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Modeling phosphorus reduction strategies from the international St. Clair-Detroit River system watershed

Awoke Dagnew[a], Donald Scavia[b], Yu-Chen Wang[c], Rebecca Muenich[d], Margaret Kalcic[e]

[a]Environmental Consulting and Technology, Inc., 2200 Commonwealth Blvd, Ann Arbor MI, 48105, USA, +1-734-2720767x23328

[b]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48104, USA

[c]Graham Sustainability institute, University of Michigan, 214 S. State St., Ann Arbor MI, 48104, USA, +1-734-763-0511

[d]Sustainable Engineering and the Built Environment, Arizona State University, 660 S. College Ave., Tempe, AZ 85281, USA,+1-480-965-1077

[e]Food, Agriculture and Biological Engineering, Ohio State University; 590 Woody Hayes Dr., Columbus, OH 43210, USA, +1-614-292-9356

Correspondence to: Awoke Dagnew, Email: adagnew@ectinc.com,

Abstract. Nutrient loading from nonpoint sources has degraded water quality in large water bodies globally. The water quality of Lake Erie, the most productive of the Laurentian Great Lakes bordering the United States and Canada, is influenced by phosphorus loads from the Detroit River that drains an almost 19,000 km^2 international watershed. We used the Soil and Water Assessment Tool (SWAT) to evaluate a range of management practices to potentially reduce total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads. Scenarios included both single practices and bundles of multiple practices. Single practice scenarios included fertilizer rate reduction (Rate) and sub-surface placement (PL), filter strips (FL), grassed waterways, cover crops (CC), wetlands (WT), controlled drainage, and changes in tillage practices. Bundle scenarios included combinations of Rate, PL, FL, CC, and WT with three adoption strategies: application on all applicable areas, on 55% of randomly selected applicable areas, and on 55% of high phosphorus yielding applicable areas. Results showed that among the single practice scenarios, FL, WT, PL, CC, and Rate performed well in reducing both TP and DRP loss from agricultural dominated sub-watersheds. Over all, the CC, FL, WT bundle performed best, followed by the CC, PL, WT bundle, reducing the load up to 80% and 70%, respectively, with 100% implementation. However, targeting high phosphorus yielding areas performed nearly as well as 100% implementation. Results from this work suggest that there are potential pathways for phosphorus load reduction, but extensive implementation of multiple practices is required.

Key words: Phosphorus load; Agricultural management practices; SWAT; Scenario analysis; Watershed modeling

Introduction

Nutrient inputs to waterbodies have increased globally and have led to increased algal production, eutrophication, and more frequent and larger harmful algal blooms and hypoxic areas (Dodds and Smith, 2016; Carpenter et al., 1998). Coastal hypoxic areas, in particular, have grown over the past few decades, with large hypoxic regions developing in the Baltic Sea, Black Sea, Gulf of Mexico, and East China Sea (Breitburg et al., 2018; Diaz and Rosenberg, 2008). Substantial hypoxic and anoxic areas have also grown in U.S. estuaries (Bricker et al., 2008) and the Laurentian Great Lakes. Lake Erie, the southernmost, shallowest, and most productive of the Laurentian Great Lakes, has experienced recent re-eutrophication and increases in toxic algal blooms and hypoxia (Scavia et al., 2014; Watson et al., 2016). In response, the U.S. and Canada revised phosphorus loading targets (GLWQA, 2016) based on public input and science synthesized in a multi-model effort (Scavia et al., 2016). The Great Lakes Water Quality

Agreement (GLWQA) set new targets to reduce annual and spring (March-July) phosphorus loads to Lake Erie by 40 percent from their 2008 levels in 9 out of 10 years. Phosphorus is the key nutrient for policy targets because harmful algal blooms and hypoxia – the primary system impairments (Bridgeman et al., 2013; Michalak et al., 2013; Zhou et al., 2015) – are driven strongly by phosphorus loads (Bertani et al., 2016; Bocaniov et al., 2016; Obenour et al., 2014; Rucinski et al., 2016, 2014; Scavia et al., 2016, 2014; Stumpf et al., 2016) .

Following the new water quality agreement, the U.S. and Canada are developing Domestic Action Plans (IJC, 2017) to reduce phosphorus loads, and substantial attention is placed on phosphorus from the Detroit and Maumee rivers. These two rivers contribute approximately 41% and 48% of total phosphorus load to the Western Basin of the lake, and 25% and 29% of the load to the whole lake, respectively (Maccoux et al., 2016; Scavia et al., 2016). While the phosphorus load from the Maumee River has been identified as the driver of the harmful algal blooms in the Western Basin, the load from the Detroit River is the major contributor to hypoxia in the central basin (Scavia et al., 2016). There have been several studies of the Maumee watershed (Bosch et al., 2013; Kalcic et al., 2016; Muenich et al., 2016; Scavia et al., 2017) assessing its relative contributions and potential controls of phosphorus loads. Those assessments identified several potential combinations of best management practices (BMPs) that could achieve the 40% load reduction target, but showed that any successful pathway would require large-scale implementation of multiple practices. For example, one pathway targeted 50% of row cropland in the Maumee watershed with the highest phosphorus loss to receive a combination of subsurface application of P fertilizers, a cereal rye winter cover crop, and buffer strips. The most recent Canada-Ontario Lake Erie Action Plan also noted that widespread implementation of multi-BMPs would be crucial for adequate reduction of phosphorus loads (ECCC, 2018).

Therefore, assessments similar to what have been done elsewhere are needed to identify potential load reduction strategies for this complex, almost 19,000 km^2, international watershed that encompasses both significant agricultural and urban areas – the St. Clair-Detroit River System (SCDRS) watershed.

If the GLWQA Lake Erie goal of a 40% reduction of annual and spring TP and dissolved reactive phosphorus (DRP) is applied to each tributary, then the load from Detroit River would have to be reduced by at least 40%. While there have been a few assessments of potential load reduction strategies for isolated parts of the watershed contributing to the Detroit River load (e.g., Hanke, 2018), this is the first integrated assessment for the entire SCDRS watershed.

The goal of this study is to use a previously calibrated and validated (Dagnew et al., in review) version of the widely used modeling tool, SWAT (Soil and Water Assessment Tool; Arnold et al., 1998), to investigate potential agricultural and urban/suburban management strategies for reducing non-point source phosphorus loads from the SCDRS watershed. To do this we 1) assess the effectiveness of individual practices and prioritize the most effective ones; 2) analyze the effectiveness of bundles of practices at different adoption rates and identify which bundles would reach the load reduction target set by the GLWQA and how this may vary for different parts of the SCDRS watershed.

Study Area

Located between 42^{o}02'10'', 43^{o}40'00' N and 80^{o}38'20'', 83^{o}39'10'' W, the St. Clair-Detroit River system (SCDRS) watershed drains parts of Southeastern Michigan, U.S. and Southwestern Ontario, Canada (Figure 1). Agriculture and urban areas cover about 60% and 20% of the 19,040 km^2 watershed, respectively, with the remaining in forests, open water, and wetlands. The watershed comprises three major 8-digit hydrologic unit codes in the U.S. (St. Clair, Clinton, and Detroit) and three major tertiary Canadian sub-watersheds (Upper Thames, Lower Thames and Sydenham). Approximately 78% of the watershed's agricultural land is located in Canada, and 83% of the watershed's urban land is in the U.S. About 67% of the Canadian and 55% of the U.S. agricultural areas are intensively drained through subsurface drainage systems, also called tile drains (Dagnew et al., in review). Except for the Detroit sub-watershed, drained mainly by Rouge River, all sub-watersheds eventually drain into Lake St. Clair, which also receives P load from Lake Huron via the St. Clair River. Outflow from Lake St. Clair and the Rouge Rivers flow into the Detroit River and ultimately to Lake Erie. For the model, the watershed was divided into 800 subbasins and 27,751 hydrologic response units (HRUs) with average areas of 24 km^2 and 69ha, respectively. HRUs were constructed explicitly to capture farm boundaries (Kalcic et al., 2015; Teshager et al., 2016) to allow for more realistic simulation of farm management strategies than lumping multiple fields with potentially different management as one modeling unit. The simulation period of our analysis, 2001-2015, included normal, wet and dry years. For example, the annual precipitation varied from740 mm in 2002 to 1200 mm in 2011 (Figure 2) with a standard deviation of 126 mm. There was also spatial variation of precipitations, ranging from 684 mm to 1101 mm with the standard deviation of 84 mm, with substantially higher values in Canada (Figure 2).

Methodology

Defining the baseline model and management strategies

We used the SWAT2012 rev635 version of SWAT, which was previously used to calibrate and validate flow and water quality for years 2001-2015 (Dagnew et al., in review) at six locations (Figure 1). Based on Moriasi et al. (2007) criteria, monthly flow statistics for both calibration and validation periods were judged as "very good" in terms of percent bias (PBs) at all six calibration locations. The Nash-Sutcliffe Efficiency coefficient (NSe) values were rated "very good" for the Thames and Sydenham River outlets, "good" for Black and Rouge River outlets, and "satisfactory" for Clinton River outlet during calibration periods and "very good" for all six calibration sites during validation periods (Table S1). Monthly water quality statistics were also rated mainly "very good" in terms of PBs and "good" or "satisfactory" in terms of NSe for most locations, with few unsatisfactory values (Table S2).

The baseline model has fertilizer application rates (Table S3) representing 2016 conditions. Fertilizer and manure were assumed to be broadcasted on the surface and incorporated through tillage practices for all crops and were applied in spring before planting of corn and soybeans. Three types of tillage practices were implemented across the watershed: conventional, conservation, and no-till (refer to Dagnew et al., in review for details). Data for the spatial distribution of tile drainage were available for Canada (OMAFRA, 2016), whereas for the U.S., tiles were assumed to be implemented in all agricultural lands with poorly drained soils. Due to lack of additional information, U.S. tile drainage systems were implemented with uniform depth and spacing but were varied based on soil types in Canada based on stakeholder advisory group feedback (Table S4). No other management practices, such as filter strips, grassed waterways, wetlands or cover crops were included in the baseline model, due to lack of available data.

According to the calibrated baseline model, the watershed delivers, on average for 2001-2015, 1756 and 746 MTA (metric tonnes per year) of TP and DRP, respectively to the St. Clair – Detroit River system (Table 1). Maccoux et al. (2016) estimated the TP value at ~1925 MTA for 2003-2013 and the DRP load at ~930 MTA for 2009-2013. Scavia et al. (2019) also estimated average TP load of ~1745 MTA for 1998-2016 in to the system. Differences in these estimations were attributed to lack of more frequent water quality data, difference in estimation techniques and years considered for averaging (Dagnew et al., under review). From the above baseline model estimated total loads, 53% (52%) and 47% (48%) of TP (DRP) comes from the U.S. and Canada, respectively. Canada contributes 67% of TP and 78% of DRP loads from non-point sources (NPS), and 13% and 12% of TP and DRP loads from point sources (PS). In contrast, the U.S. contributes 13% of TP and 12% of DRP from NPS, and 87% and 88% of TP and DRP, respectively, from PS. Overall, 65% of the TP load and 55% of the DRP load comes from NPS, and 85% of the NPS load comes from agricultural runoff. While PS account for 35% of the TP load and 45% of the DRP load, 75% of the PS loads comes from one source (the Great Lakes Water Authority – Water Resource Recovery Facility, GLWAF). That point source has already reduced its loading by about 50% from the 2008 level (Scavia et al., 2019), and while additional reductions are possible, our focus herein is on NPS runoff contributions. We report deviations from this baseline for each sub-watershed for each of the following scenarios.

Scenario development

Scenarios were constructed by altering the rate and placement of fertilizer and manure application, the extent and type of tillage, filter strips, grassed waterways, controlled drainage, cover crops, wetlands, and suburban management practices, based on stakeholder advisory group feedback. Two types of scenarios were run for the same years as the baseline (2001-2015): alterations in single practices and alterations in multiple, or bundled, practices. The single practice scenarios were used to confirm that the model responds as expected, to explore the system's sensitivity to these practices, and to inform the bundled scenarios.

Single-practice scenarios - In the single practice scenarios (Table S5), fertilizer application rates (***Rate***) were altered by reducing them 10%, 20%, 30%, 40%, and 50% from the baseline rates. For fertilizer placement (***PL***) scenarios, 25%, 50%, and 80% of fertilizers were applied in the subsurface. Wetland (***WT***) scenarios assumed that wetlands of sizes 0.5%, 1.0%, 1.5% and 2.0% of a sub-basin area, and that 10% to 100% of the sub-basin area drained to the wetlands in 10% intervals. The filter strip **(*FL*)** scenario added strips that covered 1.7% of an HRU area, with 50% of the HRU drained to the most concentrated 10% of the filter strip area of which 10% is fully channelized flow; this was assumed to simulate a filter strips of medium quality. **Grassed waterways** were placed along one side of each HRU with an assumed average width of 10 m, depth of 4.7% of the width, and a slope 0.75 times the HRU slope. One scenario applied both filter strips and grass waterways as described above. **Controlled drainage** was simulated by reducing tile depth from the baseline by 50% for mid-June through September and 75% for November through March (Figure S1). Tiles remained at the baseline depth for April through mid-June, and October. Cereal rye was planted as cover crop (***CC***) after corn, soybeans, and winter wheat.

Bundled scenarios - The bundles were chosen based on discussions and recommendations from the project advisory group, which consisted of agriculture, policy, and science experts from the U.S. and Canada (http://tinyurl.com/zusf4sx). Five sets of bundled scenarios (Table 2), each with three management practices, were evaluated. Within each bundle, four combinations were simulated with two or three practices. These combinations were applied in all applicable areas, assuming all agricultural lands as applicable areas for all practices except wetlands, which are assumed to fit within any subbasin and drain water from all its land areas. In addition, five bundles were tested under three adoption assumptions: (1) applied to all applicable areas, (2) applied randomly to 55% of applicable areas, and (3) targeted to the 55% of applicable areas with highest TP or DRP yields (Figure 3). For bundles that altered fertilizer rates, a 25% reduction from baseline values was used. For wetlands, we assumed that 1% of the sub-basin area was dedicated to it and that 50% of the water leaving that sub-basin passed through the wetland.

Urban/suburban scenarios **-** Two urban/suburban scenarios were also simulated for the Rouge and Clinton River sub-watersheds. In one scenario we simulated 5%, 15%, 25% and 50% reductions in impervious surface area simulated as non-vegetation measures representing the effect of increased infiltration, which is similar to practices such as increased pervious pavement. In the second scenario, impervious surface area reductions were simulated as increases in vegetation representing the effect of increased infiltration combined with increased evapotranspiration, which is similar to practices such as rain gardens and vegetated swales.

Results and Discussion

Single practice scenarios

Single practice scenarios performed as expected and provided boundaries and contexts for the bundled scenarios. TP and DRP flux from the agriculture-dominated sub-watersheds (Sydenham and Thames) decreased with decreasing fertilizer application rates (Figure 4). The DRP flux responded more than TP because fertilizers are applied in forms that more readily contribute to dissolved loads. The Sydenham was more responsive to changes in fertilizer application rate than the Thames for both TP and DRP. For example, for a 10% reduction in application rate, TP load was reduced by 5% and 3% and DRP load was reduced by 7% and 6% for the Sydenham and Thames, respectively. Similarly, the boundary-pushing and unlikely 50% reduction in application rate led to 23% and 15% load reductions for TP and 32% and 25% for DRP for the Sydenham and Thames, respectively. These results are similar to Her et al. (2016) assessments on effects of conservation practices implemented by USDA (US Department of Agriculture) programs, where 10% and 20% reduction in fertilizer application rates resulted in 4.2% and 8.1% TP load reductions at the field level. The difference in reduction between Sydenham and Thames could be attributed to the former having a higher percentage of cropland area and extent of tiled cropland (Table 1). As expected, there was little change in flux from sub-watersheds dominated by urban and suburban areas (Clinton and Rouge River sub-watersheds). Though mainly agricultural, the Black River sub-watershed was not as responsive as the Sydenham and Thames, most likely, because its baseline fertilizer application rates are much lower than that of Sydenham and Thames (Table S3). Because the cropping system in the Black River sub-watershed is similar to that in Canada, lower P fertilizer application rates in the Black resulted in relatively low level of P in the soil, which in turn resulted in low P yields. Hence, reducing fertilizer application rates from these already low levels would not affect phosphorus yields significantly, but would rather limit crop growth.

For the other single-practice scenarios, TP load was slightly more responsive than DRP for most of the sub-watersheds (Figures 4, 5, and S4), likely because many of the common agricultural conservation practices target surface losses. For the 1.0% wetland scenario (ca. 24 ha of wetland for each subbasin) that simulated half of each subbasin area draining into the wetland, TP load reduction ranged from 12% for the Rouge to 28% for the Sydenham (Figure 4). Except for the Black sub-watershed, DRP reductions were similar, ranging between 15% and 24%. Increasing the size of wetlands from 0.5% to 2.0% of each subbasin area increased the TP load reduction by about 7% (Rouge) to 19% (Thames) when fifty percent of the area was drained through the wetlands or 13% (Rouge) to 27% (Sydenham) when 100% of the area was drained through the wetlands (Figure S2). Similarly, DRP load reduction was increased by about 9% (Rouge) to 21% (Sydenham) when fifty percent of the area drained through the wetlands or 17% (Rouge) to 27% (Thames) when all of the area drained through the wetlands (Figure S3). There appeared to be a saturation point such that above a certain drainage area for a given wetland size there is no or little phosphorus loads reduction. This is more apparent for DRP loads. For example, in the 0.5% wetland size scenarios, draining more than 40% of the area through wetlands in Sydenham sub-watershed did not result in additional DRP load reduction. This is likely because the capacity of a wetland to absorb nutrients is limited by its volume and the settling velocity of the nutrient. This system overwhelming is also illustrated for the Black River sub-watershed that showed an increase in DRP load if more area is drained into the wetlands beyond the saturation level.

Similarly, filter strips (sizes of about 1.2 ha of each HRU) affected TP and DRP with reductions ranging between 20% (Clinton) and 39% (Sydenham) for TP and 18% (Clinton) to 37% (Rouge) for DRP. For sub-watersheds with relatively low NPS DRP loads (Rouge, Black and Clinton), DRP was reduced at a similar rate to TP, indicating that the properties of filter strips simulated in this study work well for lower levels of phosphorus loading. On the contrary, the high DRP loading sub-watersheds (Sydenham and Thames) would probably need larger or more effective filter strip designs for more DRP reduction. Grassed waterways (sizes of about 0.8 ha of each HRU) were much less effective in terms of DRP reduction than filter strips (Figure 5), even when combined with filter strips (Figure S5). The TP reduction from grassed waterways, on the other hand, were equivalent to filter strips, indicating that grassed waterways are more effective for particulate phosphorus. Implementation of both grassed waterways and filter strips produced insignificant additional phosphorus reduction compared to filter strips alone. Hence, given the need to reduce both TP and DRP in this sub-watershed, filter strips would be preferred over grassed waterways.

Subsurface placement of fertilizers reduced TP (DRP) loads by up to 35% (33%) for Sydenham, and 29% (30%) for Thames sub-watersheds (Figures 5 and S4). Phosphorus load reduction responded roughly linearly with increasing fractions of fertilizer placed in the subsurface (Figure S4). This scenario has little effect in the Black River sub-watershed. Taken with a similar response to fertilizer rate reduction scenarios, the Black River sub-watershed does not appear to respond well to nutrient management scenarios commonly applied in the 4R nutrient reduction strategy. As expected, the highly urbanized Clinton and Rouge sub-watersheds responded less to these fertilizer application scenarios.

For cover crop scenarios, TP load was reduced by 30% and 23%, and DRP by 24% and 18% for Sydenham and Thames, respectively. Load was reduced by less than 6%, 3% and 1% in the Black, Clinton and Rouge, respectively.

Controlled drainage increased both TP and DRP loads in all cases (Figure S5), with the largest increase in the Sydenham (7.5%), and the Black and Thames increasing by 2-3%. This could be a result of increased surface runoff due to the rise in subsurface water levels. A field scale study in southern Ontario, near the upper Thames areas, demonstrated a similar effect of exacerbating phosphorus loading due to controlled drainage management in agricultural lands (Hanke, 2018). Another field study in Quebec, Canada, also showed increase in phosphorus load after controlled drainage systems, which was attributed to increase in phosphorus solubility due to the shallow water table as a result of the drainage water management practice (Sanchez et al., 2007). While there is some evidence that combining controlled drainage systems with cover crops may have significant impact in reducing phosphorus loss (Zhang et al., 2017), that scenario was not included in this study.

Given that the baseline model had all three types of tillage practices present -- conventional, conservation, and no-till -- applying one of them across the entire sub-watershed did not substantially change the phosphorus load from the baseline (Figure S5). Conservation tillage reduced TP load by about 2.6% for Sydenham and Thames, but had no effect in the other sub-watersheds. The DRP load under conservation tillage was not significantly affected in all of the sub-watersheds. Applying no-till tillage practices in all applicable areas, on the other hand, increased TP and DRP by up to 2.6% and 5.3%, respectively. Previous studies also suggested similar effects of more conservative tillage practices relative to conventional tillage practices. In their studies in Great Lakes watersheds, Joosse and Baker (2011) suggested that adopting various types of conservation tillage (reduced till, no-till, etc.) may have enhanced soluble phosphorus loading and consequently fail to reduce TP. In a snowmelt-dominated Canadian Prairie watershed, Tiessen et al. (2010) also indicated that conversion from conventional to more conservative tillage practices (e.g. no-till) increased TP concentration and load by 42% and 12%, respectively. Recent work has suggested that this is likely due to increased concentrations of phosphorus at the top of the soil profile, which can be counteracted by using subsurface placement in no-till and conservation till systems (Jarvie et al., 2017; King et al., 2015).

Summarizing the single practice scenarios, assuming 100% adoption, highest load reduction was achieved with WL followed by FL, PL, CC, and Rate for both TP and DRP. Grassed waterways performed similar to FL for TP, but were very poor in reducing DRP. Controlled drainage and change in tillage practices had small or negative impact in reducing phosphorus loadings. As a result, WT, FL, PL, CC and Rate were used in the multiple practice bundled scenarios.

Multiple-practice scenarios

***Adoption across the entire watershed* -** This first set of scenarios assumed 100% implementation in applicable areas across the watershed. In the following section, we explore the impact of lower adoption rates and targeting. The first bundled scenario, *PL-Rate* (change in subsurface placement and decrease in fertilizer application rate), resulted in up to 47% reduction in TP and DRP for Sydenham, and 37% and 40% reduction in TP and DRP, respectively, for Thames (Figure 6). Given the single scenario reduction rates for placement, it is clear that *PL* was the primary driver in reducing phosphorus load in this bundled scenario. In the Sydenham, while PL alone reduced TP (DRP) load by about 35% (33%), PL-Rate reduced the loads by 44% (48%). Similarly, in the Thames, PL alone resulted in 29% (30%) reductions for TP (DRP), and 37% (40%) for PL-Rate reductions. As expected, this combination had little effect in the urban sub-watersheds (Clinton and Rouge). As anticipated from the single scenario analysis, the Black River did not respond well for this set of scenarios.

The second set of bundled scenarios added cover crops (CC) to the previous scenario, and it improved TP reduction to 50% and 42%, and DRP to 52% and 44%, for the Sydenham and Thames, respectively (Figure 6). In fact, all three bundles that included *CC* performed well, and the fact that *CC-PL* performed almost as well as *CC-PL-Rate,* implies that reduction in fertilizer rate may not be required if cover crops and subsurface fertilizer placement are implemented.

The third set of bundled scenarios included the placement, cover crops, and filter strips (*CC-PL-FL*). This bundle improved TP and DRP reduction to 63% and 65% for the Sydenham, and 52% and 54% for the Thames (Figure 6). The presence of *FL* along with *PL* and/or *CC* seemed to help reduce phosphorous, mainly TP, in the Black River sub-watershed. Because practices in this bundle scenario were implemented in only agricultural areas, the two urban dominated sub-watersheds, Clinton and Rouge, had the lowest reductions.

The fourth bundle (*CC-PL-WT)* was applied in both agricultural and urban areas. As a result, phosphorous reduction was increased significantly in the Clinton and Rouge sub-watersheds compared to previous bundles. In the previous three bundles, TP and DRP loads were reduced by less than 10% in the Clinton and Rouge. In contrast, with this bundle, TP was reduced by 36% and 29%, and DRP by 34% and 20% for the Clinton and Rouge, respectively (Figure 6). When all three practices (*CC*, *PL* and *WT*) were implemented in the Sydenham, Thames, and Black sub-watersheds, the highest TP reductions were 68%, 58% and 35%, and DRP reduction were 70%, 56%, and 28%, respectively. However, the *PL-WT* combination performed just as well, showing the effectiveness of this combination over the other two practice combinations in the bundle.

The fifth bundle excluded all practices related to fertilizer application management and considered only *CC*, *FL* and *WT*. This bundle illustrates the dominant effectiveness of combining *FL* and *WT* in agricultural sub-watersheds, reducing TP and DRP up to 81% and 83%, 68% and 69%, 61% and 38% in Sydenham, Thames and Black sub-watersheds (Figure 6).

It appears that several combinations of practices could potentially achieve a 40% reduction from the agriculturally dominated sub-watersheds (Sydenham, Thames, and Black), some could achieve over 50% (Figure 6, Table 3) if there was 100% adoption of the practices. As 100% adoption is not likely to be supported, we explored how targeting high-loss areas and including urban strategies could be as effective.

Reduced adoption rates and targeting - As expected, applying the bundles randomly on 55% of applicable areas resulted in substantially lower load reduction (Figure 7). However, targeting the practices on the 55% of the land with the highest TP and DRP yields had almost the same effect as 100% adoption.

A 55% targeted implementation of *CC-FL-WT* could achieve a 50% load reduction in the Sydenham sub-watersheds for both TP and DRP. The Thames may require slightly more than 55% to reach the same reduction levels. The Clinton and Rouge sub-watersheds clearly require other urban/suburban management practices and/or point source reductions to achieve the 40% reduction goal (explored below). The Black sub-watershed, on the other hand, may need 100% adoption to achieve the TP goal, but even that would not reach the DRP target.

In the Sydenham sub-watershed, all bundled scenarios, except PL-Rate for TP, resulted in a phosphorus load reduction of at least 40% at a targeted 55% adoption rate. Similar reduction levels were achieved for the Thames sub-watershed for the *CC-PL-WT*, *CC-FL-WT*, or *CC-PL-FL* bundles. For the other two bundles (*PL-Rate* and *CC-PL-Rate*), 100% adoption may be needed to achieve similar reduction levels in Thames sub-watersheds.

Urban/suburban specific scenarios

TP and DRP load reduction scenarios for from urban- and suburban-dominated sub-watersheds (Rouge and Clinton) indicated that reducing imperviousness through a combination of reducing impervious surfaces and planting trees is much more effective than reducing impervious surfaces alone (Figure 8). This is because increased vegetation not only increases infiltration but also evapotranspiration. As expected, the Rouge sub-watershed responds for these scenarios better than the Clinton to these scenarios, because a larger portion of the Rouge is heavily urbanized with higher impervious surfaces. For a 50% reduction in imperviousness through vegetation measures, TP and DRP reduction of 35% and 41% in Rouge, and 12% and 20% in Clinton were simulated. However, because the NPS TP loads from the Clinton is about three times that of Rouge, the actual TP load reductions are equivalent. These urban scenarios and previous agricultural scenarios indicated that adoption of both set of scenarios (urban and agricultural) is needed to achieve larger phosphorus reduction rates, especially in Clinton sub-watershed.

Conclusions and Recommendations

Single practice scenarios show that reducing the fertilizer application rate, increasing the extent of sub-surface fertilizer application, implanting filter strips, planting cover crops, or increasing the percent of land draining into wetlands substantially reduces TP and DRP loads. As expected, agricultural conservation practices were most effective for the agriculture-dominated Thames, Sydenham, and Black River sub-watersheds, whereas increasing pervious surfaces through added vegetation was most effective for the urban- and suburban-dominated lands (Clinton and Rouge River sub-watersheds). While loads decreased linearly with decreasing fertilizer application rate (Figure 4) and increasing sub-surface application (Figure S4), the impact of wetland drainage area, regardless of wetland size (Figure S2), saturates between 40% and 50% of drained land (Figure 4). A combination of filter strips and grassed waterways were effective across all sub-watersheds, controlled drainage and no-till cultivation increased phosphorus loads by a small amount, and conservation tillage had little effect on phosphorus loading (Figure S5). However, approaching the GLWQA goals with any single practice required both substantial change (e.g., > 50% fertilizer application rate, 60-70% of land draining to wetlands) and adoption across 100% of applicable areas.

In contrast, combining practices led to substantive TP and DRP load reductions at more feasible adoption rates. The most effective bundles (e.g., those producing > 40% load reductions) for the agricultural sub-watersheds were various combinations of cover crops, subsurface fertilizer placement, filter strips, and/or wetlands (Figure 6). However, these bundles were almost as effective without including cover crops. Combinations of subsurface placement and a 25% rate reduction were also effective, but not as effective as the combinations of subsurface fertilizer placement, filter strips, and wetlands. While these bundles were most effective, it is important to recognize the flexibility evident in these results. For example, there are 11 combinations of practices that would reduce TP loads by at least 40% for the Sydenham sub-watershed; 8 for the Thames, and 4 for the Black. Similar options were effective for reducing DRP loads.

It is also important to note that while the above results assume adoption across 100% of the watershed, applying the practices on 55% of the land with the highest TP and DRP yield resulted in comparable reductions (Figure 7), likely at substantially lower costs. This is fortunate because to reach a 40% load reduction from the Detroit River, it will likely require more than a 40% load reduction from these sub-watersheds (Scavia et al., 2019). In constructing a TP mass balance for the St. Clair - Detroit River system, Scavia et al. (2019) estimated that over 50% of the Detroit River load originates in Lake Huron. Because the load from Lake Huron is largely difficult to control, and because that load appears to be increasing due to climate change, it is likely that the load reduction from the sub-watersheds will have to approach 50% or more. Three of the five bundled scenarios approach that level of reduction (Figures 6 and 7) for the Sydenham and Thames sub-watersheds, assuming implementation in all applicable areas. Only one combination approaches that for both the Thames and Sydenham sub-watersheds if the 55% targeting approach is considered.

Finally, while the approach of targeting conservation practices on the 55% highest phosphorus yielding areas produced load reductions comparable to 100% adoption, it should be noted that the targeted areas identified in the model were based on publicly available information. While Dagnew et al. (under review) used various techniques to assign field level practices from the available county or provincial level data (e.g., fertilizer application rates, tillage practices) for model setup and calibration, there is still uncertainty in identifying the highest yielding locations. The absence of information on certain management practices such as filter strips, grassed waterways, wetlands or cover crops in the baseline model may also introduce uncertainties during model calibration and validation which could further translate into the reported scenario analysis in this study. So, while our analysis demonstrates the positive effect of targeting practices, it should not be used to identify those specific areas. In practice, those actions would have to be targeted to high phosphorus yielding areas that have been identified on the ground. To do this there needs to be higher temporal and spatial resolution agricultural management data and stream water quality observations than are generally available. Moreover, given the importance of wetlands in this and similar watersheds as an effective nutrient reduction strategy, SWAT's wetland nutrient processing module should include, for example, transformations among nutrient types, lake stratification options, and the capability of changing nutrient settling velocity over time.

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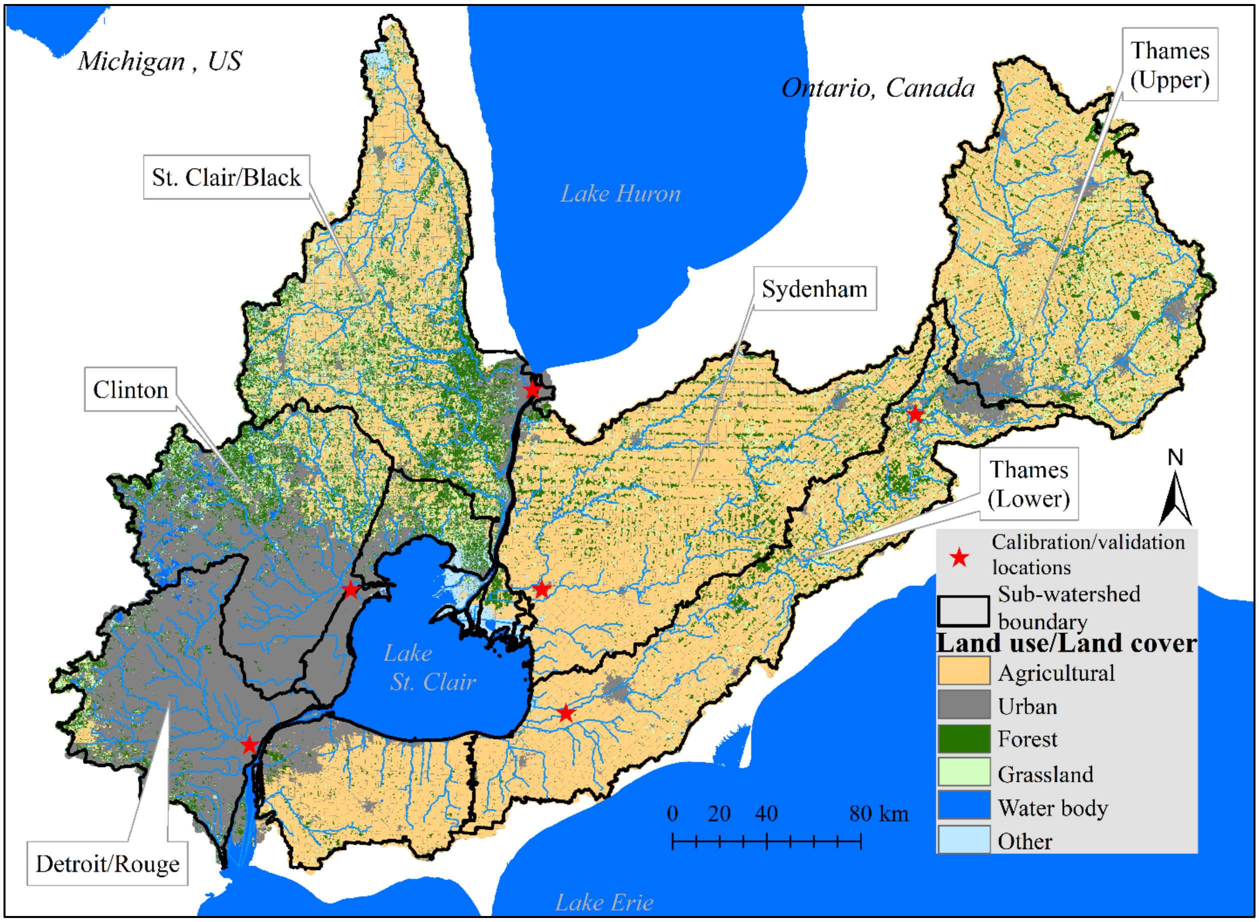

Figure 1: Study area with sub-watershed boundaries. The major six sub-watersheds are labeled in a box. If the major river name is different from the sub-watershed name, the river name was labelled with the sub-watershed name separated by "/". The Upper and Lower Thames sub-watersheds are combined and referred as Thames throughout this study. The channel which connects Lake Huron to Lake St. Clair is the St. Clair River, and the Detroit River connects Lake St. Clair to Lake Erie. Water flows from Lake Huron to Lake Erie through Lake St. Clair.

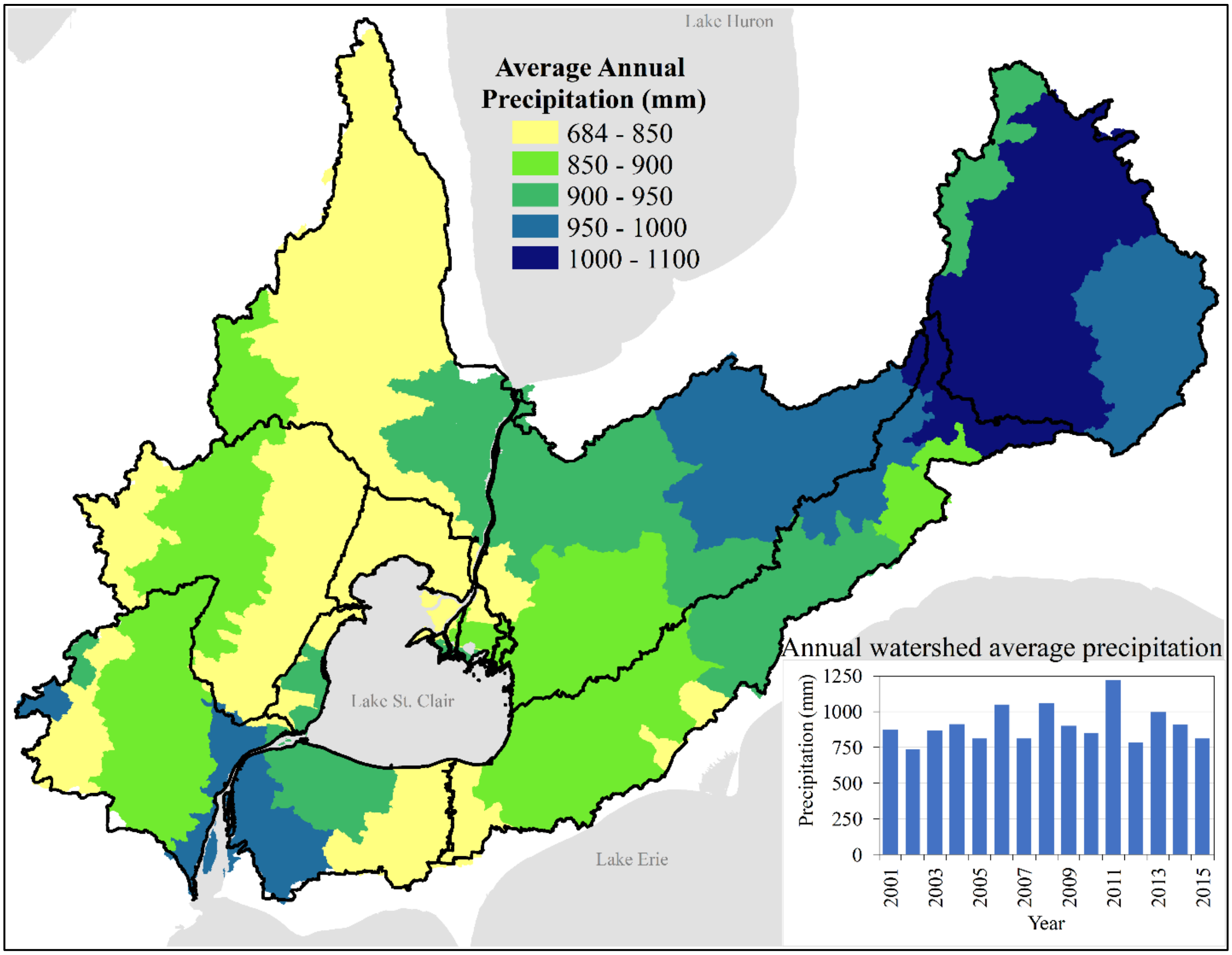

Figure 2: Spatial and temporal distribution of precipitation in the study watershed for year 2001-2015.

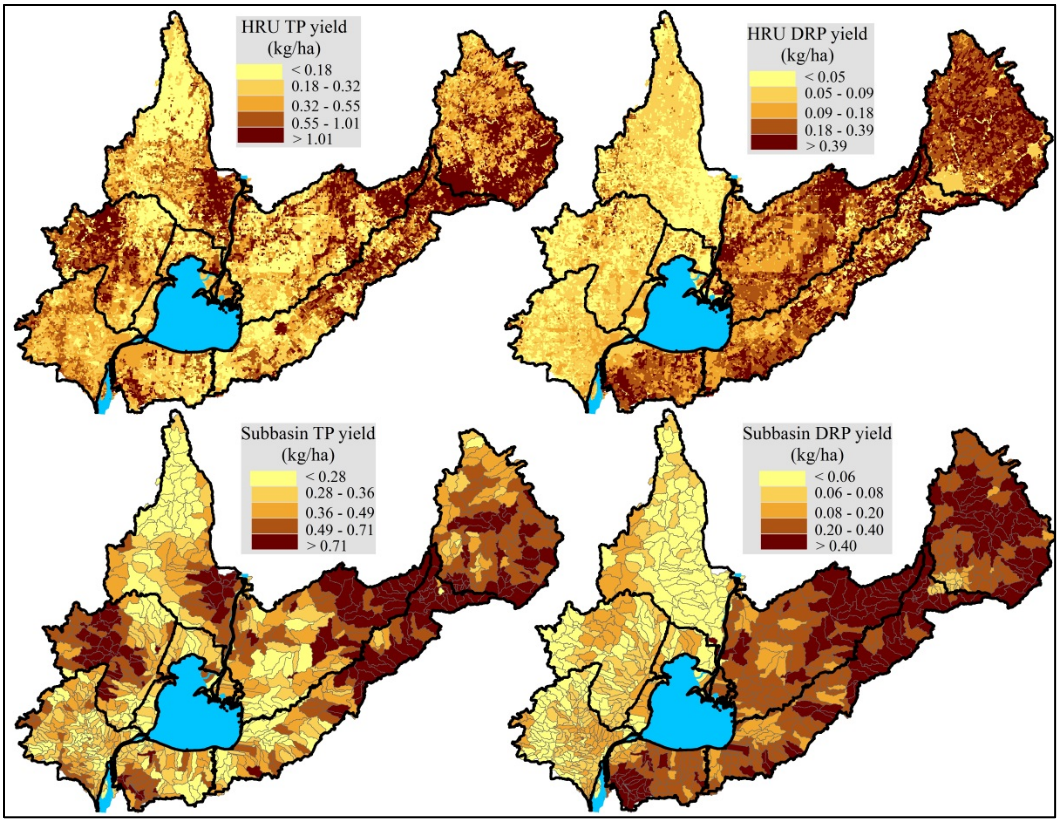

Figure 3: a) HRU-level and b) subbasin-level distributions of non-point source total phosphorus (TP) and dissolved reactive phosphorus (DRP) yields (*Source: Dagnew et al., in review*).

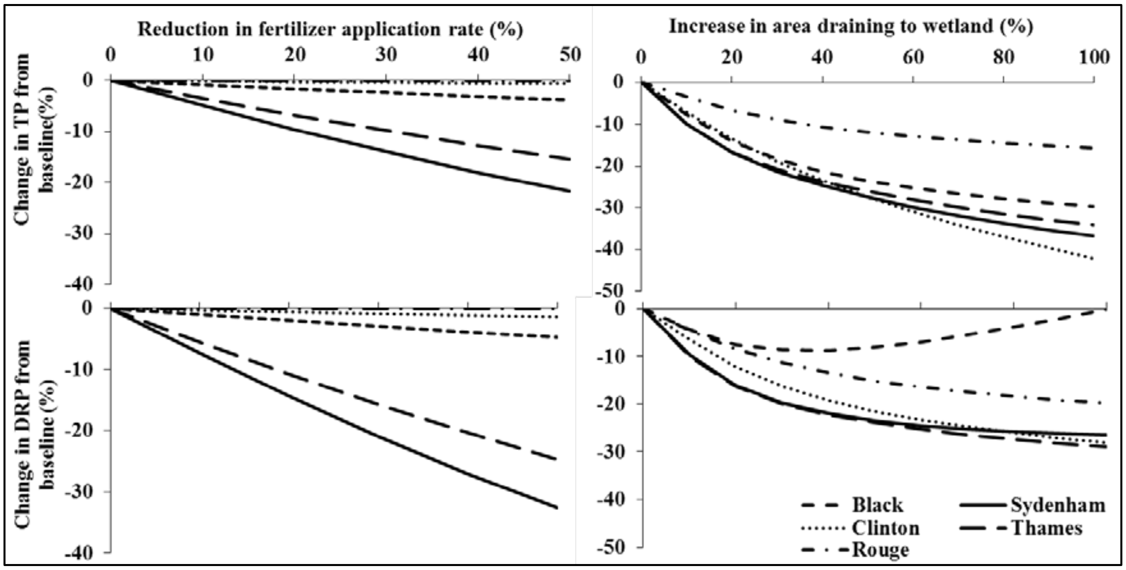

Figure 4: Effects of fertilizer reduction (left) and wetland implementation (right) on total phosphorus (TP) and dissolved reactive phosphorus (DRP) load reductions. Fertilizer rate was reduced in all agricultural lands, and wetlands were implemented in each of the 800 subbasins, assuming conversion of 1% of each subbasin’s area.

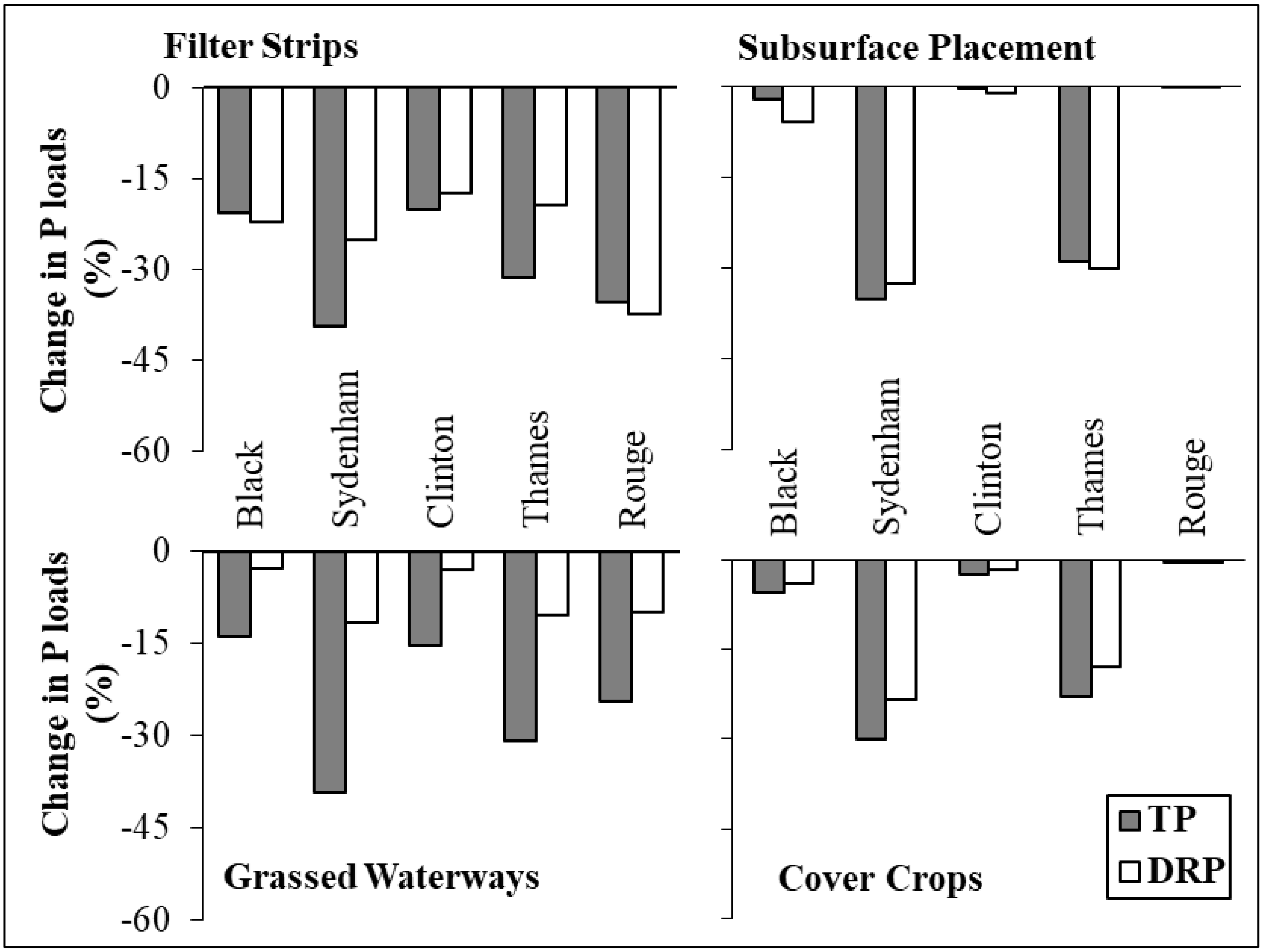

Figure 5: Effects of filter strips (top-left) grassed waterways (bottom-left), cover crops (bottom-right) and subsurface placement (top-right) on total phosphorus (TP) and dissolved reactive phosphorus (DRP) load reduction. All management practices were applied in all relevant areas.

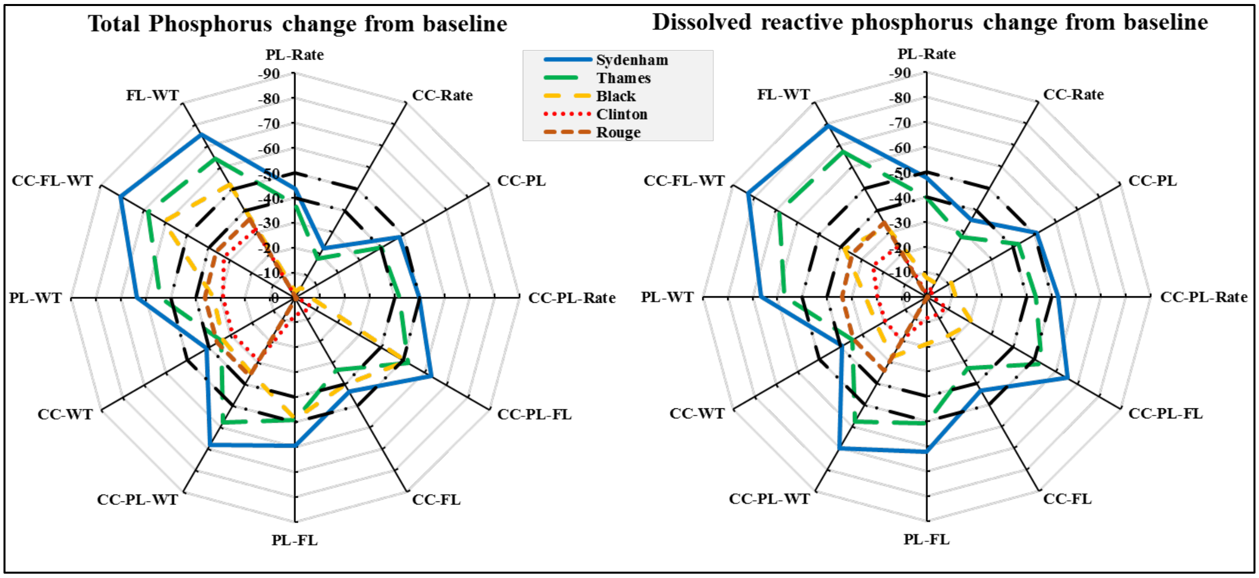

Figure 6: Phosphorus reduction effectiveness of management combination in bundle scenarios. Management practices were applied in all relevant areas (PL=Subsurface placement of fertilizers, Rate=25% decrease in fertilizer application rate, CC=cover crop, FL=Filter strips, WT=Wetlands). Black centerlines indicate 40% and 50% reduction levels.

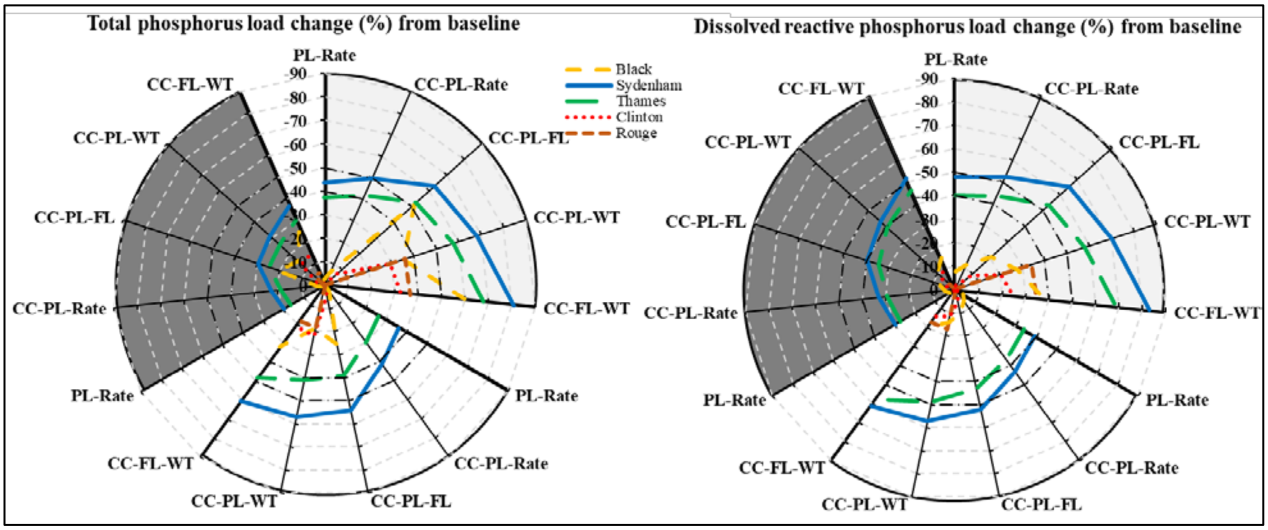

Figure 7: Effects of bundled scenarios at different adoption rates and implementation strategies on phosphorus load reduction. Light-shaded, dark-shaded and unshaded areas indicate management practices applied in all, random 55% and targeted 55% of relevant areas, respectively. Black centerlines indicate 40% and 50% reduction levels. (PL=Subsurface placement of fertilizers, Rate=25% decrease in fertilizer application rate, CC=cover crop, FL=Filter strips, WT=Wetlands).

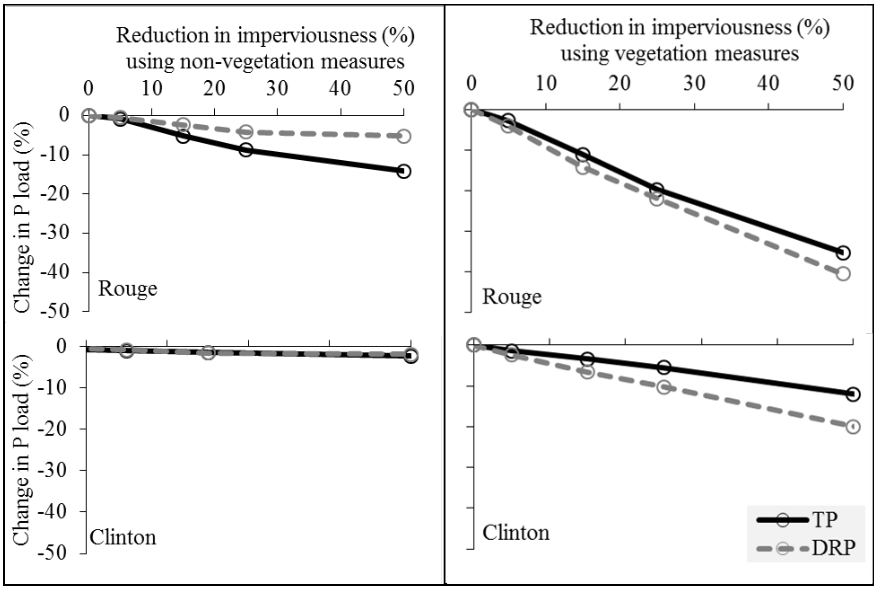

Figure 8: Effects of reduction in imperviousness through non-vegetation (left) and vegetation (right) measures in urban dominated sub-watersheds, Rouge (top) and Clinton (bottom), on total phosphorus (TP, solid line) and dissolved reactive phosphorus (DRP, broken line).

Table 1: Phosphorus load from each sub-watershed (MTA=metric ton per annum, PS=point sources, NPS=non-point sources, TP=total phosphorus, DRP=dissolved reactive phosphorus)

HUC8/Tertiary watershed name	***Major river name***	***Annual load (MTA)***						***Crop land area (%)***	***Tiled (% cropland area)***
		Total PS		***Total NPS***		***Total***			
		TP	***DRP***	***TP***	***DRP***	***TP***	***DRP***		
St. Clair	Black	28	15	150	21	177	36	50	59
Clinton	Clinton	33	18	158	39	191	57	10	46
Detroit	Rouge	492	257	55	30	547	287	2	16
Lake St. Clair	-	5	3	9	1	14	4	-	29
US Total		**558**	**293**	**372**	**91**	**929**	**384**	-	
Sydenham	Sydenham	26	12	201	83	227	95	82	77
Thames	Thames	51	24	472	224	523	248	75	59
Essex	-	6	3	71	16	77	19	-	72
Canada Total		**83**	**39**	**744**	**323**	**827**	**362**	-	
Watershed Total		**641**	**332**	**1116**	**414**	**1756**	**746**	-	

Table 2: Bundle management scenarios set up (* = management practice included in bundle).

Bundle	**Rate**	**Placement**	**Cover Crop**	**Filter Strips**	**Wetlands**
1	*	*			
2	*	*	*		
3		*	*	*	
4		*	*		*
5			*	*	*

Note: Placement = Subsurface placement of fertilizers, Rate = 25% decrease in fertilizer application rate, Wetlands = wetlands of sizes 1% of each subbasin and draining 50% of each subbasin

Table 3: Bundles of scenarios that would achieve a 40% reduction (✓) in each sub-watershed. Dark shed indicates > 60% reduction and light shed indicates > 50% reduction. Management practices were implemented in all applicable lands in all five bundles.

Bundles	Name	Black		Sydenham		Clinton		Thames		Rouge	
		TP	DRP	TP	DRP	TP	DRP	TP	DRP	TP	DRP
1	PL-Rate			✓	✓				✓		
2	CC-PL-Rate			✓	✓			✓	✓		
3	CC-PL-FL	✓		✓	✓			✓	✓		
4	CC-PL-WT			✓	✓			✓	✓		
5	CC-FL-WT	✓		✓	✓			✓	✓		

Note: Bundles 1, 2, 3, 4, and 5 represent PL-Rate, CC-PL-Rate, CC-PL-FL, CC-PL-WT, and CC-FL-WT combinations, respectively, (PL=Subsurface placement of fertilizers, Rate=25% decrease in fertilizer application rate, CC=cover crop, FL=Filter strips, WT=Wetlands).

Supporting Information for

Modeling phosphorus reduction strategies from the international St. Clair-Detroit River system watershed

Awoke Dagnew[a], Donald Scavia[b], Yu-Chen Wang[c], Rebecca Muenich[d], Margaret Kalcic[e]

[a]Environmental Consulting and Technology, Inc., 2200 Commonwealth Blvd, Ann Arbor MI, 48105, USA, +1-734-2720767x23328

[b]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48104, USA, scavia@umich.edu

[c]Graham Sustainability institute, University of Michigan, 214 S. State St., Ann Arbor MI, 48104, USA, +1-734-763-0511

[d]Sustainable Engineering and the Built Environment, Arizona State University, 660 S. College Ave., Tempe, AZ 85281, USA,+1-480-965-1077

[e]Food, Agriculture and Biological Engineering, Ohio State University; 590 Woody Hayes Dr., Columbus, OH 43210, USA, +1-614-292-9356

Correspondence to: Awoke Dagnew, Email: adagnew@ectinc.com,

Table S1: Daily, monthly and annual flow estimation performance statistics for calibration (2007-2015) and validation (2001-2006) years (R^2 = coefficient of determination, NSe = Nash-Sutcliffe efficiency, PBs = percent bias)

Time step	**Statistics**	***Performance values for calibration(validation) period***					
		Upper Thames	**Black**	**Sydenham**	**Clinton**	**Lower Thames**	**Rouge**
Daily	R^2	0.69(0.80)	0.51(0.53)	0.69(0.65)	0.63(0.80)	0.87(0.92)	0.65(0.64)
	NSe	0.68(0.80)	0.43(0.52)	0.66(0.61)	0.53(0.75)	0.87(0.91)	0.64(0.64)
	PBs	0.1(3.2)	9.4(-2.7)	-1.2(8.7)	-2.7(1.9)	-2.7(5.4)	-1.2(-8.5)
Monthly	$\mathbf{R^2}$	0.84(0.93)	0.72(0.76)	0.85(0.87)	0.63(0.80)	0.87(0.92)	0.71(0.78)
	NSe	0.84(0.93)	0.72(0.76)	0.85(0.86)	0.53(0.75)	0.87(0.91)	0.70(0.75)
	PBs	0.1(3.2)	9.2(-2.9)	-1.2(8.4)	-2.7(1.9)	-2.7(5.4)	-1.1(-8.5)
Annual	R^2	0.91(0.97)	0.88(0.78)	0.88(0.89)	0.59(0.92)	0.92(0.94)	0.73(0.94)
	NSe	0.91(0.93)	0.81(0.69)	0.88(0.76)	0.58(0.70)	0.91(0.85)	0.68(0.67)
	PBs	0.1(3.2)	9.4(-2.7)	-1.2(8.7)	-2.8(1.8)	-2.4(5.6)	-1.2(-8.5)

Source: Dagnew et al. (in review)

Table S2: Monthly water quality model performance statistics for calibration (2007-2015) and validation (2001-2006) years. PBs and NSe ratings: **bold** = "unsatisfactory". (TP = total phosphorus, DRP = dissolved reactive phosphorus, TN = total nitrogen, NO_3 = nitrate, TSS = total suspended sediment, R^2 = coefficient of determination, NSe = Nash-Sutcliffe efficiency, PBs = percent bias)

	Statistics	**Monthly statistics for water quality calibration(validation)**					
		Upper Thames	**Black**	**Sydenham**	**Clinton**	**Lower Thames**	**Rouge**
TP	**R^2**	0.54(0.63)	0.54(0.59)	0.75(0.68)	0.64(0.55)	0.62(0.75)	0.73(0.42)
	NSe	**0.48**(0.59)	**0.29**(**0.25**)	0.73(0.62)	0.64(0.54)	0.59(0.70)	0.71(**0.10**)
	PBs	22.6(9.7)	-25.6(-29.1)	5.9(6.3)	5.6(4.8)	18.0(9.6)	-5.0(-4.8)
DRP	**R^2**	0.44(0.59)	0.48(0.50)	0.64(0.57)	0.57(0.51)	0.55(0.65)	0.71(0.49)
	NSe	**0.42**(0.52)	**0.26**(**0.21**)	0.53(0.52)	0.51(**0.46**)	0.52(0.58)	0.70(**0.05**)
	PBs	27.8(12.1)	-28.7(-35.2)	-6.3(-8.2)	9.6(7.8)	21.5(10.9)	25.1(14.8)
TN	**R^2**	0.61(0.65)	0.52(0.55)	0.72(0.65)	0.55(0.54)	0.59(0.66)	0.64(0.53)
	NSe	0.54(0.57)	**0.27**(**0.32**)	0.70(0.61)	0.54(0.52)	0.57(0.62)	0.61(**0.40**)
	PBs	7.8(13.9)	36.4(42.9)	17.9(23.4)	-15.8(-14.6)	-8.0(8.6)	-5.2(-11.4)
NO_3	**R^2**	0.55(0.52)	0.49(0.47)	0.56(0.52)	0.48(0.48)	0.58(0.66)	0.63(0.42)
	NSe	0.53(**0.49**)	**0.25**(**0.27**)	0.54(**0.47**)	**0.44**(**0.42**)	0.53(0.55)	**0.44**(**0.21**)
	PBs	15.6(14.2)	-24.7(-31.1)	5.9(6.3)	-27.3(-23.4)	-3.0(13.6)	-15.1(-24.8)
TSS	**R^2**	0.66(0.77)	0.61(0.62)	0.73(0.67)	0.57(0.63)	0.67(0.70)	0.61(0.68)
	NSe	0.59(0.62)	**0.49**(0.52)	0.57(0.55)	**0.47**(0.57)	0.60(0.65)	0.58(0.60)
	PBs	-7.5(-2.9)	-15.6(-9.9)	14.3(11.6)	-16.5(-12.4)	-12.0(-7.9)	-14.0(-18.4)

Source: Dagnew et al. (in review)

Table S3: Ranges of nitrogen and phosphorus fertilizer application rates in the baseline model for each region of US (shaded) and Canadian sub-watersheds.

Sub-watershed name	Cropland Area (% sub-watershed)	Nitrogen fertilizer application rate (kg/ha)			Phosphorus fertilizer application rate (kg/ha)		
		Corn	Soybeans	Winter wheat	Corn	Soybeans	Winter wheat
St. Clair	50	84.0 - 125.9	9.5 - 16.4	62.2 - 89.7	5.9 - 10.1	4.8 - 6.5	5.7 - 10.9
Clinton	10	82.5 - 112.7	9.5 - 14.7	62.2 - 89.7	5.9 - 8.8	4.8 - 6.3	5.7 - 7.8
Detroit	2	118.8 - 122.5	23.8 - 29.4	90.3 - 93.1	7.6 - 9.8	6.7 - 7.8	7.6 - 9.8
Lake St. Clair	9	84.0 - 107.8	9.5 - 10.9	62.2 - 89.7	6.0 - 7.8	4.8 - 6.1	6.0 - 7.4
Sydenham	82	132.0 - 168.1	3.7 - 4.5	82.3 - 93.5	23.2 - 44.8	7.4 - 11.3	19.4 - 22.0
Thames	75	127.4 - 173.8	3.6 - 4.9	82.3 - 93.5	22.8 - 44.8	9.1 - 13.7	18.3 - 24.4
Essex	79	128.3 - 154.3	3.8 - 4.0	80.9 - 85.0	23.8 - 33.9	7.6 - 8.0	17.1 - 18.0

Table S4: Specifications of tile drainage systems in the baseline SWAT model

	Parameter	**Soil types**		
		Clayey	***Loamy***	***Sandy***
US	***Depth (mm)***	1000	1000	1000
	Spacing (m)	20	20	20
Canada	***Depth (mm)***	650	750	900
	Spacing (m)	8	12	15

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Practice name	ID	Implementation scale	Description
Fertilizer rate reduction	Rate	HRU	Reducing fertilizer rates by 10%, 20%, 30%, 40% and 50% from Table S3 baseline values
Fertilizer subsurface placement	PL	HRU	Applying fertilizer in the subsurface for 25%, 50% and 80% of agricultural lands
Filter strips	FL	HRU	Implementing medium quality filter strips in agricultural areas • Size: 1.7% of HRU area (~1.2 ha on average for each agricultural HRU) • 50% of HRU drain to concentrated 10% of FL • 10% of the concentrated flow is channelized, i.e., not treated by the FL
Grassed waterways	GW	HRU	Implementing grassed waterways in agricultural areas • Width: 10m • Depth: 4.7% of width=0.47m • Slope: 0.75*(HRU slope)
Wetland	WT	Subbasin	Implementing wetlands of different sizes and drainage areas • Size: percent of a subbasin. Multiple percentage values were tested. 0.5%, 1.0%, 1.5% and 2.0%. • Drains: part or all of the subbasin area. 10% to 100% were tested at 10% interval.
Cover crops	CC	HRU	Planting cover crops in agricultural areas • Type: cereal rye, oats or red-clover • planted after soybeans or corn harvests • harvested before planting soybeans or corn
Controlled drainage	CD	HRU	Controlling tile flow during agriculturally inactive seasons • Tile depth reduced by 50% for Mid-June through September, and by 75% for November through March
Conservation tillage practice	Cs	HRU	Applying conservation tillage in all agricultural lands
No-till practice	NT	HRU	Applying No-till tillage in all agricultural lands

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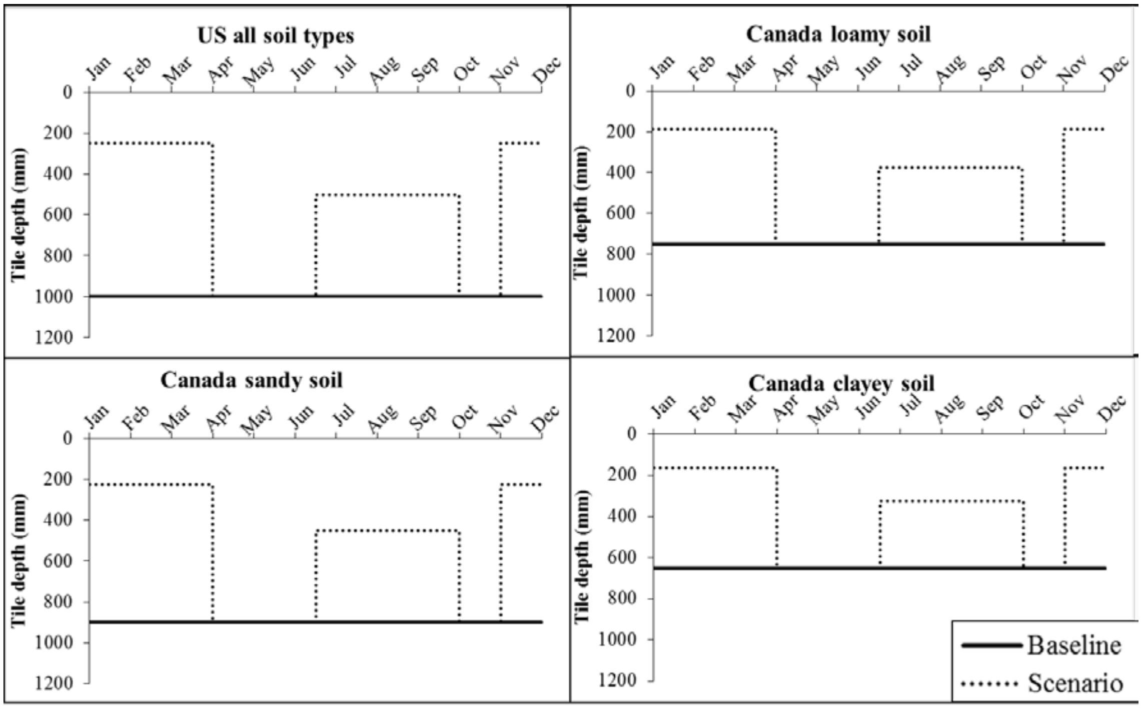

Figure S1: Implementation strategy for controlled drainage system management scenarios.

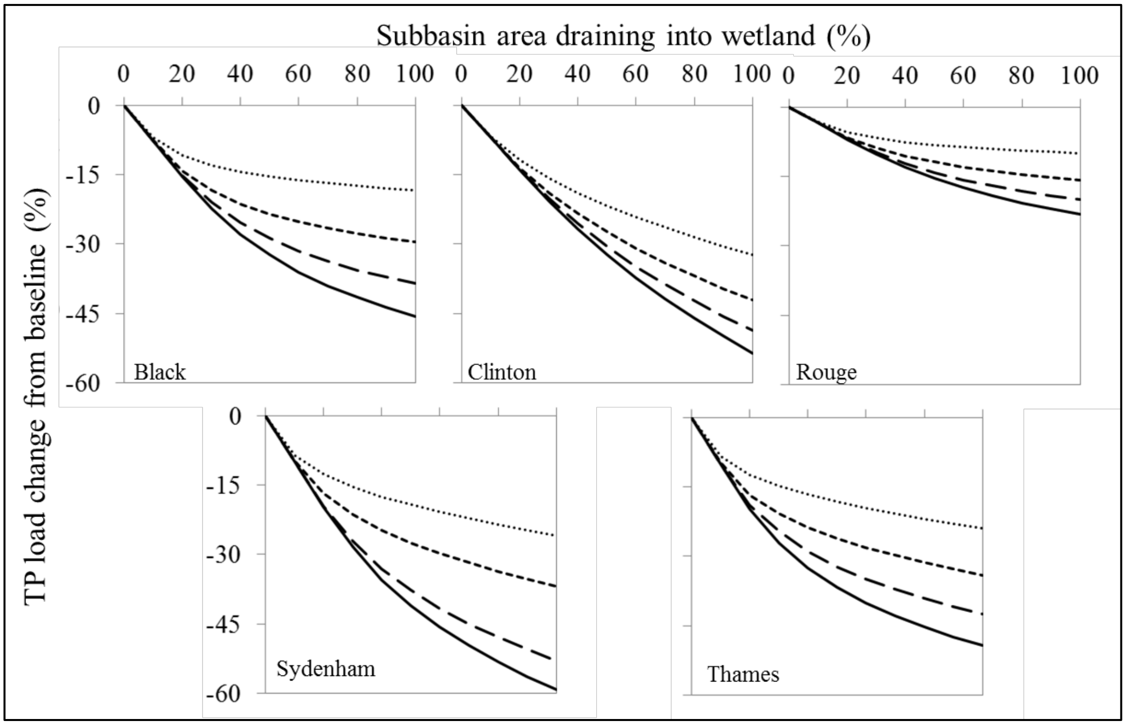

Figure S2: Total phosphorus (TP) reduction for the various sizes of wetlands (solid, large broken, small broken and dotted lines represent wetland sizes of 2.0%, 1.5%, 1.0% and 0.5% of subbasin areas, respectively, which is equivalent on average to 120 acres, 90acres, 60 acres, and 30 acres of wetlands, respectively, for each subbasin)

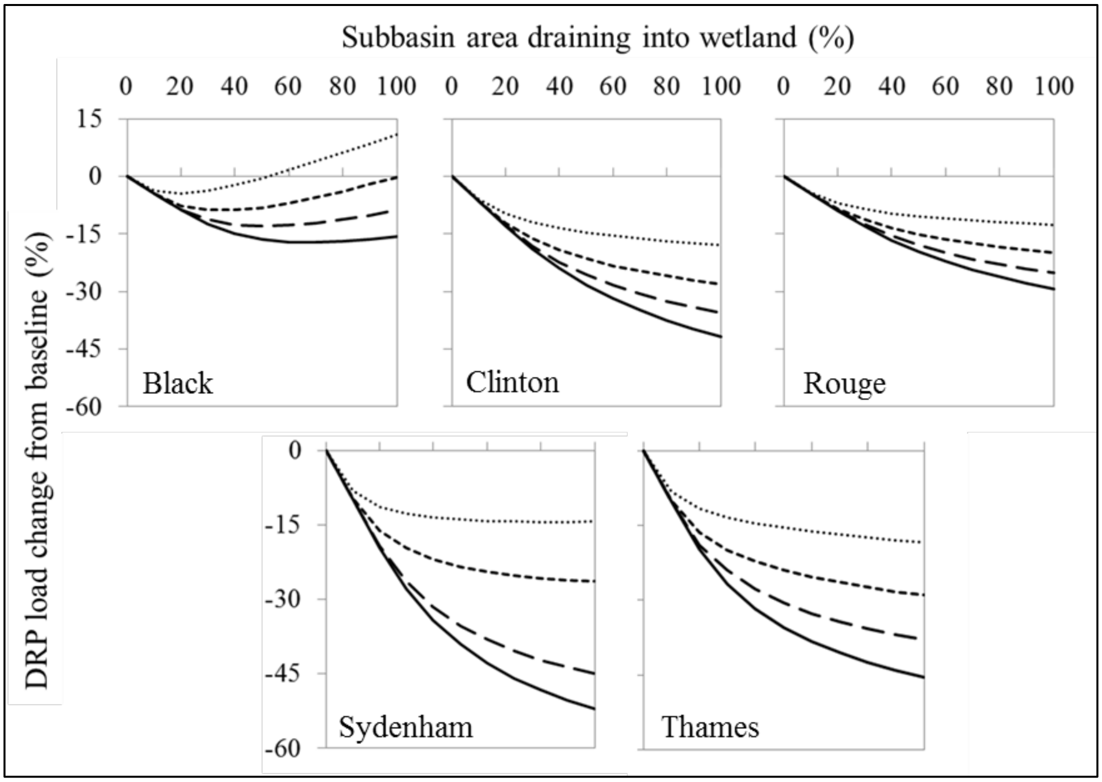

Figure S3: Dissolved reactive phosphorus (DRP) reduction for the various sizes of wetlands (solid, large broken, small broken and dotted lines represent wetland sizes of 2.0%, 1.5%, 1.0% and 0.5% of subbasin areas, respectively, which is equivalent on average to 120 acres, 90acres, 60 acres, and 30 acres of wetlands, respectively, for each subbasin)

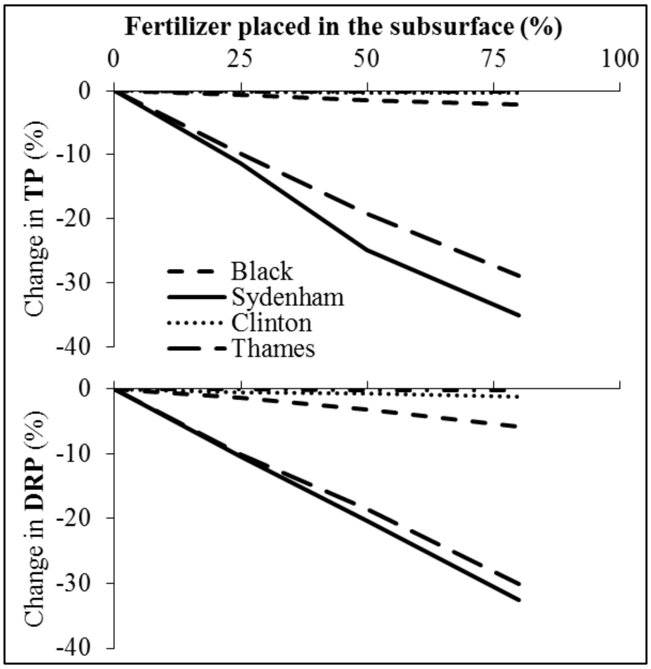

Figure S4: Effects of subsurface placement of fertilizer on total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads.

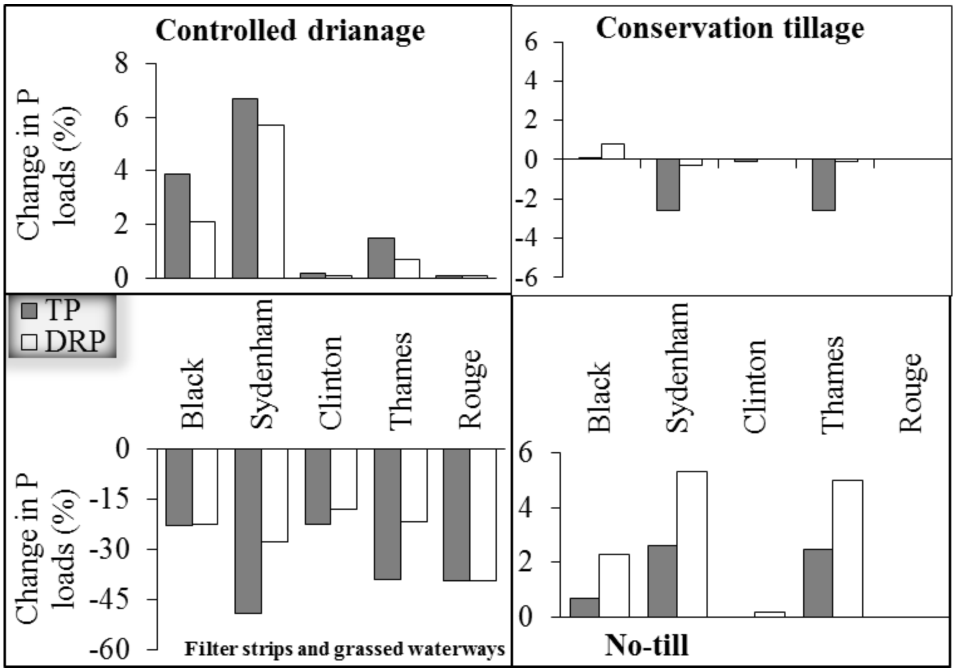

Figure S5: Effects of controlled drainage (top-left), combination of filter strips and grassed waterways (bottom-left), No-till practices (bottom-right) and conservation tillage (top-right) on total phosphorus (TP) and dissolved reactive phosphorus (DRP) load reduction. All management practices were applied in all relevant areas.