A synthesis and comparative evaluation of factors influencing the effectiveness of drainage water management

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Abstract

Viable large-scale crop production in the United States requires artificial drainage in humid and poorly drained agricultural regions. Excess water removal is generally achieved by installing tile drains that export water to open ditches that eventually flow into streams. Drainage water management (DWM) is a conservation practice that allows farmers to artificially raise the outlet elevation of a field's drain tile and can reduce nutrient loss during wet periods by storing more water in the field. We intended to assess the effectiveness of DWM to reduce drainage discharge and nutrient loads and additionally identify predictor variables that influence DWM effectiveness. We compared managed (i.e., DWM) and free draining records using paired t-tests, and identified factors associated with DWM effectiveness using a multiple linear regression approach. T-test results indicated that DWM was highly effective in reducing drainage water discharge and nutrient losses via drain tiles as tile discharge volumes were reduced on average 46%, while tile nitrate loads were reduced by 48%. In addition, total phosphorus and dissolved reactive phosphorus loads were reduced by 55% and 57%, respectively. Based on regression results, we found that several aspects of farm and tile drain management were associated with DWM effectiveness, while site specific landscape characteristics were less likely to predict effectiveness. While DWM is effective as a conservation practice to reduce discharges of water and nutrients from drain tiles, we also identified several knowledge gaps. Future research should investigate effects of DWM on water and nutrients lost in other pathways such as surface runoff, preferential flow, groundwater recharge and biological uptake, and also focus more attention on phosphorus as there is a paucity of research on this topic.

Keywords: Agricultural drainage, Surface runoff, Nitrate-nitrogen, Dissolved reactive phosphorus, Total phosphorus, Water quality

1. Introduction

Consistent and profitable large-scale crop production in the United States has in part relied upon artificial (tile) drainage, as some of the most fertile soils are found in humid climates and are naturally poorly drained (Fausey et al. 1995). Artificial drainage is achieved by installing subsurface pipes (i.e., tile drains) that help to export excess soil water to drainage ditches that eventually flow into streams. While artificial drainage has led to increased crop yields, as well as reductions in surface runoff and associated sediment loss (Skaggs et al. 1982), it has also contributed to extensive alterations in watershed hydrology and increased transport of nutrients from farm fields into surface waters (Blann et al. 2009). Increased nutrient loading to streams degrades water quality leading to eutrophication of marine and freshwater bodies. This promotes harmful algal blooms (HABs) and subsequent hypoxic and anoxic conditions, including those often found in the Gulf of Mexico and shallow portions of the Great Lakes (David et al. 2010, Smith et al. 2015). These water quality impacts degrade biological integrity in streams and receiving waters (Ludsin et al. 2001, Miltner 2010, Weigel and Robertson 2007) and impact ecological services such as safe drinking water and productive fisheries (Breitburg et al. 2009, Ludsin et al. 2001, Smith et al. 2015).

Drainage water management (DWM), also referred to as controlled drainage, is an agricultural conservation practice that allows tile outlet elevations to be managed. By adding and removing control structures such as weir boards, subsurface drainage is restricted or promoted by raising and lowering tile outlet elevations (Frankenberger et al. 2006). Drainage water management is gaining popularity and being increasingly implemented in the Midwestern U.S. and has received considerable attention in the scientific literature (e.g., Adeuya et al. 2012, Fausey 2005, Jaynes 2012). Current estimates of land under DWM are not available; however,

the implementation of DWM is increasing as a result of water quality concerns. Additionally, state and federal cost share opportunities have contributed to increased implementation of the practice (e.g., Environmental Quality Incentives Program; Minnesota's Clean Water Fund). Many studies have documented that this practice can effectively reduce drainage outflow and nutrient loading from tiles across a range of geographic regions (Skaggs et al. 2012). With the growing body of data and information on DWM comes the opportunity—as well as the need—for synthesizing and evaluating the performance of the practice across these studies.

Our main goal is to assess the performance of DWM as a conservation practice intended to reduce losses of water and nutrients (i.e., nitrogen (N) and phosphorus (P)) from tile discharge while also considering subsequent changes in surface runoff due to DWM. In our analysis we:

- 1) compare managed and free draining observations to evaluate the effectiveness of DWM, and
- 2) identify site-specific landscape (e.g., climate, weather, and topography) and farm and tile drain management factors (e.g., nutrient application rate, drain spacing, drain depth, timing of managing tiles) potentially important in influencing the effectiveness of DWM. Our review also takes note of key knowledge gaps that have not been sufficiently addressed in previous studies in an effort to guide future research toward influences of DWM that are currently unclear.

2. Methods

2.1. Literature review and article selection criteria

We searched for both measured and modeled studies evaluating the effects of DWM on water quantity and quality in surface runoff and tile discharge from plots, fields, or small watersheds. For any particular study to be included, it had to assess the influence of DWM compared to free draining tiles, and report quantitative values or easily interpretable graphs of at

least one response variable of interest. We used literature database search engines, primarily Google Scholar and to a limited extent, Web of Science in our literature search. We used a variety of keywords related to drainage control including but not limited to: controlled drainage, drainage water management, and tile drain management. We considered research from any time period located in any tile drained landscapes flowing into a drainage network. We additionally searched for technical reports, symposium papers, and investigated references from both reviews and the selected papers to identify relevant research not initially obtained in our literature search.

Water quantity and quality response variables of interest included: discharge (surface runoff and tile drainage), and annual nutrient loads (nitrate-nitrogen, dissolved reactive phosphorus, and total phosphorus) in both surface runoff and tile drainage.

We had concerns of confounding effects with studies where sub-irrigation was used concurrently with DWM as details regarding implementation of this practice was either not reported (e.g., volume applied) and/or would likely have an influence on drain flow and nutrient loads because of the added water and the increased crop growth due to irrigation. Because of this, we continued to analyze only those observations that did not employ sub-irrigation. All successive methods and results presented will focus on the use of DWM without the use of sub-irrigation.

2.2. Database organization

Depending on how data were reported, we considered individual treatments unique observations within the database. For example, if a study reported the average of multiple plots or perhaps the average annual value over multiple years from a single or multiple plots, we treated this as a single observation (i.e., one single row) within the database. In contrast, if a

study reported individual values from multiple plots or years, we treated these as separate observations within the database to maximize the sample size available for subsequent analyses. To support our first objective, we paired individual observations to be compared for differences. For example, if a study compared free with managed drains across multiple plots or years, but reported each plot or year separately, we paired free and DWM data from each corresponding plot or year.

We calculated the percent (%) reduction from free drainage to DWM from each pair of observations. If a study reported % reduction of a particular response variable of interest, but raw data values used to calculate the % reduction were not clearly reported or were displayed in a coarse graphical format, we extracted only the % reduction for subsequent analyses. Reporting of the % reduction in flow or nutrients as a result of using DWM is common in the literature (Skaggs et al. 2012), and provides a measure of DWM performance that is relative to traditional drainage performance under the same conditions. Additionally, we feel that a standardized % reduction provides a more comparable response variable than raw hydrologic and nutrient load values, given the range of conditions from which synthesized data were collected. Treating % reduction as a measure of performance allowed us to address our second objective which was to identify site specific landscape and farm and tile drain management variables that are potentially important in influencing DWM performance.

2.3. Data analyses

To determine whether the use of DWM was effective in altering water quality and quantity relative to free drainage, regardless of site specific landscape and farm and tile drain management practices, we performed two paired t-tests for each response variable using the

paired observations described above. The first set of paired t-tests only used data from empirically measured studies, while the second set combined measured and modeled studies together. Combining measured and modeled data together provided DWM influences to be synthesized from a larger pool of studies than using measured data alone, and also gave us the opportunity to explore whether impacts from DWM are consistent across each type of investigation. Due to the lack of data characterizing the effect of DWM on phosphorus loads, an *a priori* decision was made to use a significance level of $P \leq 0.10$ for P analyses. As weather patterns and drain management strategies often differ between the growing and non-growing seasons, we also performed separate t-tests on measured tile discharge and tile NO_3N loads for growing season alone, as well as non-growing season alone when data were partitioned between seasons.

We identified potentially important site specific landscape and farm and tile drain management predictor variables from articles discovered through our literature search (Table 1). We wanted to account for differences in study location conditions by gathering a variety of potentially important predictive information ranging from long-term regional characteristics (e.g., mean regional precipitation) to site specific natural (e.g., soil texture) and farm management attributes (e.g., crop type). Predictor variable reduction began by excluding those that had > 30% missing values in our compiled dataset. Next, a Pearson's correlation analysis was performed on the remaining predictor variables to reduce redundancy. If a pair of variables were highly correlated (i.e., Pearson's $r = \text{absolute value} > 0.70$), one was retained based on its ecological relevance (e.g., when highly correlated, precipitation during the study would be chosen over average regional precipitation).

Next, we used a multiple linear regression approach to examine associations between our response variables with site specific landscape and farm and tile drain management factors (i.e., potential predictors). We used % reduction of flow and nutrient loads as our response variables. We performed separate regressions on each response variable to identify predictor variables that are influential in affecting the performance of DWM to reduce discharge of water and nutrients. This approach tests whether statistically significant relationships exist between each response variable of interest with a suite of potential predictors. We argue that significantly associated predictor variables have the potential to affect the ability of DWM to reduce discharge of water and nutrients. We used a stepwise variable selection procedure to identify influential predictor variables, and we used a pairwise deletion approach to missing data. Unlike listwise deletion that only takes into account observations having a complete set of data, a pairwise approach maximizes the available data by considering observations that may have missing data for one or more potential predictors. After we identified predictor variables, we assessed multi-collinearity based on a variance inflation factor threshold of four ($VIF < 4$), and any models with variables exceeding this threshold were not considered for further reporting. Multicollinearity occurs when multiple predictor variables are highly correlated among each other. High multicollinearity among predictors within a regression model can result in increased variation in estimates of regression coefficients for predictor variables. This can lead to unwarranted relationships to be inferred between predictors and the response variable of interest. Variance inflation factors are calculated for each predictor variable, and determine the amount of increased variance in estimated coefficients due to multicollinearity. Rules of thumb regarding the use of VIFs to indicate multicollinearity problems have commonly been suggested as high as 10 (e.g., Hair et al. 1995; Chatterjee et al. 2000), so our threshold of 4 is somewhat conservative. If multiple models

were still available after investigating collinearity issues, we selected the one with the lowest Akaike Information Criterion (AIC) (Akaike 1973) as the best model. The AIC selection approach quantifies the quality of models relative to other models produced with the same dataset. The goodness of fit of a particular model is weighed against the number of predictors included by selecting the one that fits relatively well but contains the least number of predictors. For regression models, this is determined by the equation: $AIC = n * \ln\left(\frac{RSS}{n}\right) + 2 * K$ where n is the number of observations, K is the number of predictors, and RSS is the residual sums of squares. As with the paired t-test analyses, we developed two sets of regression models for each % reduction response variable; one for reductions based off measured observations alone, and one for reductions based off modeled and measured observations combined. We report the proportion of variance explained as R² for models with one predictor variable and as adjusted R² for models with more than one variable.

3. Results

3.1 Literature review

Our literature review initially resulted in 45 studies investigating a variety of topics related to artificial drainage. A number of reasons led to excluding various studies from our review including: the response variable tested was not of interest (e.g., crop yields); DWM + subirrigation was the only drainage treatment tested; or drainage management occurred in open ditches rather than subsurface tiles. After excluding research not suited for this review, we ended up with 17 measured field studies that document the effectiveness of DWM to reduce nutrient loading and drainage outflow from farm fields across a range of geographic regions (Table A.1). For example, annual reductions of nitrate (NO₃-N) and flow within managed drain tiles both

ranged from 60-95% in southern Sweden (Wesstrom and Messing 2007), while 62-96% and 41-95% reductions in tile NO_3^- N and tile flow were observed during two growing-seasons in Ontario, Canada (Lalonde et al. 1996). In the Midwestern region of the U.S., average reductions of NO_3^- N and flow from tiles were 36% and 37% in Iowa (Helmert et al. 2012) and 45% and 40% in Ohio (Fausey 2005). Cooke and Verma (2012) observed flow reductions of 35-96% and NO_3^- N reductions of 37-79% in Illinois. Various versions of DRAINMOD (Skaggs 1978) and the Root Zone Water Quality Model (RZWQM; Hanson et al. 1998) were used in the 11 modeling studies presented in our synthesis, with the majority utilizing DRAINMOD (i.e., 8 studies). Thorp et al. (2008) used a hybrid version of RZWQM combined with elements from the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al. 2003) to simulate the long-term performance of DWM across much of the midwestern United States. The geographic range of the remaining simulations included in our paper also occurred in states across the Midwest including Indiana (e.g., Ale et al. 2009; 2010; 2012a; 2012b), Iowa (e.g., Fang et al. 2012; Ma et al. 2007; Singh et al. 2007), and Minnesota (e.g., Luo et al. 2010). North Carolina was the only non-midwestern state represented in the modeling studies obtained for our review (e.g., Breve et al. 1998).

Relative to nitrogen, little research has occurred on the effectiveness of DWM to reduce phosphorus loads (Figure 1), although the current research is promising. For example, Wesstrom and Messing (2007) found total phosphorus load reductions of 56-95% in managed compared to free flowing drain tiles in southern Sweden. Williams et al. (2015) observed annual dissolved P load reductions from 40-68% in managed drains of Ohio. Further, Feser et al. (2010) found evidence of 50% and 63% reductions of total and ortho-phosphorus loads respectively in managed drain tiles of Minnesota.

The reporting of potentially influential factors was highly variable across all studies reviewed (Table 2). For example, greater than 90% of studies included information on drainage components that have been well-studied in the tile drain literature (e.g., drain spacing, drain depth). To contrast, we found relatively lesser rates (i.e., 30% - 60%) in reporting of some potential predictors important to field hydrology (e.g., restrictive layer depth, precipitation during the study). Surprisingly low rates (< 50%) were observed in other predictors that are known to be important influences on nutrient characteristics (e.g., fertilizer application method and timing) (Johnston and Bruulsema 2014).

3.2. Overall performance of using DWM

3.2.1. Tile drainage and surface runoff volumes

Drainage water management reduced tile flow by 46.3% (+/- 10%) relative to free drainage when considering all measured data (p-value < 0.001; Table 3). For measured and modeled data together, tile flow reductions were strikingly similar averaging 46.6% (+/- 6%) less flow than free drainage (p-value < 0.001; Table 4). Surface runoff was 32.5% (+/- 37%) greater under DWM than free drainage for measured observations (n=12), but this difference was not statistically significant (p-value = 0.08; Table 3). For measured and modeled observations together (n=82), average surface runoff increased by 153.6% (+/- 32%) with DWM and this difference was highly significant statistically (p-value < 0.001; Table 4). Tile discharge was reduced by 43.8% (+/- 14%) and 54.3% (+/- 25%) when considering measured data that was partitioned between growing and non-growing seasons respectively (Figure 2a; both p-values < 0.001).

3.2.2. Nitrate-nitrogen loads in tile drainage and surface runoff

Using all measured observations pooled, DWM was effective in reducing NO_3^- N lost through subsurface drain tiles, with an average reduction of 47.8% (+/- 12%) (p-value < 0.001; Table 3). Including modeled observations resulted in similar results, with DWM reducing NO_3^- N losses by 44.8% (+/- 5%) from tiles (p-value < 0.001; Table 4). Measured NO_3^- N loads (n=10) in surface runoff were not different with DWM (p-value = 0.67; Table 3). The inclusion of modeled observations (n=83) into comparisons of NO_3^- N lost in surface runoff resulted in a 63.9% (+/- 29%) increase with DWM (p < 0.001; Table 4). Tile NO_3^- N was reduced by 57.5% (+/- 28%) and 67.4% (+/- 24%) when comparing measured data that was partitioned between growing and non-growing seasons respectively (Figure 2b; both p-values < 0.001).

3.2.3. Total and dissolved reactive phosphorus loads in tile drainage

Drainage water management was also effective in reducing phosphorus loads being exported through drain tiles (Figure 3). Total phosphorus lost through managed drains was reduced (p-value = 0.004) by 55.0% (+/- 14.9%) while dissolved reactive phosphorus loads were reduced (p-value = 0.06) by 56.7% (+/- 26.4%) (Table 3).

3.3 Associating site specific landscape and farm management practices to percent reductions

3.3.1 Tile drainage and surface runoff volumes

The % reduction of tile discharge was related to three farm and tile drain management variables. Greater relative reductions in tile discharge were associated with narrower drain spacing, deeper drain depths, and when tiles were managed during the non-growing season. Additionally, this model explained a low to moderate amount of variation (p-value = 0.001, R^2 (adj) = 0.23; Table 5). When considering measured and modeled observations together only one

drain management variable, drain depth, was positively associated with % reduction of tile discharge and explained a low amount of variation ($p\text{-value} = 0.04$, $R^2 = 0.04$; Table 6).

No associations were identified between predictor variables and % reduction of surface runoff when considering only measured observations (Table 5). When both measured and modeled observations were considered, % reduction of surface runoff was associated with one site specific landscape and three farm and tile drain management variables. Regional precipitation and drain depth were both negatively related, while outlet depth during the growing season and outlet depth during the non-growing season were both positively related. A moderate amount of variation was explained with this model ($p\text{-value} < 0.001$, $R^2(\text{adj}) = 0.35$; Table 6).

3.3.2 Nitrate-nitrogen loads in tile drainage and surface runoff

The % reduction of $\text{NO}_3\text{^-N}$ in tile drainage water was associated with one predictor variable, considering measured observations only; fertilizer application rate had a negative association with % reduction of $\text{NO}_3\text{^-N}$ lost in tile discharge (Figure 4). A low amount of variation was explained in this model ($p\text{-value} = 0.03$, $R^2 = 0.14$; Table 5). Considering measured and modeled observations together, % reduction of $\text{NO}_3\text{^-N}$ in drain tiles was related to four farm and tile drain management predictor variables. Growing season DWM, drain spacing and fertilizer application rate were all negatively associated (Figures 5a-c), while drain depth was positively related to the % reduction of $\text{NO}_3\text{^-N}$ within drain tiles (Figure 5d). This model explained a moderate amount of variation ($p\text{-value} < 0.001$, $R^2(\text{adj}) = 0.28$; Table 6).

No relationships were evident between predictor variables and % reduction of $\text{NO}_3\text{^-N}$ in surface runoff when considering only measured observations (Table 5). When considering both measured and modeled observations, one farm and tile drain management predictor variable was

related; outlet depth during the non-growing season had a positive association with % reduction of $\text{NO}_3\text{-N}$ loads in surface runoff. This model explained a moderate amount of variation (p-value < 0.001 , $R^2 = 0.25$; Table 6).

3.3.3 Total and dissolved reactive phosphorus loads in tile drainage

The % reduction of dissolved reactive phosphorus was unrelated to any predictor variables used in this analysis (Table 5). We did however relate % reduction of total phosphorus loads in drain tiles with two farm and tile drain management predictor variables; drain spacing and fertilizer application rate, and explained variation was high at R^2 (adj) = 0.73 (p-value = 0.004; Table 5). Percent reductions were greater with more narrowly spaced drains, and when lower fertilizer application rates were applied.

4. Discussion

4.1 Literature review

The use of DWM to reduce losses of water and nutrients is not without limitations. A major consideration is that DWM implementation is generally restricted to flat areas (slopes $< 0.5\%$) or where drainage systems have been installed on the contour so that larger areas can be effectively managed by an individual structure (Frankenberger et al. 2006). All reported slopes in this review were less than 1% (e.g., Jaynes 2012, Lalonde et al. 1996, Williams et al. 2015). Drainage water management also requires a tile drainage system to be available for management, and is most effective where a pattern drainage system exists or is planned (Cooke et al. 2005; Frankenberger et al. 2006).

The reporting of potentially important predictors was highly variable across all studies reviewed. Consideration of missing data while using traditional analytical techniques (e.g., multiple regressions) can be problematic; a challenge similarly noted in a previous DWM review (Amenumey et al. 2009). Skaggs (2016) proposed that drainage research studies should report three standard parameters that characterize the system, which he called the Kirkham Coefficient, drainage intensity, and drainage coefficient. Including these three coefficients in future studies will increase robustness of future comparisons and synthesis. We encourage researchers to report these and as many potentially important factors as possible in their methods or in supplemental materials to allow the reader to investigate potential influences from a suite of important factors. For example, while different fertilizer types, application methods and timing vary in their nutrient use-efficiencies, mobility, and subsequent losses (e.g., Ladha et al. 2005), $\leq 50\%$ of the studies reviewed reported sufficient detail regarding these variables. So, we were unable to test potential influences from these predictors given our statistical methods.

Less focus has been placed on investigating the role drain tiles play in P lost from farms compared to N loss as drain tiles were historically considered a minor factor in P movement (Baker et al. 1975). While recent efforts have illustrated the importance of tile drainage in P transport (King et al. 2015, Kleinman et al. 2015), the literature is lacking on the effectiveness of DWM to reduce P lost through both subsurface tiles and surface runoff. As there is a paucity of research focused on the effects of DWM on P lost in these pathways, there are additionally few studies on the effectiveness of DWM in altering the movement of water and nutrients in various other pathways including preferential flow, lateral flow, biological uptake, and groundwater recharge (Skaggs et al. 2012).

4.2 Hydrology

The effectiveness of DWM to reduce discharge of water from tiles across a range of climates and farm management strategies has long been measured and reported in the literature (Evans et al. 1989, Fausey 2005, Gilliam et al. 1979, Helmers et al. 2012, Lalonde et al. 1996). Empirical research on the influence of DWM on surface runoff has received far less attention as illustrated by our small sample size and insignificant results from t-tests using measured data alone.

The consistency in tile discharge results between measured, and measured and modeled evaluations combined provides strong evidence that modelling of tile discharge is consistent with the empirically measured studies. The inconsistency of results regarding surface runoff volumes could be a result of various factors. First, our synthesis considers data from a number of tile management strategies that have occurred in a range of geographies having a variety of physical soil properties that influence surface runoff (e.g., hydraulic conductivity, water holding capacity). Additionally, there is little empirical research actually measuring surface runoff due to difficulties in measuring water lost through this pathway, so somewhat variable responses due to DWM is not necessarily unexpected. Future research should explicitly quantify surface runoff responses to DWM and be sure to include information about site specific soil properties (e.g., soil type and texture) to help clarify the circumstances where DWM may increase surface runoff. What is clear is that regardless of whether DWM leads to increased surface runoff, any increase is likely, at least an order of magnitude smaller than the reduction of flow through drain tiles (see Mean difference from Tables 3 & 4). This supports the notion that DWM is an effective agricultural conservation practice for reducing discharge of water from farm fields.

We identified non-growing season DWM as having a positive influence on the % reduction of tile discharge when analyzing both measured and modeled data. This result is

supported by our comparison of growing and non-growing reductions separately as a greater % reduction (and raw difference) was observed for non-growing season than growing season data (Figure 2a). This is not surprising as a substantial amount of agricultural runoff can occur during the non-growing season (Stuntebeck et al. 2011) when snow melts and spring rains tend to be frequent. So, more water flowing through drain tiles during the non-growing season should generally provide a greater opportunity to reduce discharge through managed tile drains relative to free draining tiles. As this is also a period when crop production is typically not possible, the outlet depth can be held closer to the soil surface to more aggressively manage the drainage water with little to no risk of negatively influencing crop yields (Skaggs et al. 2012).

Wider spaced drains were associated with lower % reductions in tile discharge while deeper drains were associated with greater reductions using both measured and modeled observations. Both are major components of any subsurface drainage system and in part rely on natural factors such as climate and soil characteristics to determine the proper design. Shallower drain depths have been shown to be an effective means of reducing tile discharge in fields that are not managed with DWM structure (Sands et al. 2008), while wide compared to narrow drain spacing additionally result in less intensive drainage (Kladivko et al. 2004). Our results (i.e., whether using only measured or measured and modeled data) suggest that under DWM, deeper and/or narrower drain spacing provides more opportunity to reduce tile discharge relative to free flowing tiles. This is plausible as both deep tiles and narrow tile spacing more intensively drain the soil in unmanaged systems. Therefore, managing deep vs. shallow or narrow vs. wide drains should result in larger volumes of water being held back and provide greater reductions, given the water table is not flowing over the DWM structure flashboards for extended periods of time.

Considering measured and modeled data together suggested that the use of DWM in climates with higher mean annual precipitation (and presumably wetter seasons) will result in increased surface runoff compared to less wet climates or seasons. The occurrence of surface runoff depends on various factors, including rainfall intensity and antecedent soil moisture (Kim and Lee 2008) with overland flow more likely to occur on previously saturated soils that receive intense rainfall. The use of DWM potentially keeps the soil more saturated (Helmets et al. 2012) so the use of this practice in wetter climates or seasons potentially increases the chance of surface runoff. The outlet depth (i.e., from the soil surface) during both the growing and non-growing season showed a positive relationship with % reduction of surface runoff. This suggests that surface runoff is reduced with a deeper outlet depth. A lower water table should provide more soil space available for infiltration of precipitation and a reduced risk of surface runoff to occur.

4.3. Nutrient loads

Considerable attention within the literature has been focused on measuring the influence of DWM on $\text{NO}_3^- \text{N}$ lost through drain tiles, and results have illustrated considerable reductions (Drury et al. 2009, Tan et al. 1998, Wesstrom and Messing 2007, Williams et al. 2015). Consistency between measured and modeled tile $\text{NO}_3^- \text{N}$ responses to DWM further illustrate the potential of DWM to reduce $\text{NO}_3^- \text{N}$ loading, and emphasizes the consistency of field-scale simulations to predict N loss for both drain management treatments. Substantially greater reductions in tile $\text{NO}_3^- \text{N}$ were additionally observed during the non-growing season compared to the growing season, likely linked to greater reductions in tile discharge (Figures 2a & 2b). Similar to hydrologic comparisons, the small sample size and range of climatic and physical soil characteristics likely resulted in notably variable results for increased $\text{NO}_3^- \text{N}$ loads in surface

runoff. This highlights a need for more research to be focused on surface runoff characteristics to help clarify the specific site parameters that might lead to increased nutrient loading within surface runoff when implementing DWM. Regardless, our results suggest that DWM is an effective conservation practice for reducing $\text{NO}_3^- \text{N}$ loads exported from farm fields as any potential increase in surface runoff loads due to DWM are overshadowed by the reduction of $\text{NO}_3^- \text{N}$ being lost through subsurface drain tiles (see Mean difference from Tables 3 & 4).

A negative association between fertilizer application rate and % reduction of $\text{NO}_3^- \text{N}$ loads from drain tiles was identified whether using measured only, or measured and modeled data. Greater application rates lead to greater proportions of $\text{NO}_3^- \text{N}$ lost from farm fields. If nutrient application exceeds instead of simply meeting crop requirements, it is expected that a greater proportion will be lost whether managed under DWM or free draining. This concurs with previous research on $\text{NO}_3^- \text{N}$ lost in free drainage systems as the greatest fertilizer application rate resulted in greater losses of $\text{NO}_3^- \text{N}$ within drain tiles in Iowa compared to two lower application rates (Jaynes et al. 2001). The negative relationship (i.e., when pooling measured and modeled data) between % reduction of tile $\text{NO}_3^- \text{N}$ loads with both drain spacing and growing season DWM, and the positive relationship with drain depth is plausible as the reduction of $\text{NO}_3^- \text{N}$ from drain tiles from using DWM has typically resulted from reductions in tile flow rather than reducing concentrations (Evans et al. 1989, Gilliam et al. 1979, Helmers et al. 2012, Lalonde et al. 1996, Tan et al. 1998, Wesstrom and Messing 2007). While denitrification is often speculated as being promoted by DWM (e.g., Lalonde et al. 1996), its role in reducing $\text{NO}_3^- \text{N}$ lost through tiles is typically secondary to reduced tile discharge (Wahba et al. 2001). This is partially because the anaerobic conditions necessary to enhance denitrification are promoted to a greater extent using DWM in the non-growing season compared to the growing season as outlets can be

managed more aggressively, thus keeping more soil saturated for longer periods of time. Temperatures are also cooler in the non-growing season, restricting the biological activity necessary for denitrification to occur (e.g., Woli et al. 2010). This mismatch in suitable denitrification conditions that come with implementing DWM have limited this mechanism as a way to reduce $\text{NO}_3^- \text{N}$ loads. As this influence of DWM has generally been consistent, drain system parameters that increase or decrease relative reductions in tile flow should additionally alter $\text{NO}_3^- \text{N}$ loads from tiles.

Lower % reduction in $\text{NO}_3^- \text{N}$ (and flow) is more likely on fields with drains spaced wider vs. narrower or drains installed shallower vs. deeper. Drainage intensity integrates these two variables, along with effective saturated hydraulic conductivity of the profile and depth to restrictive layer (Skaggs, 2016) and provides a parameter to consistently document this. Greater relative reductions are possible when using DWM in fields with higher drainage intensity. Similarly, the negative relationship with growing season DWM is likely because a substantial amount of agricultural runoff occurs during the non-growing season. Comparing $\text{NO}_3^- \text{N}$ partitioned between seasons illustrate that only managing tiles during the growing season will generally result in lower relative reduction in tile $\text{NO}_3^- \text{N}$ loads and flow than if drains were managed during the non-growing season or year round (Figure 2b).

Just as deeper drains were positively associated with reductions in surface runoff volume, a similar relationship was identified with $\text{NO}_3^- \text{N}$ lost in surface runoff (i.e., analyzing measured and modeled data together). Specifically, our results suggest that keeping the drainage outlet deeper in the non-growing season will lead to less increase in $\text{NO}_3^- \text{N}$ loads within surface runoff. This is likely because more intense drainage leads to a lower water table, which also lowers the risk of surface runoff and associated nutrient losses to occur.

While there is promising evidence that DWM can be an effective strategy for mitigating phosphorus losses from agricultural landscapes, we only had 12 observations from 3 studies for total phosphorus and 10 observations from 4 studies for dissolved reactive phosphorus. Analyzing these few data resulted in relatively large standard errors and 90% confidence intervals for the mean difference of P response variables. This gap needs to be addressed with future researchers placing more emphasis on assessing the effects of DWM on P exported from farm fields. Further, the only study we found measuring the influence of DWM on P lost within surface runoff also included sub-irrigation (Tan and Zhang 2011), so the effect of DWM was not possible to determine given our methods. Regardless, the authors of this study found increased concentrations of various forms of phosphorus in surface runoff and tile discharge due to DWM and sub-irrigation. These results demonstrate a need to more thoroughly understand P dynamics for all pathways under DWM including not only surface runoff, but also preferential flow, lateral flow, deep groundwater recharge and biological uptake.

The altered hydrology may also extend the time that the water table is interacting with the topsoil which tends to be rich in phosphorus, especially in agricultural landscapes with a long history of annual fertilizer applications (Mardamootoo et al. 2010). Additionally, elevated water tables for prolonged periods may promote anoxic conditions suitable for reduction of phosphorus bound minerals like aluminum and especially iron (Yaghi and Hartikainen 2013). Both have the potential to increase the mobility of biologically available forms of phosphorus.

Greater relative reductions of total phosphorus loads in drain tiles are possible in fields with lower fertilizer application rates and fields with narrower spaced drain tiles. These results appear to be opposite sides of the same coin; one side suggests that over-application of fertilizer will reduce the effectiveness of DWM to mitigate P losses, potentially due to the management

system not being able to keep up with the amount of fertilizer being applied. The other side of this coin implies that more narrowly spaced tiles provide more intense drainage and greater nutrient export (King et al. 2015). This would allow for more water (and total phosphorus) to be held back by raising tile outlets than in a field with wider spaced tiles.

5. Conclusions

5.1 Review summary

This review illustrates that DWM is an effective conservation practice for reducing drainage outflow and $\text{NO}_3^- \text{N}$ loads to receiving water-bodies in a variety of agricultural landscapes. The greatest potential for DWM to reduce discharge of water and $\text{NO}_3^- \text{N}$ from tiles is during the non-growing season when outlets can be managed most aggressively, and is also when most drain flow often occurs. Reductions in tile $\text{NO}_3^- \text{N}$ are mainly due to reduced tile discharge rather than enhanced denitrification. While intensively managed drain tiles may increase $\text{NO}_3^- \text{N}$ lost with surface runoff, concentrations are much lower in surface runoff and there is little evidence that this increase would overshadow the reductions observed in drain tiles.

5.2 Limitations and future research suggestions

Drainage water management appears to be an effective strategy for reducing P losses through drain tiles. However, there is a paucity of research currently available and this needs further investigation. For example, while the % reductions presented for P are substantial, the actual loads they are based off are quite low, so the effectiveness of DWM to reduce greater P loads could be a topic of future research. Key knowledge gaps on the impact of DWM to affect other flow pathways, particularly surface runoff and associated nutrients (especially phosphorus) lost through this pathway need further attention in the literature. We did not have the ability to

470 assess relationships between DWM and preferential flow paths, which can be a major pathway
471 for P to reach drain tiles in unmanaged systems (King et al. 2015). We additionally did not
472 specifically assess any potential effects of crop type on DWM effectiveness, or influences of
473 DWM on shallow groundwater flow or deep groundwater recharge; all of which warrant further
474 investigation in future studies. Further, we suggest that future research continue to quantify how
475 DWM in combination with other agricultural practices (e.g., sub-irrigation) enhance or inhibit
476 the effectiveness of DWM to reduce drainage water discharge and nutrient loads from farm fields
477 relative to traditional free draining tiles. Finally, continued investigation and comparisons of the
478 potential impact of DWM on hydrology and water quality via large-scale watershed modeling
479 efforts can help save time and money by prioritizing those areas that will benefit most from
480 DWM implementation. So, modeling efforts should continue to provide insight on adoption of
481 this practice in highly agricultural landscapes and the resulting impacts at various spatial scales.

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Table 1. Potentially important predictor variables identified in literature search.

Study setting	<u>Site specific landscape</u>	<u>Farm and tile drain management</u>	
	Site condition context	Farm practices	Tile management practices
General location	Plot area	Crop type	Growing season DWM
Overall study period	Plot slope	Cover crops	Non-growing season DWM
Regional topography	Soil type	Herbicide application	Dates tiles are managed
Regional climate	Soil classification	Tillage practices	Drain diameter
Regional precipitation	Hydraulic conductivity	Nutrient application rate	Drain spacing
Regional temperature	Percent (%) sand	Nutrient application method	Drain depth
Regional evapotranspiration	Percent (%) silt	Nutrient application timing	Drain slope
Growing season	Percent (%) clay		Drainage coefficient
	Precipitation during the study		Growing season outlet depth
	Temperature during the study		Non-growing season outlet
	Evapotranspiration during study		depth
	Water table depths during study		
	Restrictive layer depth		

Table 2. Potentially important predictor variables across all studies used in analyses organized by the rate (% of papers) at which they were reported.

$\leq 25\%$	26% - 50%	51% - 75%	76% - 100%
Drain slope	Drain diameter	Percent (%) sand ^a	Drain depth
Drainage coefficient	Fertilizer application timing	Percent (%) silt ^a	Drain spacing
Evapotranspiration during the study	Fertilizer type	Percent (%) clay ^a	Soil type
Fertilizer application method	Growing season	Fertilizer application rate	Season outlets are managed ^b
Herbicide application	Hydraulic conductivity	Precipitation during the study	Seasonal outlet depths ^b
Regional climate	Plot slope	Soil classification	Cover crops ^c
Regional evapotranspiration	Restrictive layer depth	Dates tiles are managed	Crop type
Regional topography			General location
Temperature during the study			Overall study period
Water table depths during study			Plot area
			Regional precipitation ^a
			Regional temperature ^a
			Tillage practices ^c

^aEfforts were taken to fill in data for these variables when not reported

^bSeason and seasonal refers to growing season or non-growing season

^cIf not reported, we assumed cover crops were not grown and tillage practices were conventional

Table 3. Paired t-test results comparing all measured free drainage (FD) to drainage water management (DWM) observations for hydrology and nutrient response variables of interest. Growing and non-growing season data are pooled together.

Response variable	Mean % reduction ^a	n ^b	p-value	Mean difference ^a	95% CI of mean difference ^c			
					FD	DWM	Lower	Upper
Discharge					mm			
Tile	46.26	58	< 0.001	140.68	304.10	163.42	110.12	171.24
Surface	-32.48	12	0.08	-27.58	84.92	112.50	-59.29	4.12
Tile load					kg ha ⁻¹ yr ⁻¹			
Nitrate-N	47.82	56	< 0.001	13.53	28.29	14.76	10.12	16.94
DRP ^{d,e}	56.74	10	0.06	0.10	0.18	0.08	0.02	0.19
Total-P ^e	54.97	12	0.004	0.07	0.13	0.06	0.04	0.10
Surface load								
Nitrate-N	-13.25	10	0.67	-0.35	2.62	2.97	-1.41	2.10

^aNegative reduction and difference refers to an increase from FD to DWM

^bn refers to the number of paired observations used for comparison

^cCI refers to confidence interval

^d DRP refers to dissolved reactive phosphorus

^e90% CI of the mean difference is presented for phosphorus response variables

Table 4. Paired t-test results comparing measured and modeled free drainage (FD) to drainage water management (DWM) observations of hydrology and nutrient response variables of interest. Growing and non-growing season data are pooled together.

Response variable	Mean % reduction ^a	n ^b	p-value	Mean difference ^a	95% CI of mean difference ^c			
					FD	DWM	Lower	Upper
Discharge					mm			
Tile	46.57	131	< 0.001	128.90	276.78	147.88	112.32	145.48
Surface	-153.59	82	< 0.001	-59.73	38.89	98.62	-72.34	-47.13
Nitrate-N load					kg ha ⁻¹ yr ⁻¹			
Tile	44.84	205	< 0.001	11.61	25.89	14.28	10.23	12.98
Surface	-63.88	83	< 0.001	-0.62	0.97	1.60	-0.91	-0.34

^aNegative reduction and difference refers to an increase from FD to DWM

^bn refers to the number of paired observations used for comparison

^cCI refers to confidence interval

Table 5. Multiple linear regression results using only measured observations to identify relationships between the percent (%) reduction of response variables of interest with site specific landscape and farm and tile drain management predictor variables.

Percent (%) reduction variable	Predictor variable	Predictor sig ^a	Standardized beta (β)	VIF ^b	R ² (adj)	Model sig	Regression df ^c	Residual df ^c	Total df ^c
Tile discharge	Drain spacing	0.001	-0.56	1.85	0.23	0.001	3	54	57
	Drain depth	0.001	0.53	1.75					
	Non-growing season DWM	0.006	0.35	1.08					
Surface runoff	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d
Tile NO ₃ ⁻ N load	Fertilizer rate	0.03	-0.38	1.00	0.14	0.03	1	32	33
Surface NO ₃ ⁻ N load	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d
Total-phosphorus load	Drain spacing	0.002	-0.91	1.20	0.73	0.004	2	7	9
	Fertilizer rate	0.008	-0.70	1.20					
Dissolved reactive phosphorus load	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d	NS ^d

^asig refers to statistical significance

^bVIF refers to variance inflation factor

^cdf refers to degrees of freedom

^dNS indicates that no statistically significant predictors were identified in regression

Table 6. Multiple linear regression results using measured and modeled observations to identify relationships between the percent (%) reduction of response variables of interest with site specific landscape and farm and tile drain management predictor variables.

Percent (%) reduction variable	Predictor variable	Predictor sig ^a	Standardized beta (β)	VIF ^b	R ² (adj)	Model sig	Regression df ^c	Residual df ^c	Total df ^c
Tile discharge	Drain depth	0.04	0.20	1.00	0.04	0.04	1	100	101
Surface runoff	Drain depth	< 0.001	-0.58	1.55	0.35	< 0.001	4	72	76
	Regional precipitation	< 0.001	-0.37	1.18					
	Non-growing season outlet depth	0.003	0.32	1.23					
	Growing season outlet depth	0.03	0.25	1.61					
Tile NO ₃ -N load	Growing season DWM	< 0.001	-0.42	1.10	0.28	< 0.001	4	164	168
	Drain spacing	< 0.001	-0.25	1.03					
	Fertilizer rate	0.01	-0.18	1.10					
	Drain depth	0.02	0.16	1.12					
Surface NO ₃ -N load	Non-growing season outlet depth	< 0.001	0.50	1.00	0.25	< 0.001	1	72	73

^asig refers to statistical significance

^bVIF refers to variance inflation factor

^cdf refers to degrees of freedom

Figure captions

Figure 1. Number of studies obtained for each response variable of interest.

Figure 2. Tile discharge volumes (a) and nitrate loads (b) for managed (DWM) and free draining (FD) treatments partitioned between growing and non-growing season data. Bars represent means $\pm$ 1 standard error, and numbers in parentheses indicate the number of observations for each treatment.

Figure 3. Dissolved reactive phosphorus (DRP) and total phosphorus tile loads for managed (DWM) and free draining (FD) treatments. Bars represent $\pm$ 1 standard error, numbers in parentheses indicate the number of observations for each treatment, and all data are from measured observations.

Figure 4. Univariate relationship between fertilizer application rate (kg/ha) and percent (%) reduction of tile NO_3N loads using only data from measured observations.

Figure 5. Partial regression plots of factors associated with percent (%) reduction of tile NO_3N load when pooling measured and simulated observations together. Partial regression plots represent percent (%) reduction of tile NO_3N as a function of (a) growing season DWM, (b) drain spacing, (c) fertilizer application rate, and (d) drain depth. Axes from partial regression plots should not be interpreted as real life values, but rather are a way to visualize relationships between the response variable with each predictor variable while holding all other predictors included in the model constant.

Figure

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8