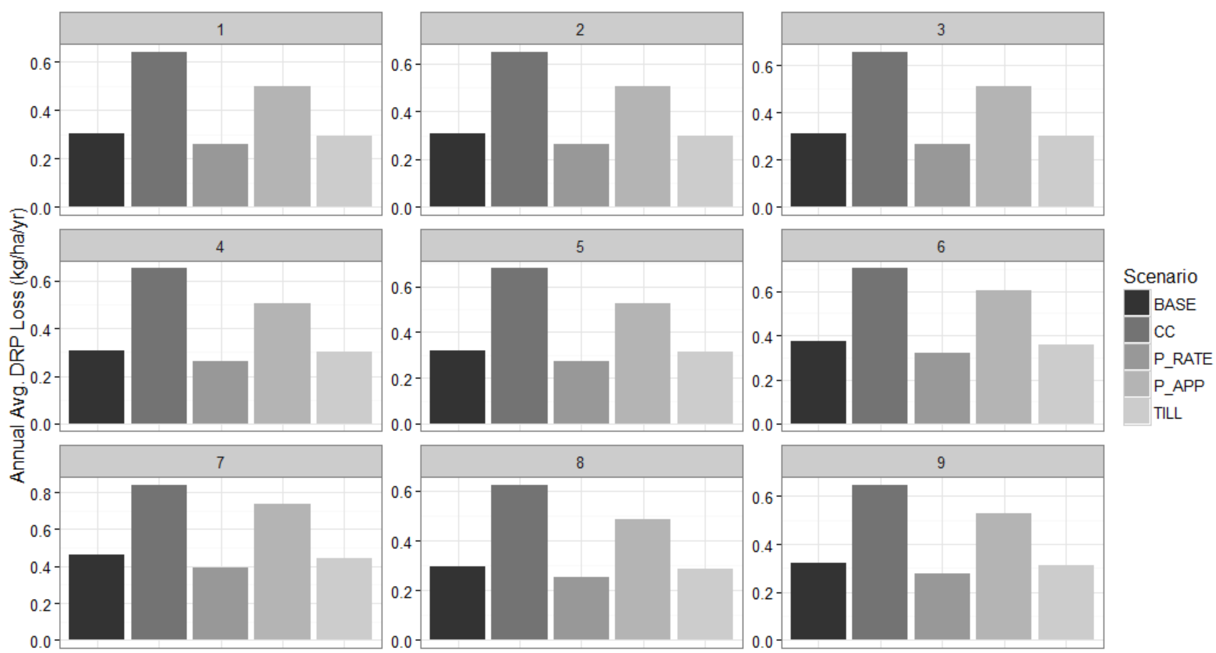
Farm ID	E
Total Acres	68
# Fields	9
Generalized Management	> Rotation: CSW > Average P applied: 56 kg/ha > P timing: primarily fall > P application method: primarily broadcast without incorporation (some added with planter) > Tillage system: no tillage > Existing BMPs: No additional
Physical Characteristics	> Average slope: 2.5%; Range: [0.18% - 8.1%] > Tile drains: on all fields > Soil orders: alfisols (92%), entisols (8%) > Soil drainage classes: well drained (42%), moderately drained (8%), somewhat poorly drained (50%) > Soil particle size: all fines
Scenarios of Interest	> Reduce P applications > Cover crops (rye, oats) > Subsurface P applications > Adding a tillage operation before corn > Broadcasting all P fertilizers

Farmer E Results

Results by Field: TP



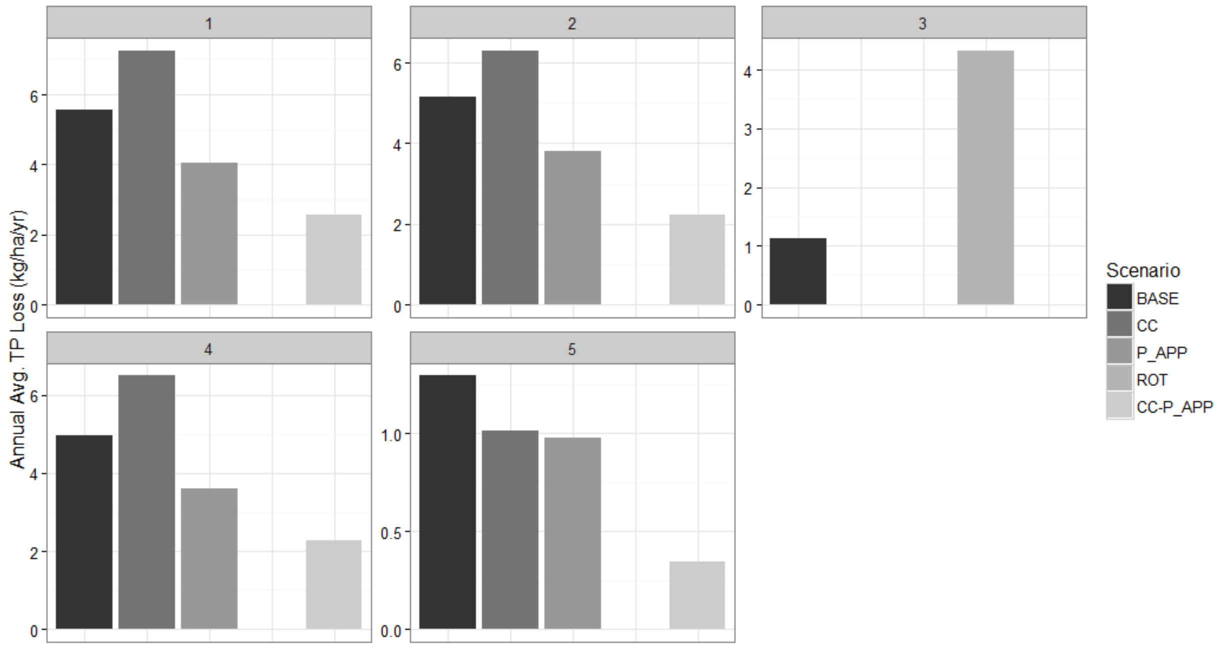
Results by Field: DRP



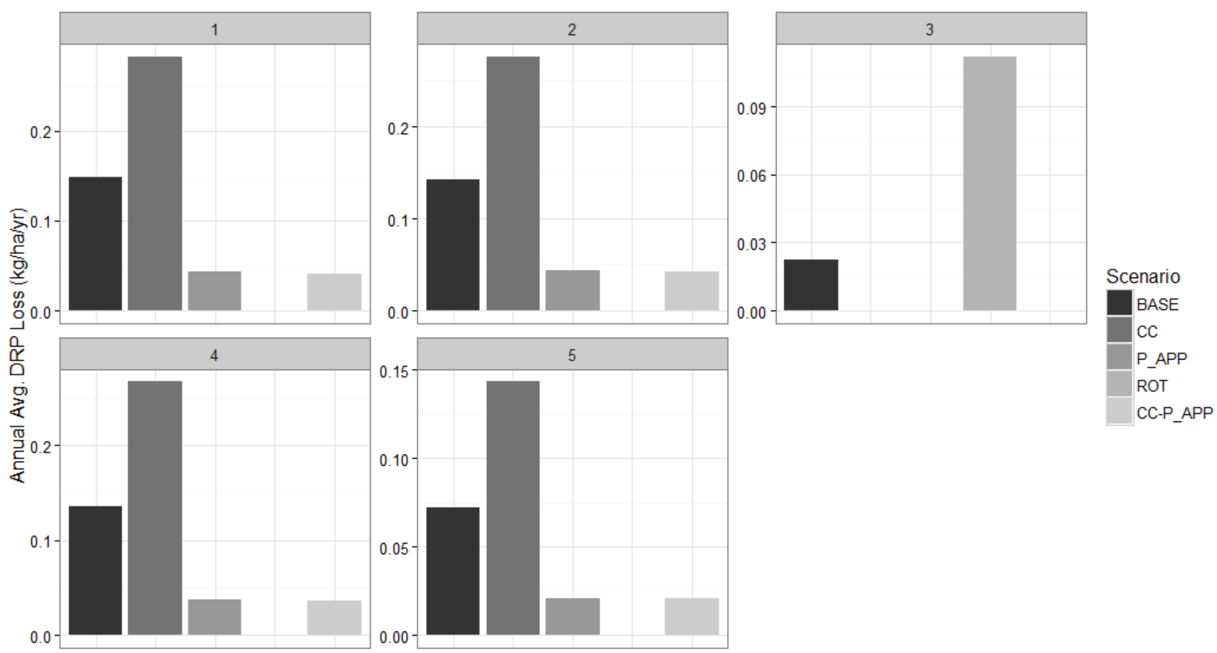
Farm ID	F
Total Acres	47
# Fields	5
Generalized Management	> Rotations: CSC, Hay > Average P applied: 11 kg/ha to corn only > P timing: spring > P application method: broadcast without incorporation > Tillage system: no tillage > Existing BMPs: No additional
Physical Characteristics	> Average slope: 2.2%; Range: [0.22% - 6.6%] > Tile drains: some with and some without > Soil orders: alfisols (83%), mollisols (17%) > Soil drainage classes: well drained (33%), poorly drained (8%), somewhat poorly drained (50%), very poorly drained (8%) > Soil particle size: mostly fines
Scenarios of Interest	> cover crops (rye, oats) > subsurface application of P > cover crops and subsurface application of P > going from continuous hay to CSC

Farmer F Results

Results by Field: TP



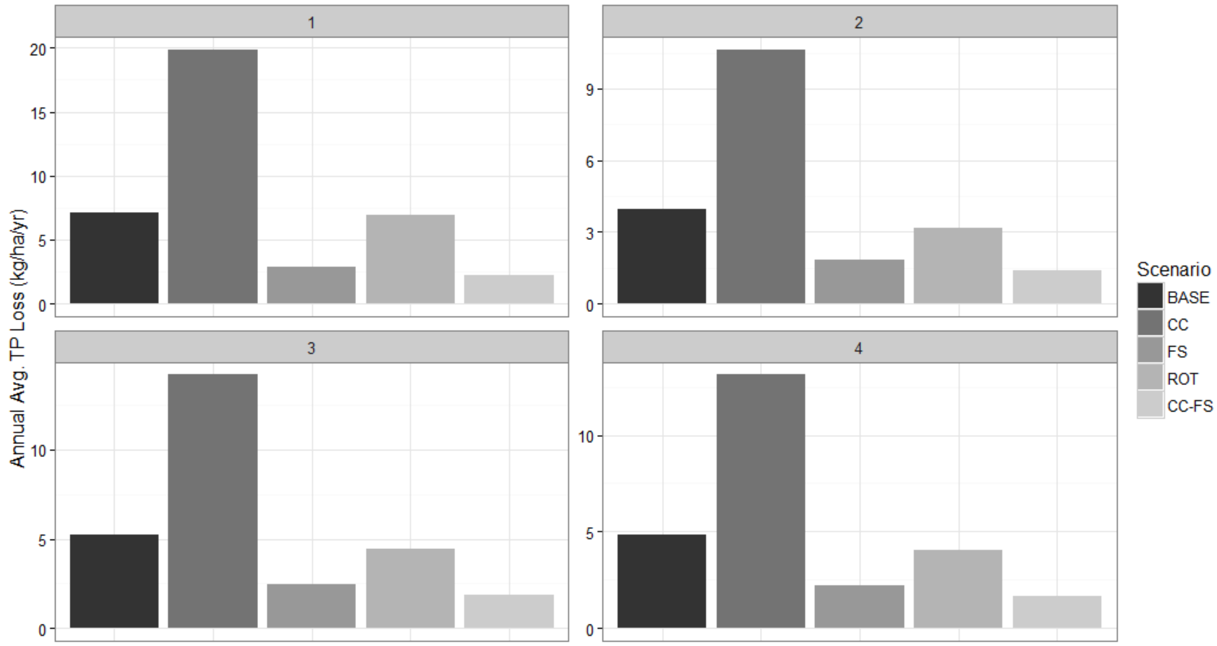
Results by Field: DRP



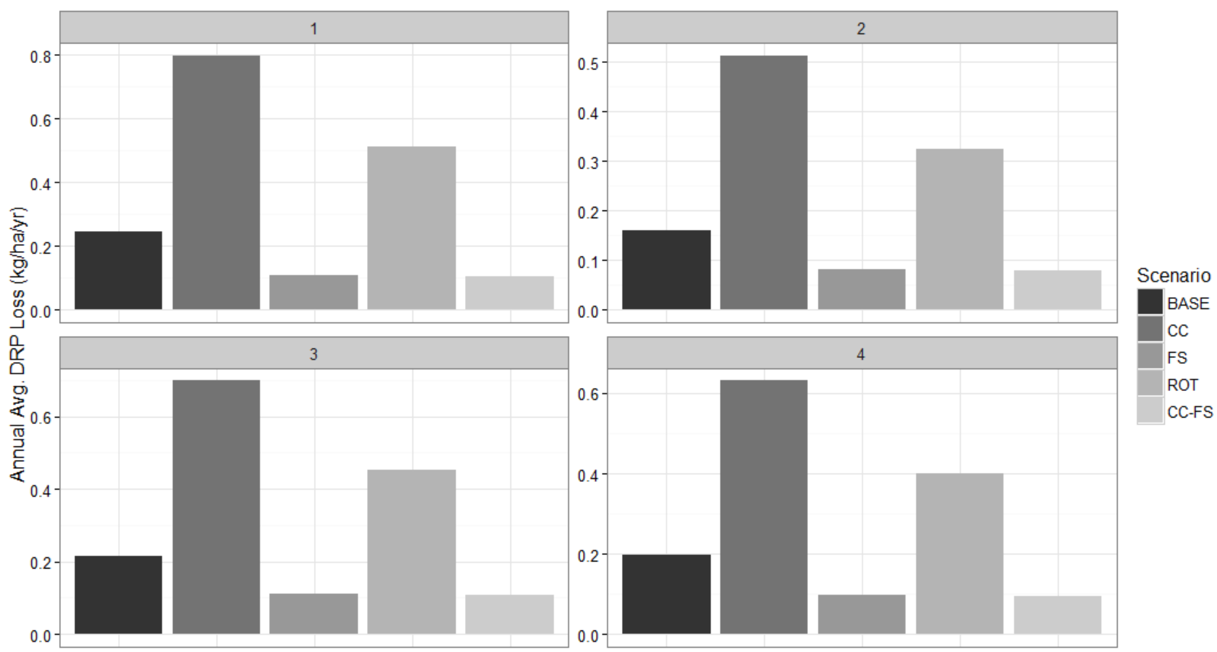
Farm ID	G
Total Acres	125
# Fields	4
Generalized Management	> Rotation: CSW > Average P applied: 20 kg/ha > P timing: mix of fall and spring > P application method: broadcast without incorporation > Tillage system: no tillage > Existing BMPs: No additional
Physical Characteristics	> Average slope: 1.7%; Range: [0.07% - 8.4%] > Tile drains: none > Soil orders: alfisols (100%) > Soil drainage classes: well drained (42%), somewhat poorly drained (58%) > Soil particle size: mostly fines
Scenarios of Interest	> cover crops (radish, clover, cereal rye) > change from CSW to CSS rotation > filter strip (30') on some fields > filter strip plus cover crops (cereal rye)

Farmer G Results

Results by Field: TP



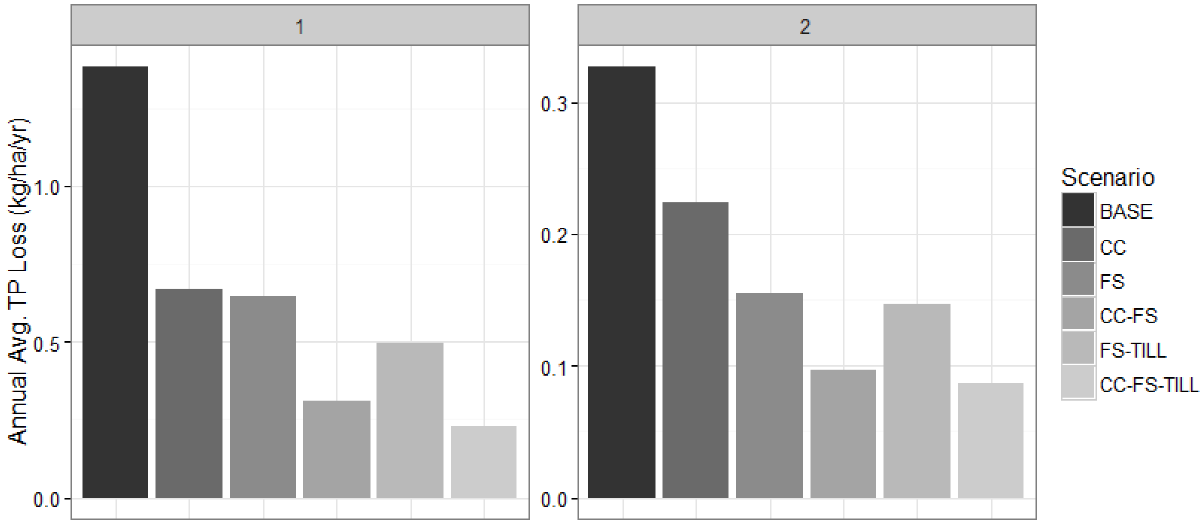
Results by Field: DRP



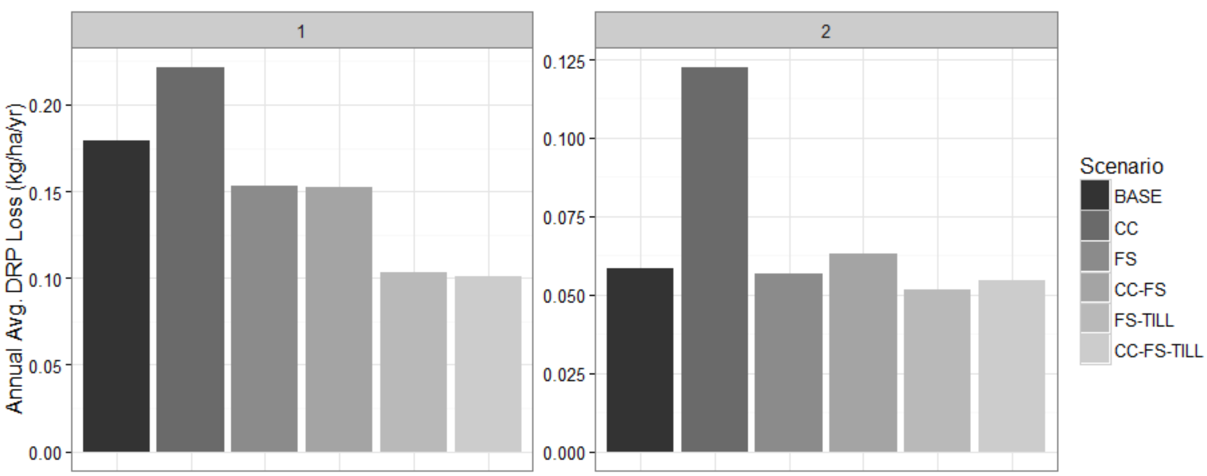
Farm ID	H
Total Acres	41
# Fields	2
Generalized Management	> Rotation: continuous corn silage > Average P applied: 24 kg/ha > P timing: spring > P application method: manure tilled in, other P in starter subsurface with planter > Tillage system: conventional tillage > Existing BMPs: winter wheat as harvested cover crop
Physical Characteristics	> Average slope: 3.2%; Range: [0.15% - 13.3%] > Tile drains: none > Soil orders: alfisols (67%), mollisols (17%), histosols (17%) > Soil drainage classes: well drained (50%), somewhat poorly drained (17%), very poorly drained (33%) > Soil particle size: mostly fines and fine-loamy
Scenarios of Interest	> changing winter wheat to non-harvested cover crop (clover, rye) > adding filter strip (60’) > combinations of cover crops and filter strips > filter strip and change to lighter tillage

Farmer H Results

Results by Field: TP



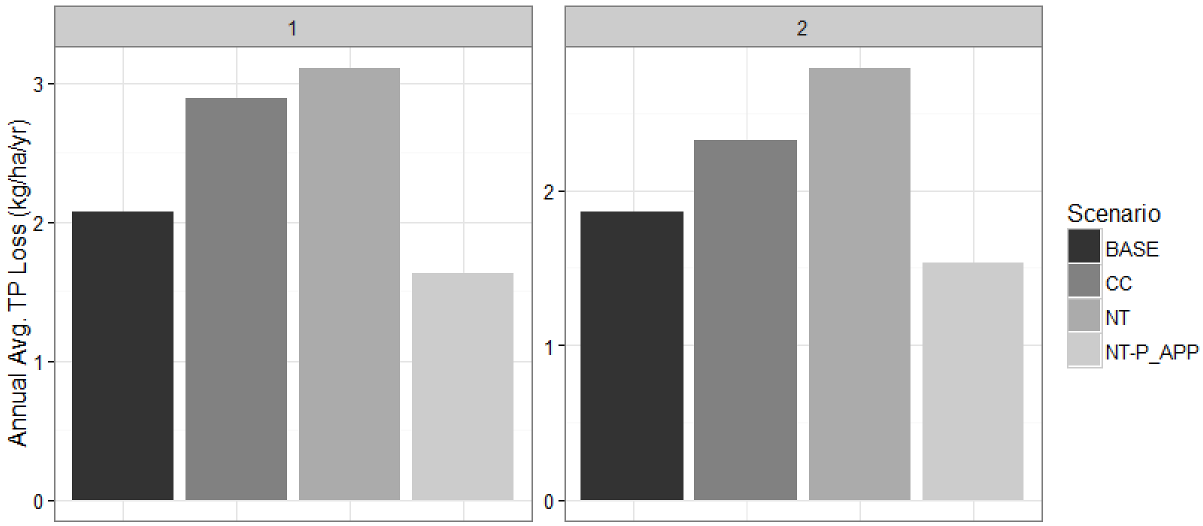
Results by Field: DRP



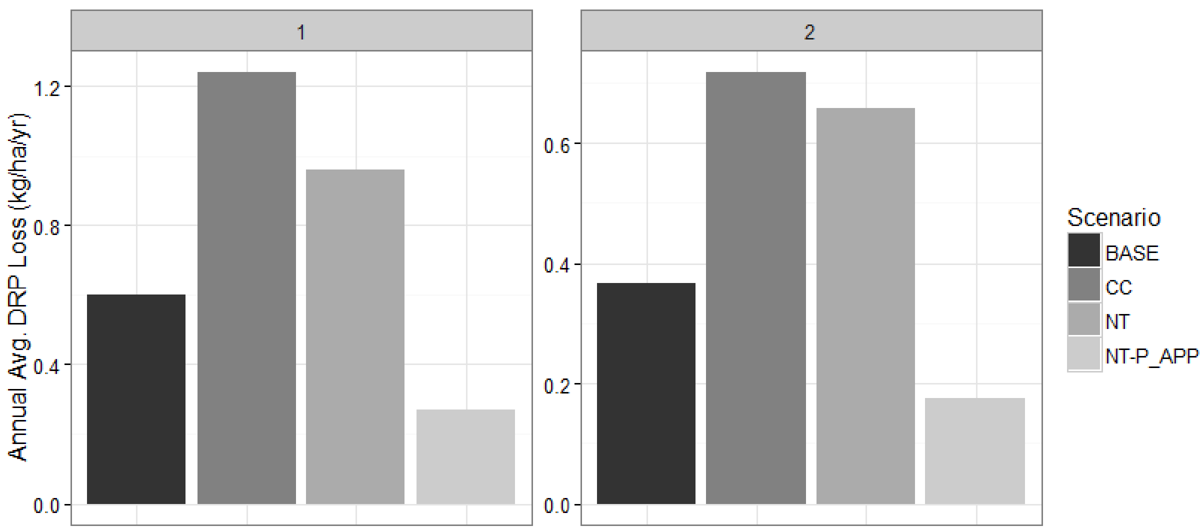
Farm ID	I
Total Acres	25
# Fields	2
Generalized Management	> Rotation: SWS > Average P applied: 54.7 kg/ha > P timing: mix of spring and fall > P application method: broadcast without incorporation > Tillage system: conventional tillage > Existing BMPs: No additional
Physical Characteristics	> Average slope: 1.5%; Range: [0.04% - 7.2%] > Tile drains: on all fields > Soil orders: alfisols (75%), mollisols (25%) > Soil drainage classes: well drained (25%), somewhat poorly drained (50%), very poorly drained (25%) > Soil particle size: mostly fines and fine-loamy
Scenarios of Interest	> no tillage > cover crops (oats, rye) > no tillage with subsurface application

Farmer I Results

Results by Field: TP



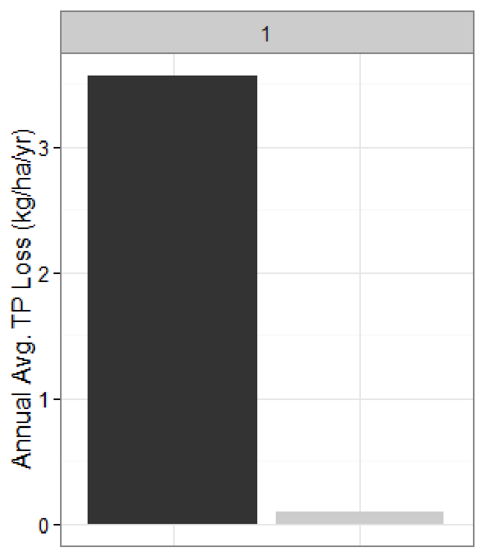
Results by Field: DRP



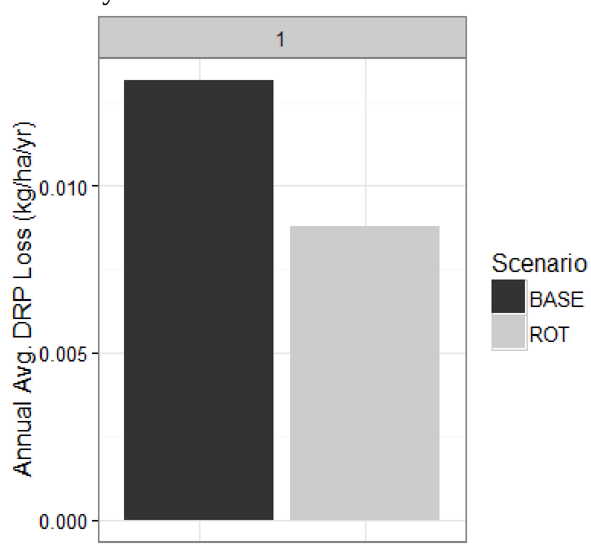
Farm ID	J
Total Acres	3
# Fields	1
Generalized Management	> Rotations: fallow field > Average P applied: manure from 4 horses > P timing: NA > P application method: NA > Tillage system: NA > Existing BMPs: None
Physical Characteristics	> Average slope: 1.4%; Range: [0.43% - 2.2%] > Tile drains: none > Soil orders: alfisols (100%) > Soil drainage classes: well drained (100%) > Soil particle size: fines and fine-loamy
Scenarios of Interest	> seed pasture (without fertilizer addition) for better cover

Farmer J Results

Results by Field: TP



Results by Field: DRP



References

Han H, Allan JD, Bosch NS. 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. Journal of Great Lakes Research, 38: 289.298. DOI: 10.1016/j.jglr.2012.03.004

National Agricultural Statistics Service (NASS). 2002. 2002 Census of Agriculture. Available at: http://www.agcensus.usda.gov/Publications/2002/ [Last accessed 27 January 2015].

National Agricultural Statistics Service (NASS). 2007. 2007 Census of Agriculture. Available at: http://www.agcensus.usda.gov/Publications/2007/index.php [Last accessed 27 January 2015].

Ruddy BC, Lorenz DL, Mueller DK. 2006. County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. U.S. Geological Survey National Water-Quality Assessment Program Scientific Investigations Report 2006-5012. Available at: http://pubs.usgs.gov/sir/2006/5012/pdf/sir2006_5012.pdf [Last accessed 27 January 2015].

United States Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS). 2016. Effects of Conservation Practice Adoption on Cultivated Cropland Acres in Western Lake Erie Basin, 2003-06 and 2012. 120 pp.

United States Environmental Protection Agency (USEPA). 2013. Fertilizer use and price. Available at: http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx [Last accessed 27 January 2015].