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Review

Evaluating best management practices for nutrient load reductions in tile-drained watersheds of the Laurentian Great Lakes Basin: A literature review

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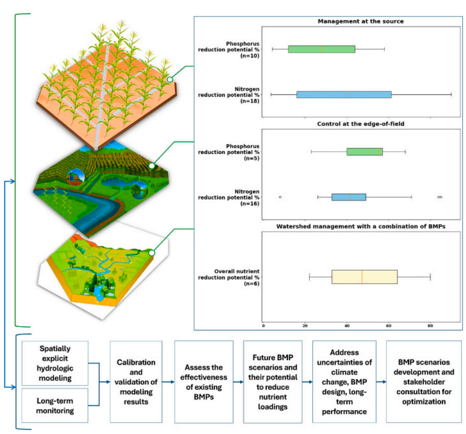
HIGHLIGHTS

- Tile drainage systems substantially contribute to excess nutrient loadings in the Great Lakes Basin
- BMP performance in tile-drain conditions depends on site-specific factors influenced by field and watershed characteristics
- Climate change intensifies nutrient loading from tile-drained fields and watersheds
- Long-term monitoring and advanced hydrologic modeling are critical for evaluating BMP effectiveness and uncertainties
- An integrated and adaptive approach combining multiple BMPs at different scales can substantially reduce nutrient loadings

GRAPHICAL ABSTRACT



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ABSTRACT

Tile drainage systems are extensively implemented across the Laurentian Great Lakes Basin (GLB) to enhance agricultural productivity on poorly drained soils. However, these systems substantially contribute to excess nutrient runoff, particularly phosphorus (P) and nitrogen (N), exacerbating eutrophication and harmful algal blooms in the Great Lakes. This literature review synthesized current knowledge on nutrient loadings from tile-drained agricultural watersheds and evaluated the effectiveness of various agricultural best management practices (BMPs) in mitigating nutrient losses in the GLB. Through a meta-synthesis of field and watershed scale monitoring and modeling studies and statistical analysis using Box-Whisker plots and Monte Carlo simulations, we assessed the nutrient reduction potential of representative BMPs, including cover cropping, nutrient management, controlled drainage, and constructed wetlands in tile-drained landscapes. Findings indicated that

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individual BMPs substantially reduced nutrient loadings, but the effectiveness of these BMPs depended on site-specific factors, including climate conditions, soil type, and drainage system design. Integrated approaches at field, edge-of-field, and watershed scales with a combination of multiple BMPs enhanced nutrient reduction benefits, aligning with regional water quality targets. The review also highlighted the challenges of climate change that may undermine BMP performance by altering precipitation patterns and increasing extreme weather events. To address these complexities, we proposed a framework for developing adaptive BMP scenarios tailored to specific watershed conditions, emphasizing the need for long-term monitoring and hydrologic model enhancements. This framework was designed to help policymakers, stakeholders, and farmers protect water quality and balance agricultural productivity in the GLB and similar agricultural regions globally.

1. Introduction

Tile drainage systems are extensively used throughout the Laurentian Great Lakes Basin (GLB) to enhance agricultural productivity on poorly drained soils. In the United States (U.S.), approximately 22.5 million hectares of cropland are tile-drained, with 83.8 % (18.8 million hectares) situated in six Midwestern states within the Great Lakes region (Valayamkunnath et al., 2020). Similarly, over 50 % of Ontario's arable land utilizes tile drainage systems (Golmohammadi et al., 2021), and tile-drained land continues to expand (Tedeschi et al., 2024). The widespread adoption of tile drainage is driven by its economic benefits, including increased crop yields (Blann et al., 2009; Christianson and Harmel, 2015a, 2015b; King et al., 2015a, 2015b), and its adaptive capacity to address climate impacts by preventing excess water accumulation, facilitating earlier planting, and enabling timely field operations (Mehan et al., 2019).

However, extensive use of tile drainage has substantial environmental implications. It increases nutrient runoff, particularly phosphorus (P) and nitrogen (N), into the Great Lakes, exacerbating eutrophication and harmful algal blooms (King et al., 2015a, 2015b; Macrae et al., 2023; Tedeschi et al., 2024). While excess phosphorus primarily influences the scale and frequency of algal blooms, excess nitrogen affects the toxicity of cyanobacteria blooms, posing additional risks to aquatic ecosystems (Gobler et al., 2016). Wan et al. (2023) reported that Lake Michigan and Lake Erie receive the highest total nitrogen (TN) loadings from U.S. lands, with 62.9 and 61.5 kt per year (kt/yr), respectively. Lake Erie also collects the highest total phosphorus (TP) loadings, followed by Lake Michigan, with 2.4 and 2.3 kt/yr, respectively. Agricultural sources, including manure and chemical fertilizer, dominate these nutrient fluxes, accounting for approximately 58 % to 66 % of nitrogen and 59 % to 67 % of phosphorus inputs from the U. S. portion of the GLB. Excessive chemical fertilizers and manure application on agricultural fields with tile drainage systems significantly increase nutrient transport through these pathways. Tile-drained fields contribute a significant proportion of TN (56 % to 70 %) and TP (30 % to 37 %) transport delivered to the lakes, leading to water quality degradation (Wan et al., 2023). With climate models predicting increased extreme weather events and heavy precipitation in the GLB (Wang et al., 2018; Golmohammadi et al., 2021), reliance on tile drainage systems is expected to grow, underscoring the need for tile-drainage related conservation practices that balance agricultural productivity with water quality protection.

Tile drainage substantially influences water quality in the GLB by altering hydrological pathways and speeding up nutrient transport. By providing direct channels from fields to water bodies, tile drainage contributes substantially to watershed discharge, accounting for 42 % to 60 % of annual watershed discharge in the region (Drury et al., 2014; Boles et al., 2015; Macrae et al., 2023). As a result, tile drainage becomes a major route for nutrient losses from agricultural lands to water bodies. For example, subsurface tile drainage in a corn-soybean field in southern Ontario accounted for up to 97 % of P lost to waterways (Tan and Zhang, 2011). Phosphorus concentrations in tile drainage often exceeded eutrophication thresholds (0.02–0.03 mg/L), reaching up to 8.0 mg/L in Ohio (King et al., 2015a, 2015b). Annual dissolved reactive phosphorus (DRP) loadings from tile flow ranged from 0.01 to 1.34 kg P/ha/yr in Ontario (Esbroeck et al., 2016) and from 0.08 to 2.7 kg P/ha/yr in Ohio (King et al., 2015a, 2015b; King et al., 2016). Similarly, annual nitrate (NO_3–N) loadings via tile drainage varied from 0.4 to 49.9 kg N/ha/yr in Ontario and Quebec (Zhang et al., 2017; Michaud et al., 2019) and up to 133.2 kg N/ha/yr in Ohio (Hanrahan et al., 2020). The elevated export of nutrients through tile flow has been linked to increased algal blooms in the Great Lakes over the past two decades (Kane et al., 2014; Dagnew et al., 2019; Macrae et al., 2023), highlighting the critical impact of tile drainage on nutrient dynamics and regional water quality.

Different best management practices (BMPs) have been implemented in the GLB to mitigate nutrient runoff from agricultural fields. These include conservation tillage (no-till and reduced tillage), cover cropping, nutrient management strategies such as the 4R approach (right source, rate, time, and place), controlled drainage systems, buffer strips, grassed waterways, and wetland restoration (Kerr et al., 2016). Traditionally, these BMPs have focused on reducing nutrient losses through surface runoff. However, recent studies have revealed that these practices reduce nutrient losses associated with surface runoff while less effectively controlling nutrient transport via tile drainage systems (King et al., 2015a, 2015b; Liu et al., 2017; Lintern et al., 2020; Ren et al., 2022a, 2022b). Consequently, despite increased BMP implementation, nutrient loadings from nonpoint agricultural sources remain a persistent challenge, particularly concerning DRP and NO_3–N runoff into the Great Lakes (Drury et al., 2014; Bauwe et al., 2019).

Some BMPs have effectively reduced surface and subsurface nutrient loadings from agricultural fields to streams. For instance, cover crops have been reported to reduce NO_3–N losses by up to 84 % in surface runoff and 62 % in tile flow (Drury et al., 2014; Speir et al., 2022). Controlled drainage has decreased annual NO_3–N loadings by up to 44 % and reduced dissolved P loadings by 40 % to 68 % in tile discharge (Sunohara et al., 2015; Saadat et al., 2018; Carstensen et al., 2019). Nutrient management practices, including precise rate, timing, and placement of fertilizers, along with structural BMPs like wetlands, can substantially reduce nutrient loadings from tile-drained watersheds (Christianson and Harmel, 2015a; King et al., 2015a, 2015b; Lemke et al., 2022). However, the effectiveness of these BMPs can vary depending on site-specific factors such as soil type, topography, and climatic conditions. Further, the effectiveness of some practices may have trade-offs; for example, no-till practices may increase dissolved P (DRP) losses through enhanced macropore flow (Bauwe et al., 2019). Therefore, widespread and combined implementation of multiple BMPs is often necessary to achieve the nutrient loading reduction targets (Merriman et al., 2018), established under initiatives like the Great Lakes Water Quality Agreement (1972, updated in 2012) and the Canada-Ontario Lake Erie Action Plan (2018).

Despite these efforts, substantial challenges persist in understanding the long-term performance of BMPs in tile-drained agricultural landscapes. The Drivers-Pressure-State-Impact-Response (DPSIR) framework (Bodrud-Doza et al., 2023) illustrates the complexity of tile drainage, agricultural nonpoint source pollution, and their control measures in the GLB (Fig. 1, Supplementary Table S1). Current research inadequately explores how BMPs designed to reduce nutrient loadings from surface runoff perform differently in tile-drained fields than non-tile-drained fields or watersheds. There is a critical need to enhance our understanding of tile drainage impacts on the effectiveness of various BMPs and to identify the most effective practices under various local climate and landscape conditions in the GLB. Moreover, it is essential to investigate how these BMPs perform over extended periods under dynamic conditions influenced by agricultural intensification, climate change, and hydrological regimes. These knowledge gaps limit the development of tailored, sustainable BMP strategies crucial for enhancing water quality and agricultural sustainability in these intensively managed landscapes.

Addressing these knowledge gaps is imperative for formulating adaptive management practices that can substantially reduce nutrient pollution while supporting sustainable agriculture in the GLB. Therefore, this review aims to (1) synthesize the nutrient loadings from tile-drained agricultural fields and watersheds in the GLB, (2) assess the performance of various BMPs in field and watershed scales for reducing nutrient loadings in different hydrological, soil, and climatic conditions, and (3) propose a framework for optimal BMP scenario development for effectively reducing nutrient loadings in tile-drained watersheds.

By systematically synthesizing the performance and identifying effective management strategies for BMPs, this review addresses the knowledge gaps that currently hinder the optimization of water resource management in extensively tile-drained agricultural landscapes. The outcomes of this study provide empirical evidence and theoretical insights from recent studies to guide policymakers, stakeholders, and farmers in implementing more effective and sustainable BMPs. Ultimately, this research aims to facilitate the development of adaptive best management practices that can mitigate nutrient pollution, enhance agricultural productivity, and support climate change adaptation and ecological health in the GLB and similar agricultural settings globally.

2. Methodology

We employed a systematic search, appraisal, synthesis, and analysis approach to conduct this critical literature review (Bodrud-Doza et al., 2023). This included performing a robust and comprehensive literature search, analyzing nutrient loadings in tile-drained agricultural landscapes, critically appraising the effectiveness and limitations of current management practices, identifying knowledge gaps, and conducting a meta-synthesis of effective best management practices (BMPs) to outline potential optimal solutions and future research needs. The review aimed to address the question: "How can BMPs be optimized in tile-drained agricultural watersheds of the GLB to effectively reduce nutrient loadings, particularly phosphorus and nitrogen, while balancing agricultural productivity with water quality protection under varying hydrological, soil, and climatic conditions?"

We developed a systematic literature search strategy detailed in Supplementary Table S2 following the methodology proposed by Bramer et al. (2018). The databases used to identify relevant literature included Scopus, Web of Science, Google Scholar, and the Omni Academic Search Tool. The initial search returned 328 relevant articles, including original research papers, review papers, and book chapters written in English, which were organized using Zotero. We then narrowed down the literature items to 116 peer-reviewed published journal articles focusing on the GLB, as presented in Fig. 2, by applying the inclusion and exclusion criteria outlined in Supplementary Table S3.

A meta-synthesis and analysis of the selected 116 articles were conducted using the Preferred Reporting Items for Systematic Reviews

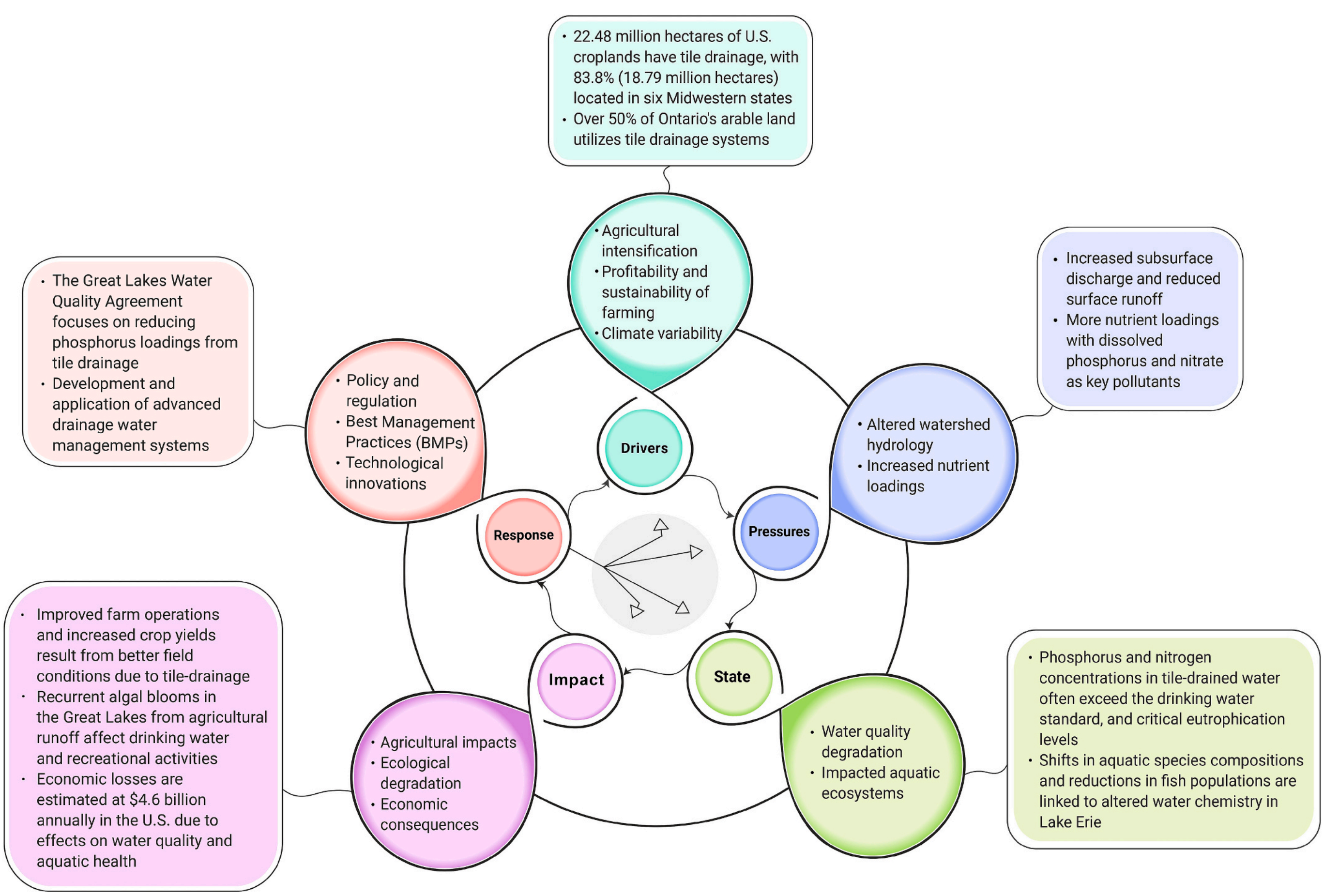

Fig. 1. Drivers-Pressure-State-Impact-Response (DPSIR) framework of tile drainage in the GLB. Supplementary Table S1 compiles a review of the literature that informs the framework.

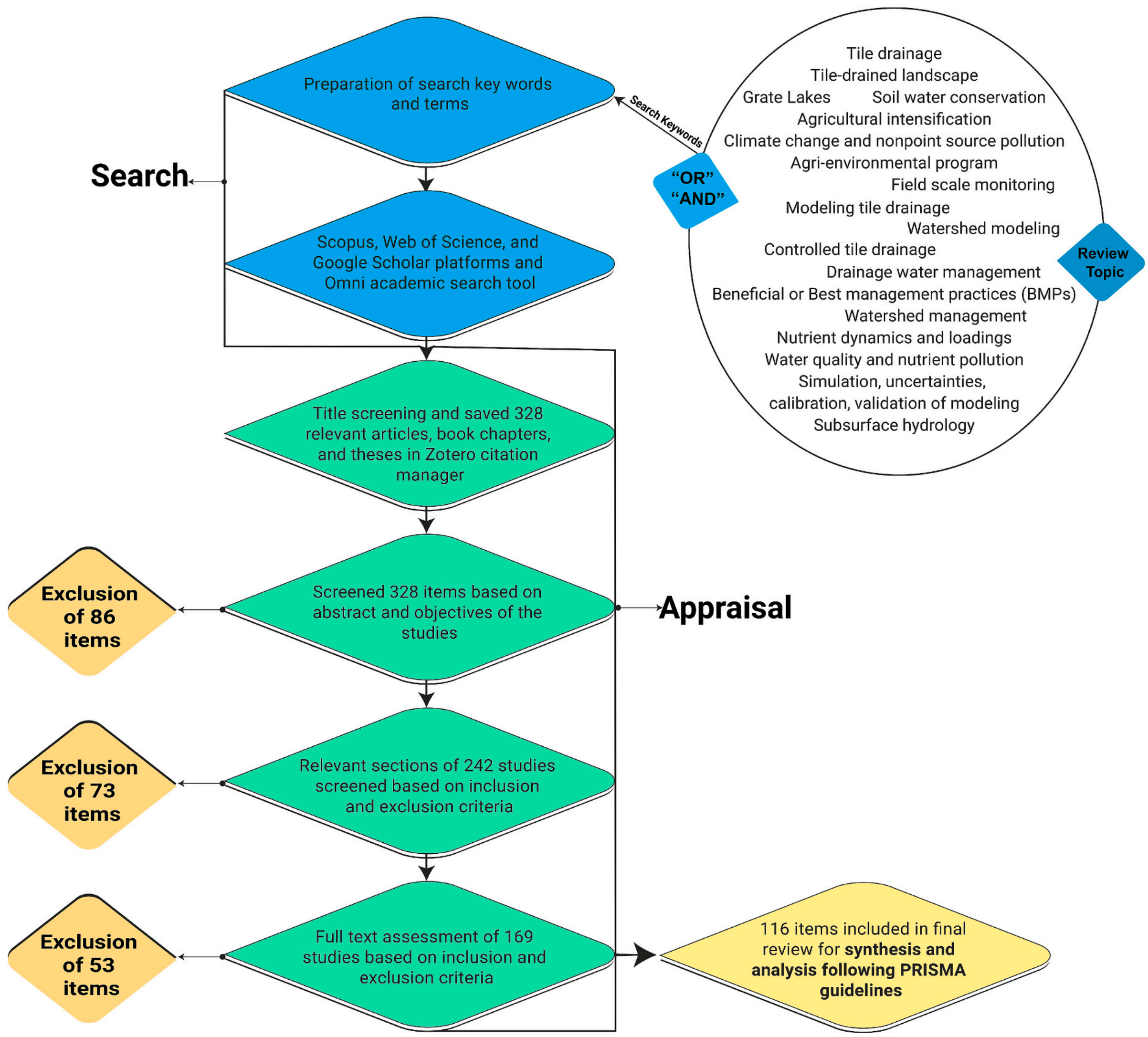

Fig. 2. A workflow of the literature review and article selection process.

and Meta-Analyses (PRISMA) guidelines (Page et al., 2021a; Dsouza et al., 2023). PRISMA is a well-recognized framework that ensures transparency and rigor in the search and selection of studies and in reporting the methodology and findings (Page et al., 2021b). By adhering to this standardized approach, the review process improves clarity and reproducibility, reduces bias, ensures a balanced representation of findings, and enhances credibility (Page et al., 2021c). Following PRISMA guidelines, we extracted relevant data and information from each article on the following parameters:

- Study features: Location, objectives, methodologies, scale, watershed description, tile drain details, land use, soil characteristics, temperature, and precipitation.
- Hydrological data: Surface runoff, subsurface runoff, and tile flow.
- Nutrient loadings: Total phosphorus (TP), soluble/dissolved reactive phosphorus (SRP/DRP), particulate phosphorus (PP), total nitrogen (TN), and nitrate-nitrogen (NO_3–N) in surface runoff and tile flow.
- Best management practices: BMPs mentioned, evaluated, or recommended in the studies, nutrient reduction rates of BMPs, and any remarks or major findings.
- Additional information: Other important data and critical findings cited by the selected studies.

While extracting nutrient loading data, we aimed to collect numerical values in kilograms per hectare (kg/ha). If values were not provided in kg/ha, we recalculated the nutrient loadings based on available data. We also collected numerical values representing the percentage of nutrient reduction to assess the effectiveness of specific BMPs. These literature values were synthesized and visualized using a Box-Whisker plot to represent the distribution of minimum, lower quartile (Q1), median, upper quartile (Q3), and maximum values based upon grouping of BMPs into at the source, edge-of-field, or watershed scales (Krzywinski and Altman, 2014; Faust et al., 2018). To address uncertainties associated with nutrient loadings and BMP effectiveness, the Monte Carlo simulation method was applied (Karamouz et al., 2015). For nutrient loading data, simulated values were generated using a fitted log-normal distribution, which accounts for the non-negative nature of the dataset (Appling et al., 2015). For BMP effectiveness data, simulations were based on a normal distribution to reflect the heterogeneity inherent in the reported effectiveness values (Ding et al., 2023). From the Monte Carlo simulations, we reported the geometric mean (GM) and geometric standard deviation (GSD) for log-normal nutrient loading data, arithmetic mean and standard deviation (SD) for BMP effectiveness data, and 95 % confidence intervals (CIs) (Karamouz et al., 2015). This dual approach ensured robust statistical representation and improved consistency of the findings.

In total, 60 study sites in the Canadian and US portions of GLB and connected states (Neff and Nicholas, 2005) were summarized in

Supplementary Table S4, which includes primary monitoring and modeling-based studies. This table describes the key characteristics of the local watersheds and study sites. Moreover, Supplementary Table S4 connects with other tables to explain the influence of local field and watershed characteristics on nutrient loadings and BMP reduction efficiencies discussed in the article. We identified most sites (about 65 %) in southwestern Ontario, southeastern Michigan, northeastern Indiana, northwestern Ohio, eastern Wisconsin, and parts of upstate New York that drain directly into the GLB. In addition, some studies covered the St. Clair–Detroit River system, the Western Lake Erie Basin, the Maumee River watershed, and various subwatersheds in Ontario, spanning the basin's key tributaries and nearshore areas. Approximately 35 % of sites are from regions outside the GLB (e.g., Iowa, central Illinois, southern Minnesota, and southern Quebec). We included these studies to compare findings on similar agricultural drainage practices, nutrient management, and hydrologic conditions. Findings from these study sites help illustrate broad trends of nutrient loadings from tile-drained landscape and BMP implementation under varied climate and soil conditions, supporting context for interpreting GLB-specific research.

3. Effect of tile drainage on hydrological processes and runoff

Tile drainage has profoundly altered hydrological processes in the GLB by modifying water movement pathways and timing within agricultural landscapes. In the GLB, tile drainage is typically installed in relatively flat terrain with slopes <1 % to 3 % (Wan et al., 2023). Tile depths and spacing are typically measured considering the influence of soil texture, permeability, hydraulic conductivity, depth of the impermeable layer, crop types, and management practices. In the GLB, tile depths typically range from 0.6 to 1.2 m (Supplementary Table S5), considering soil texture, drainage coefficient (depth of water to be removed from drainage area in 24 h, e.g., mm/day), and drainage needs. For instance, tiles at a depth of 0.6 m were installed in Perth clay soil in southern Ontario to manage excess water under a corn-soybean rotation (Tan and Zhang, 2011), while depths up to 1.2 m were used in sandy loam soils at the University of Minnesota's Southwest Research and Outreach Center (Oquist et al., 2007). Tile spacing varied from narrow spacings of around 4.6 m in poorly drained clay soils to wider spacings of up to 55 m in well-drained soils to reduce installation cost (Oquist et al., 2007; Tan and Zhang, 2011; Lam et al., 2016). An average example included tiles at 0.9 m depth and 15 m spacing in silt loam and clay loam soils in Ohio's Upper Big Walnut Creek watershed to support corn-soybean rotations while managing excess soil moisture (Williams et al., 2015a).

The main function of the tile drain system is to accelerate the removal of excess soil water, enhancing soil water storage capacity and infiltration rates. This alteration reduces surface runoff volumes and peak flows (Zhang et al., 2015). However, it also increases the base flow and total annual water output volume at field and watershed scales. Tile-drained fields can discharge 1.7 to 2.2 times more water than undrained fields (Eastman et al., 2010), and tile flow can constitute up to 74 % of annual watershed discharge (King et al., 2014). Consequently, tile drainage affects not only water quantity but also the timing and pathways of nutrient export (Clement and Steinman, 2017), highlighting the need for integrated water management strategies in the GLB.

At the field level within the GLB, tile drainage substantially increases subsurface discharge and often reduces surface runoff. Studies have shown that tile drainage systems contribute a substantial portion of annual precipitation to subsurface flow (Table 1). For example, in the Pike River watershed in southern Quebec, subsurface outflow ranged from 24 % to 66 % of annual precipitation across different sites (Eastman et al., 2010). In Ontario, tile drainage was the dominant hydrological pathway, accounting for 78 % to 97 % of total runoff at several sites (Esbroeck et al., 2016; Plach et al., 2019). Similarly, Sadhukhan et al. (2019a, 2019b) observed that, on average, 68 % of water left agricultural fields through tile drainage, predominantly during the nongrowing season from December to May. At the watershed scale, tile drainage substantially increases subsurface flow contributions to total watershed discharge in the GLB. Studies have shown that tile drainage can account for a considerable portion of annual precipitation and watershed discharge (Table 1). For example, in central Ohio's Upper Big Walnut Creek watershed, tile outflow constituted approximately 34 % of annual rainfall and 47 % of average monthly watershed discharge (King et al., 2015a, 2015b). Moreover, tile flow was estimated to contribute up to 42 % of annual watershed discharge in some areas in Ontario's headwater watershed (Macrae et al., 2007), projected to increase significantly under future climate scenarios (Boles et al., 2015; Mehan et al., 2019; Hanke et al., 2024).

Table 1
Effects of tile drainage on flow at the field and watershed scales (Supplementary Tables S6 and S14 provide a review of the specific studies that inform this Table).

Location	Field-scale tile flow			Watershed-scale tile flow		
	Tile flow (mm/year)	% of annual precipitation	% of total flow	Tile flow (mm/year)	% of annual precipitation	% of total flow
Canadian portion of the GLB	• 121 to 229 mm in Ontario (Lam et al., 2016) • 294 to 505 mm in Ontario (Esbroeck et al., 2016) • 183 to 250 mm in Ontario (Macrae et al., 2023)	• 16 to 41 % in Ontario (Lam et al., 2016) • 24 to 66 % in Quebec (Eastman et al., 2010)	• 78 to 90 % in Ontario (Esbroeck et al., 2016) • 80 % under CDS, 97 % under RFD in Ontario (Tan and Zhang, 2011) • 81 to 96 % in Ontario (Plach et al., 2019)	• No data	• No data	• 42 % in Ontario (Macrae et al., 2007) • 53 to 80 % in Quebec (Michaud et al., 2019)
US potion of the GLB	• On average 210 mm in Wisconsin (Madison et al., 2014)	• 11 to 40 % for corn, 17 to 22 % for pasture in Wisconsin (Madison et al., 2014) • 13.7 % to 21.9 % for alternative farming and 17.5 % to 32.0 % for conventional farming in Minnesota (Oquist et al., 2007)	• 83 to 90 % in Illinois (Algoazany et al., 2007)	• 85 to 172 mm in Indiana (Boles et al., 2015) • 150 mm under corn-soybean rotation in Ohio (Ren et al., 2022a, 2022b)	• 8.5 % to 16.2 % in Indiana (Boles et al., 2015) • 13 to 19 % in Illinois (Algoazany et al., 2007) • 34.14 % in Ohio (King et al., 2015a, 2015b) • 45 % in Midwestern U.S. (Dinnes et al., 2002)	• 40 % in Lake Erie watersheds (King et al., 2014) • 45 % in Iowa (Bailey et al., 2022) • 47 % in Ohio (King et al., 2015a, 2015b)

Note: CDS (controlled drainage with a subsurface irrigation system), RFD (regular free tile drainage).

Fig. 3 compares tile flow relative to annual precipitation and total annual flow at field and watershed scales. At the field scale, tile flow as a percentage of precipitation ranges from 11 % to 66 %, with a median of 21.95 % (Q1 = 16.75 %, Q3 = 34.00 %). At the watershed scale, tile flow shows a narrower span of 8.5–45 % of precipitation, centered around a median of 17.6 % (Q1 = 13.80 %, Q3 = 30.36 %). These differences show that tile flow represents a considerable fraction of total precipitation at the field scale. Moreover, tile flow as a percentage of total annual flow at the field scale is above 80 %, with a minimum of 78 % and a maximum reaching 97 % (median = 86.50 %, Q1 = 80.75 %, Q3 = 91.50 %). At the watershed scale, tile flow contributes substantially to the total flow, ranging from 40 to 80 %, with a median of 46 % (Q1 = 42.75 %, Q3 = 51.50 %). These results demonstrate that tile drainage substantially altered the hydrological balance at the field and watershed scales, which has important implications for nutrient transport, water quality, and water resource management in tile-drained agricultural landscapes in the GLB.

4. Effect of tile drainage on nutrient loading and water quality

Tile drainage systems alter hydrological pathways, often increasing the transport of nutrients such as N and P from fields to adjacent water bodies. Understanding the effects of tile drainage on nutrient loading is crucial for developing effective management practices aimed at reducing nutrient losses and improving water quality in the GLB. This section provides a comprehensive overview of the impact of tile drainage on nutrient loading and water quality, drawing insights from monitoring and modeling studies.

4.1. *Effect of tile drainage on nutrient loading and water quality based on monitoring studies*

Monitoring nutrient export from tile-drained fields and watersheds is essential for understanding nutrient dynamics, identifying sources and pathways, and assessing impacts on water quality. Field and watershed scale monitoring studies generally consider continuous flow measurements, water sampling at tile drains and watershed outlets, and detailed chemical analysis of grab samples to provide critical insights into hydrologic processes and water quality dynamics across various spatial and temporal scales (Amado et al., 2017). For instance, automated samplers connected to tile outlets have been used to collect high-frequency data on P and N concentrations, capturing the effects of storm events, seasonal variations, and agricultural practices on nutrient losses (Tan and Zhang, 2011; Esbroeck et al., 2017). These comprehensive datasets enable researchers to assess the influence of different management practices on nutrient export, such as tillage, cover crops, and controlled drainage systems. Furthermore, observed data serve as a fundamental basis for model calibration, validation, and uncertainty analysis, which are crucial for developing water quality models to evaluate BMPs and predict the impacts of climate change scenarios in tile-drained watersheds (Liu et al., 2024). Therefore, monitoring studies at field and watershed scales are vital for advancing our understanding of nutrient cycling and informing effective water quality management strategies.

4.1.1. *Phosphorus (P) loading from tile-drained fields*

Field-scale monitoring studies in the GLB demonstrated that subsurface tile flow P loading was often more than surface P loading (Table 2). For example, Eastman et al. (2010) reported that in the Pike River watershed in southern Quebec, total phosphorus (TP) loadings from tile flow ranged from 0.3 to 2.3 kg/ha, while TP loadings from surface runoff ranged from 0.4 to 1.9 kg/ha over two hydrological years. Dissolved and particulate forms of P (DRP and PP) can move into tile drainage systems through soils with substantial macropore networks or soils with little remaining P sorption capacity, suggesting that tile drainage can increase P loss from agricultural fields. For example, Esbroeck et al. (2016) observed that tile drainage accounted for DRP and PP loadings ranging from 0.017 to 0.023 kg/ha and 0.15 to 0.23 kg/ha across three sites in southern Ontario, exceeding surface runoff DRP and PP loadings of 0.01 to 0.08 kg/ha and 0.07 to 0.20 kg/ha respectively.

Some management practices, such as no-till farming, were identified to increase DRP losses due to enhanced macropore development and

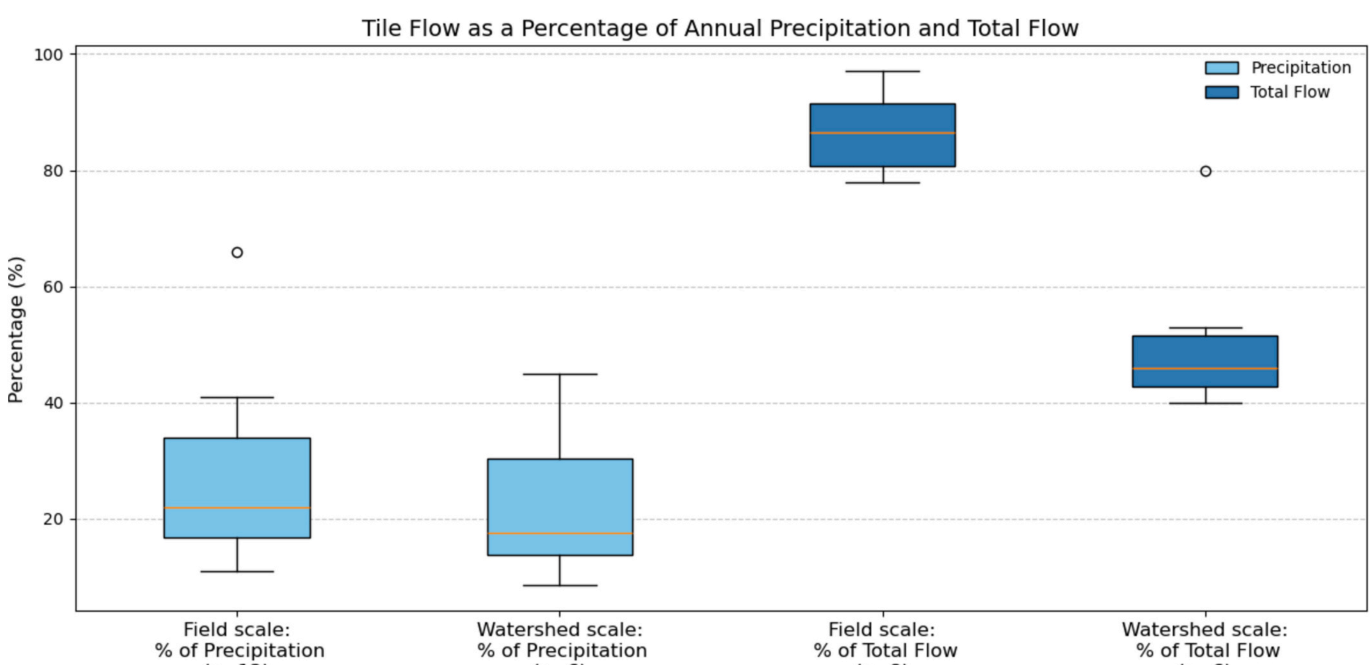

Fig. 3. Tile flow as a percentage of annual precipitation and total flow at the field and watershed scale. n = sample size. The central line within the box represents the median, while the box edges denote the first quartile (Q1, 25th percentile) and the third quartile (Q3, 75th percentile). The interquartile range (IQR) spans from Q1 to Q3. The whiskers extend to the 10th and 90th percentiles, and any points beyond those whiskers represent values outside this range. Data sources were Table 1, Supplementary Tables S6 and S14.

Table 2
Major Findings from monitoring studies of nutrient loadings from tile-drained fields and watersheds (Supplementary Tables S7, S8, S9 and S14 provide a review of the specific studies that inform this Table).

Location	Scale	Nutrient loading in surface runoff (kg/ha)	Nutrient loading in tile flow (kg/ha)
Canadian portion of the GLB	Field-scale nutrient loading	1. TP 0.40 to 1.90, DRP 0.17 to 0.43, PP 0.08 to 0.73 in Quebec (Eastman et al., 2010) 2. Under CDS: TP 0.05 to 0.56, DRP 0.003 to 0.08, PP 0.04 to 0.51; Under RFD: TP 0.01 to 0.13, DRP 0.001 to 0.013, PP 0.008 to 0.102 in Ontario (Tan and Zhang, 2011) 3. TP 0.08 to 0.25, DRP 0.01 to 0.08, PP 0.07 to 0.20 in Ontario (Esbroeck et al., 2016) 4. Under CDS-NCC: TP 0.51 to 1.38, DRP 0.26 to 0.34, PP 0.46 to 0.99; Under CDS-CC: TP 0.41 to 0.49, DRP 0.11 to 0.21, PP 0.14 to 0.29; Under RFD-NCC: TP 0.45 to 0.89, DRP 0.18 to 0.24, PP 0.23 to 0.58; Under RFD-CC: TP 0.37 to 0.92, DRP 0.15 to 0.38, PP 0.17 to 0.47 in Ontario (Zhang et al., 2017) 5. TP 0.02 to 0.34, DRP 0.009 to 0.120 in Ontario (Plach et al., 2019)	1. TP 0.30 to 2.30, DRP 0.21 to 0.53, PP 0.09 to 1.77 in Quebec (Eastman et al., 2010) 2. Under CDS: TP 0.14 to 1.62, DRP 0.008 to 0.152, PP 0.10 to 1.33; Under RFD: TP 0.21 to 2.14, DRP 0.01 to 0.12, PP 0.19 to 1.82 in Ontario (Tan and Zhang, 2011) 3. TP 0.17 to 0.26, DRP 0.017 to 0.023, PP 0.15 to 0.23 in Ontario (Esbroeck et al., 2016) 4. Under CDS-NCC: TP 0.60 to 0.93, DRP 0.06 to 0.28, PP 0.33 to 0.64; Under CDS-CC: TP 0.64 to 1.47, DRP 0.14 to 0.32, PP 0.23 to 1.15; Under RFD-NCC: TP 0.66 to 1.34, DRP 0.19 to 0.55, PP 0.24 to 1.27; Under RFD-CC: TP 0.58 to 1.47, DRP 0.24 to 0.51, PP 0.17 to 0.98 in Ontario (Zhang et al., 2017) 5. TP 0.15 to 0.72, DRP 0.02 to 0.20 in Ontario (Plach et al., 2019) 6. DRP 0.01 to 0.03 in Ontario (Coelho et al., 2010) 7. TP 0.01 to 0.46, DRP 0.003 to 0.104 in Ontario (Lam et al., 2016) 8. TP 0.73 to 8.36, DRP 0.19 to 6.28, PP 0.46 to 1.46 in Ontario (Zhang et al., 2015) 9. Under CT: TP 2.02 to 3.21, DRP 0.18 to 0.90; Under NTCC: TP 1.04 to 3.45, DRP 0.27 to 2.43 in Ontario (Macrae et al., 2023) 10. Under CD: TP 0.58 to 0.60, DRP 0.28 to 0.34; Under PD: TP 0.18 to 0.90, DRP 0.06 to 0.69 (Grenon et al., 2023) 11. NO_3-N 3.1 to 3.8 in Ontario (Coelho et al., 2010) 12. Under CT: NO_3-N 1.0 to 18.4; Under NTCC: NO_3-N 3.6 to 15.4 in Ontario (Macrae et al., 2023) 13. Under CD: NO_3-N 24.63 to 43.76, TN 34.73 to 52.86; Under PD: NO_3-N 0.67 to 5.88, TN 2.09 to 20.63 (Grenon et al., 2023)
	Watershed-scale nutrient loading	1. 46 to 67 % of TP at the watershed outlet originates from surface runoff during peak flow events in Ontario (Michaud et al., 2019) 2. TP 0.94, DRP 0.10 to 0.15, NO_3-N 9.15 to 11.55 in Ontario (Irvine et al., 2019)	No data
US potion of the GLB	Field-scale nutrient loading	1. In chisel-plowed sites: TP 0.60 to 4.55, DRP 0.22 to 0.95; in no-till sites: TP 1.05 to 8.73, DRP 0.52 to 7.84; in grazed pasture sites: TP 3.32 to 8.91, DRP 3.32 to 7.84 in Wisconsin (Madison et al., 2014)	1. In chisel-plowed sites: TP 0.24 to 1.53, DRP 0.22 to 0.95; in no-till sites: TP 0.49 to 6.93, DRP 0.36 to 5.86; in grazed pasture sites: TP 0.27 to 2.63, DRP 0.13 to 2.08 in Wisconsin (Madison et al., 2014) 2. Under AL farming: TP 0.01 to 0.08, DRP 0.01 to 0.06; under CN farming: TP 0.01 to 0.19, DRP 0.01 to 0.15 in Minnesota (Oquist et al., 2007) 3. TP 0.44 to 0.75, DRP 0.36 to 0.61 in Ohio (King et al., 2016) 4. Under AL farming: NO_3-N 2.88 to 8.34; Under CN farming: NO_3-N 5.71 to 42.95 in Minnesota (Oquist et al., 2007) 5. NO_3-N 23.9 to 56.8, TN 28.3 to 64.2 in Ohio (King et al., 2016) 6. NO_3-N 2.9 to 153, TN 6.6 to 97.7 in WLEB (Hanrahan et al., 2020)
	Watershed-scale nutrient loading	1. TP 0.52 to 1.85, DRP 0.33 to 1.26 in Ohio (King et al., 2015a, 2015b) 2. DRP 0.471, NO_3-N 15.54 in Western Lake Erie Basin (Miller and Lyon, 2021) 3. DRP 0.05 to 0.13 in Illinois (Algoazany et al., 2007)	1. TP 0.28 to 0.92, DRP 0.22 to 0.84, contributing 48 % of DRP and 40 % of TP exported to the watershed outlet in Ohio (King et al., 2015a, 2015b) 2. DRP 0.11 to 0.23 in Illinois (Algoazany et al., 2007) 3. TP 0.003 to 0.322, DRP 0.002 to 0.248 annually in Michigan (Clement and Steinman, 2017)

(continued on next page)

Table 2 (*continued*)

			4. TP export through tile drainage to watershed outlet ranged from 17 % to 41 % of the total TP loading (Madison et al., 2014)

Note: TP (total phosphorus), DRP (dissolved reactive phosphorus), PP (particulate phosphorus), NO_3-N (nitrate nitrogen or dissolved nitrogen- according to Coelho et al. (2012) and Tan and Zhang (2011) approximately 80 % of nitrate nitrogen losses from tile-drained lands occur through tile drainage), TN (total nitrogen), CDS (controlled drainage with a subsurface irrigation system), RFD (regular free tile drainage), CDS-NCC (controlled drainage with a subsurface irrigation system with no cover crop), CDS-CC (controlled drainage with a subsurface irrigation system with cover crop), RFD-NCC (regular free drainage with no cover crop), RFD-CC (regular free drainage with cover crop), CT (conventional conservation-till), NTCC (no-till cover crop), CD (controlled drainage), PD (pumped drainage), AL (alternative farming included diverse crop rotations with minimal inorganic inputs and organic management strategies-building soil health, buffer zones, maintaining biodiversity), CN farming (conventional farming involved typical rotations of corn and soybean with standard inorganic fertilizer and pesticide applications), WLEB (Western Lake Erie Basin).

phosphorus stratification in the subsurface soil profile, leading to increased connectivity between surface soils and tile drainage systems and more P desorption to water (Kleinman et al., 2015; Madison et al., 2014). The studies on temporal patterns of tile drainage effects indicated that substantial P loading occurred during the nongrowing season, particularly during snowmelt events, contributing up to 52 % of annual TP and DRP exports (Lam et al., 2016; Macrae et al., 2007). Furthermore, peak flow events disproportionately contributed to annual P loadings, with TP loadings during such events accounting for 46–67 % of the total annual loading (Michaud et al., 2019). These findings underscored the importance of tile drainage as a pathway for phosphorus transport in the GLB.

4.1.2. Nitrogen (N) loading from tile-drained fields

Field-scale monitoring studies also showed that tile drainage was a major pathway for nitrate transport, often accounting for approximately 80 % of NO_3–N losses from agricultural fields (Coelho et al., 2012), with notable variability influenced by agricultural practices and regional conditions (Table 2). In Ontario's Sydenham River watershed, nitrate-nitrogen (NO_3–N) loadings in tile flow ranged between 3.1 and 3.8 kg/ha (Coelho et al., 2010). In the Chatham-Kent region of southern Ontario, mean NO_3–N loadings from tile drainage were higher under conventional conservation-till (11.25 kg/ha) compared to no-till with cover crops (7.83 kg/ha), indicating the effectiveness of conservation practices in reducing nitrogen losses (Macrae et al., 2023). Similarly, at the University of Minnesota's Southwest Research and Outreach Center, alternative farming practices, including diverse crop rotations with minimal inorganic inputs and organic management strategies (e.g., building soil health, considering buffer zone), reduced NO_3–N loadings in tile flow to between 2.88 and 8.34 kg/ha, whereas those in conventional practices ranged from 5.71 to 42.95 kg/ha (Oquist et al., 2007).

Tile drainage NO_3–N loadings averaged 39.57 kg/ha from the sampling field sites in the Upper Big Walnut Creek watershed in Ohio, highlighting substantial nitrogen contributions from agricultural lands (King et al., 2016). Across various sites in the Western Lake Erie Basin, NO_3–N loadings in tile flow averaged 26.68 kg/ha, with values ranging from 2.9 to 153 kg/ha, showing substantial variability and potential for high nitrogen losses (Hanrahan et al., 2020), particularly during the fall and early spring. The substantial nitrogen loadings through tile drainage emphasize the need for implementing effective land management practices to mitigate nitrogen leaching from agricultural fields.

4.1.3. Nutrient loading at the watershed scale

At the watershed scale, monitoring studies demonstrated that tile drainage substantially contributed to P and N loadings (Table 2). In the Upper Big Walnut Creek watershed in central Ohio, tile drainage accounted for 48 % of dissolved P and 40 % of TP exported to the watershed outlet, with tile-derived P loadings ranging from 0.28 to 0.92 kg/ha annually (King et al., 2015a, 2015b). Seasonal patterns revealed that the most substantial P loading through tile drainage occurred during late fall, winter, and early spring. Similarly, in the Ewing Brook subwatershed of the Pike River watershed in southern Quebec, tile drainage was a significant contributor to total P loadings during peak flow events, with DRP dominating tile flow during winter and spring and PP losses increasing in summer due to soil cracking and preferential flow pathways (Michaud et al., 2019).

The tile drainage system also increased N loadings to watershed outlets. Amado et al. (2017) demonstrated that subsurface tile drainage delivered up to 80 % of the nitrogen loading to streams despite contributing only 15–43 % of the streamflow. In a headwater watershed in Ohio, the annual watershed NO_3–N loading varied from 12.4 to 39.6 kg/ha, with tile drainage contributing 44 to 82 % (average: 62 %) of the annual watershed NO_3–N export (Williams et al., 2015a). In Ontario's Hopewell Creek watershed, agricultural land use led to markedly higher nutrient exports compared to natural sites, with NO_3–N loadings reaching up to 11.55 kg/ha in agricultural areas versus 0.04 kg/ha in natural sites (Irvine et al., 2019). These findings underscore that tile drainage is a major pathway for nutrient export from agricultural fields to watersheds in the GLB, influenced by factors such as soil composition, land management practices, and hydrological conditions. Moreover, past regional policies such as the Swamp Land Acts (1850) in the U.S. and Ontario's Tile Drainage Act (1990) promoted widespread adoption of tile drainage in the GLB to facilitate agricultural productivity without considering the implications on water quality, wetland ecosystems, and hydrological integrity.

Furthermore, Basu et al. (2023) demonstrated that watersheds in the GLB that have high levels of developed land use, high tile drainage coverage, and low wetland densities contributed higher concentrations of dissolved nutrients (DRP and NO_3-N), while higher concentrations of PP occurred in areas with more silt-clay soils and lower wetland cover areas. The substantial contributions of tile drainage to watershed nutrient loadings highlight the need for precision conservation strategies to mitigate nutrient losses, particularly during nongrowing seasons and peak flow events.

4.2. Effect of tile drainage on nutrient loading and water quality based on modeling studies

Modeling nutrient loadings from tile-drained landscapes in the GLB is crucial for understanding and managing the complex interactions between agricultural practices and water quality. Computer-based models offer a cost-effective means to simulate intricate hydrological and nutrient transport processes, providing insights that would be impractical to obtain through field measurements alone (Askar et al., 2021a, 2021b). By simulating interactions among agricultural practices, soil properties, and hydrological dynamics, models help improve our understanding of phosphorus and nitrogen losses, identify knowledge gaps, and evaluate the effectiveness of BMPs (Sadhukhan et al., 2019a, 2019b; Radcliffe et al., 2015).

4.2.1. Models for simulating nutrient dynamics in tile-drained agricultural fields and watersheds

Various models have been developed to simulate nutrient losses in tile-drained fields and watersheds (Radcliffe et al., 2015; Stempvoort et al., 2021; Ellafi et al., 2024). These models include the Hydrologic Simulation Program–Fortran (HSPF), MIKE SHE, Phosphorus LEAching from Soils to the Environment (PLEASE), Environmental Policy Integrated Climate (EPIC), Annualized Agricultural Non-Point Source

Pollution (AnnAGNPS), Watershed Analysis Risk Management Framework (WARMF), Agricultural Policy Environmental eXtender (APEX), Soil and Water Assessment Tool (SWAT), DRAINMOD, ICECREAM, Agricultural Drainage and Pesticide Transport (ADAPT), Root Zone Water Quality Model 2 (RZWQM2), and Model of Assessing Contaminant Release of Organics (MACRO). Field-scale models (e.g., DRAINMOD, RZWQM2) focus on site-specific detailed hydrological and nutrient transport processes within agricultural fields. In contrast, watershed-scale models (e.g., SWAT, AnnAGNPS) can integrate field-scale processes over larger spatial extents to simulate the collective impact of multiple fields and land use on watershed hydrology and water quality.

Considerable efforts have been made to enhance hydrological models to accurately simulate nutrient dynamics in tile-drained agricultural fields and watersheds. An overview of recent modeling approaches is summarized in Supplementary Table S10. However, actual representation of tile drainage in models is a challenge, and substantial research has been conducted on DRAINMOD, RZWQM2, and SWAT models for predicting nutrient loadings and assessing the impacts of tile drainage on water quality (Dayyani et al., 2010; Moriasi et al., 2013).

DRAINMOD is a widely used field-scale model developed to quantify the hydrology of subsurface-drained soils (Askar et al., 2020). It simulates hydrology using simple water-balance equations and requires inputs including weather, soil, crop, and drainage system parameters. DRAINMOD has been proven efficient in simulating subsurface flows from poorly drained, high-water table soils experiencing freeze-thaw cycles, making it suitable for cold regions (Askar et al., 2021a, 2021b; Golmohammadi et al., 2021). Despite its robust hydrological simulation capabilities, the original DRAINMOD model has methodological limitations in simulating phosphorus loadings and is limited to field-scale applications. To overcome these limitations, Dayyani et al. (2012) developed the DRAIN-WARMF model by coupling DRAINMOD with the Watershed Analysis Risk Management Framework (WARMF) to estimate water flow and nitrogen losses in watersheds with partial subsurface tile drainage under frozen and unfrozen soil conditions. Building upon these advancements, Askar et al. (2020) modified DRAINMOD to recognize the macropore flow in clay soils (Eastman et al., 2010) as it accounts for the rapid movement of water and associated nutrients through soil cracks and preferential pathways. Furthermore, Askar et al. (2021a, 2021b) developed DRAINMOD-P to simulate phosphorus cycling and transport in tile-drained croplands. DRAINMOD-P simulates the effects of drainage system design, climatic conditions, crop rotations, and management practices, including tillage and drainage water management on surface and subsurface phosphorus export. The improved model also incorporated snowmelt, freezing, and thawing processes to simulate soil hydrology and phosphorus loss in cold regions. Fully integrated with the DRAINMOD-NII model, DRAINMOD-P is a valuable tool for predicting phosphorus and nitrogen losses from tile-drained lands under various management practices (Askar et al., 2021a, 2021b).

On the other hand, the Root Zone Water Quality Model (RZWQM2) has undergone enhancements by incorporating a phosphorus module that simulates detailed soil P pools and the processes affecting P movement and transformations (Sadhukhan et al., 2017). The updated P module in RZWQM2-P integrated macropore flow mechanisms and water table-based tile drainage components (Radcliffe et al., 2015; Qi and Qi, 2017), utilizing Richards' equation for matrix flow and Hooghoudt's equation for tile drainage (Sadhukhan et al., 2017). Unlike the ICECREAM model, which assumes immediate mixing of manure or fertilizer P with the soil without separate P pools(Qi et al., 2018), RZWQM2-P includes distinct pools for manure and fertilizer P, allowing for more accurate simulation of P dynamics following organic and inorganic fertilizer applications (Sadhukhan et al., 2019a, 2019b). These enhancements have considerably improved the model's ability to simulate P losses, particularly DRP and PP, through tile drainage and surface runoff (Sadhukhan et al., 2017; Sadhukhan et al., 2019a, 2019b). Despite these advancements, RZWQM2-P, a one-dimensional field-scale model, cannot directly apply to large-scale watersheds (Radcliffe et al., 2015). Additionally, while RZWQM2-P has shown potential in simulating PP and TP losses under varying tillage and compost management practices, further enhancements are needed to improve DRP loss predictions (Pan et al., 2023).

While SWAT, a semi-distributed, process-based hydrological model, has effectively estimated discharge and nutrient losses at a watershed scale (Merriman et al., 2019), earlier versions of the model (e.g., SWAT2000) faced limitations in accurately representing subsurface drain flow and nutrient transport in tile-drained watersheds (Moriasi et al., 2007). Moriasi et al. (2007) incorporated Hooghoudt's and Kirkham's tile drain equations into SWAT, allowing subsurface drainage flow to be calculated as a function of drain size, spacing, and depth. Although this modification improved simulations in specific contexts (Moriasi et al., 2012), it could not evaluate different water table management practices. Golmohammadi et al. (2016) combined SWAT's surface hydrology simulation with DRAINMOD's subsurface drainage simulation to improve the accuracy of modeling the effect of controlled drainage on water table depth and tile drainage outflow at the watershed scale. Furthermore, Bauwe et al. (2019) introduced SWAT-P to address DRP losses through tile drainage systems, including the specification of DRP concentrations in tile drainage water and DRP pathways in the model. Similarly, Kim et al. (2023) developed a SWAT-tile version by revising the subsurface drainage routine in the model to enhance NO_3-N loading prediction and capture the complexities of nitrate transport in tile-drained systems. Despite these improvements, SWAT has not been extensively used to simulate the effectiveness of drainage water management practices in reducing nutrient loadings. SWAT+ is a restructured version of the SWAT model that introduced a drainage water management (DWM) simulation module (Bieger et al., 2017). Sharma et al. (2024) assessed SWAT+'s performance in simulating daily tile flow for a paired DWM field site in eastern South Dakota, highlighting its potential for evaluating DWM practices at a watershed scale.

These progressive enhancements to DRAINMOD, RZWQM2, and SWAT have improved the accuracy of simulating nutrient loadings in tile-drained agricultural landscapes. However, capturing surface and subsurface hydrological processes and evaluating BMP effectiveness from individual fields to watersheds requires a spatially explicit approach to ensure a location-specific representation of BMPs within the model (Bodrud-Doza et al., 2023). Therefore, there is a need to incorporate detailed representations of tile drainage and nutrient (e.g., TP, DRP, PP, TN, NO_3-N) dynamics in a spatially explicit fine-resolution modeling approach that can better predict the effectiveness of agricultural management practices under climate change, which can contribute to developing optimum BMP scenarios to mitigate nutrient pollution and improve water quality (Moriasi et al., 2013; Askar et al., 2021a, 2021b; Sadhukhan et al., 2019a, 2019b).

4.2.2. *Modeling results in tile-drained agricultural fields and watersheds*

Modeling studies across the GLB consistently demonstrated that tile drainage was a major pathway for substantial nutrient transport from agricultural fields to water bodies (Table 3). For example, at the field scale, Sadhukhan et al. (2019a, 2019b) applied the RZWQM2 model to a corn-soybean field near Harrow, Ontario, and found that over 50 % of TP loss occurred through tile flow. Golmohammadi et al. (2021) used the DRAINMOD model to simulate the effects of climate change on tile discharge and nitrate loading at a field site in southern Ontario. Calibrated with field monitoring data, the model projected that annual average NO_3–N losses could increase from 17 kg/ha during 1960–1990 to 37 kg/ha by 2071–2100. The significant increase in nitrate losses (about 50 %) was attributed to elevated tile flows under future climatic conditions, underscoring the critical role of tile drainage in nutrient export and the potential exacerbation under climate change at a field scale.

Cao et al. (2023) applied the Dynamic Land Ecosystem Model to four watersheds in Iowa and found that subsurface flows, including tile flow

Table 3
Major findings from modeling studies of nutrient loadings from tile-drained fields and watersheds (Supplementary Table S10 details the modeling approaches used in different studies, while Supplementary Tables S11 and S14 provide a review of the specific studies that inform this table).

Location	Scale	Nutrient loading in surface runoff (kg/ha)	Nutrient loading in tile flow (kg/ha)
Canadian portion of the GLB	Field-scale nutrient loading	1. Observed and simulated DRP 0.39 and 0.35, PP 1.29 and 1.14 in Ontario (Sadhukhan et al., 2019a, 2019b)	1. Observed and simulated DRP 0.89 and 0.79, PP 2.11 and 2.11 in Ontario (Sadhukhan et al., 2019a, 2019b) 2. 54 % TP loss while 75 % of that is PP in Ontario (Sadhukhan et al., 2019a, 2019b) 3. NO_3-N (baseline 17) projected to increase 23 (2011–2040), 30 (2041–2070), 37 (2071–2100) due to elevated flow in Ontario (Golmohammadi et al., 2021). 4. TP 2.85 (measured 65.4 % and simulated 53.8 % of total TP loss in tile flow from the field), PP 3.14 (measured 72 % and simulated 69.1 % of TP loss), DRP observed 0.383 simulated 0.344 in Ontario (Qi et al., 2018).
	Watershed-scale nutrient loading	1. NO_3-N (baseline 33.84), 33.60 (2011–2040), 32.40 (2041–2070), 31.68 (2071–2100) in Quebec (Dayyani et al., 2012) 2. Observed and simulated NO_3-N 5.27 and 4.67 in Quebec (Dayyani et al., 2010) 3. Simulated TP 0.18 to 1.80, TN 0.93 to 6.40 in Ontario (Liu et al., 2016)	1. NO_3-N (baseline 27.36), 26.04 (2011–2040), 24.60 (2041–2070), 22.80 (2071–2100). Tile flow contribution to annual NO_3-N loading was 14 % of total loading project to increase by 39.3 % during 2071–2100 (Dayyani et al., 2012).
US potion of the GLB	Field-scale nutrient loading	1. Contributed 78 % of predicted TP loading in Ohio (Askar et al., 2021a, 2021b)	1. Macropore contributed 21 % of DRP loss in Ohio (Askar et al., 2021a, 2021b). 2. DRP 0.68 (median annual) (44 % from macropore pathways and 56 % from matrix percolation) in Ohio (Ford et al., 2017).
	Watershed-scale nutrient loading	1. TP 0.77, DRP 0.34, PP 0.07, TN 6, NO_3-N 2.4 in a watershed of U.S. Corn Belt, part of the Lake Erie basin (Ren et al., 2022a, 2022b) 2. DRP (baseline 0.051 kg/ha) could increase up to 70 % under RCP4.5 and 75 % under RCP8.5, NO_3-N is projected to increase by 5 % to 50 % under RCP4.5 and 50 % to 100 % under RCP8.5 in Indiana (Mehan et al., 2019). 3. Under all BMP constructed scenarios, loading from different landuses such as Dairy: TP 1.11, DRP 0.34, TN 9.90, NO_3-N 1.21; Cash Grain: TP 0.99, DRP 0.82, TN 16.35, NO_3-N 2.78; Continuous Corn: TP 1.85, DRP 0.63, TN 15.11, NO_3-N 1.69 (Merriman et al., 2019). 4. NO_3-N loading decreased from 0.132 at 0.6 m depth to 0.127 at 1.2 m depth in Illinois (Kim et al., 2023). 5. From Green Lake watershed TP 1.1 (increase by 28 % to 89 %), NO_3-N 2.6 (increase by 1.1 % to 38 %); and Walworth watershed TP 3.3 (increase by 25 % to 108 %), NO_3-N 1.5 (increase by 8 % to 95 %) in Wisconsin (Wang et al., 2018)	1. TP 0.18, DRP 0.1, TN 7.6, NO_3-N 6.5 in a watershed of U.S. Corn Belt, part of the Lake Erie basin (Ren et al., 2022a, 2022b). 2. DRP (baseline 0.017 kg/ha) is projected to decrease by 35 % to 60 %, NO_3-N loading (baseline 0.549 kg/ha) could decrease by 25 % to 75 % by mid-century under medium emissions scenarios in Indiana (Mehan et al., 2019). 3. 0.023 kg/ha (2 % of the DRP loading simulated for the watershed) DRP is exported with tile drainage (Merriman et al., 2019). 4. NO_3-N loading increased with deeper tiles, from 9.2 at 0.6 m to 11.4 at 1.2 m depth (Kim et al., 2023). 5. Subsurface flows govern 77–82 % of NO_3-N loading, while tile flow delivers 53–76 % of the loading in Iowa (Cao et al., 2023).

Note: TP (total phosphorus), DRP (dissolved reactive phosphorus), PP (particulate phosphorus), NO_3-N (nitrate nitrogen or dissolved nitrogen), TN (total nitrogen), RCP (representative concentration pathway).

and lateral flow, are the primary contributors to in-stream NO3–N loadings, governing 77–82 % of NO_3–N loading. Tile flow alone delivered 53–76 % of these loadings, emphasizing the dominant role of tile drainage in nitrogen transport at a watershed scale. Wan et al. (2023) applied the Spatially Explicit Nutrient Source Estimate and Flux model (SENSEflux) across the U.S. coastline of the GLB to simulate total annual phosphorus and nitrogen loadings. The model identified that tile drainage was responsible for over 66 % of TN and 76 % of TP loadings in the GLB, highlighting its significant influence on nutrient delivery to the Great Lakes.

Ren et al. (2022a, 2022b) used the SWAT model to simulate nutrient losses via tile drainage in the St. Joseph River Watershed of the Lake Erie Basin. This study calibrated and validated the model against observed data from 2011 to 2019 by incorporating additional phosphorus and nitrogen loss pathways. Modeling results showed that tile drainage substantially contributes to nutrient loading, particularly nitrogen. At the watershed outlet, TN loading (7.6 kg/ha) in tile flow was higher than that (6 kg/ha) in surface runoff. In the corn system, tile flow contributed 17.8 kg/ha of TN, surpassing the 4.3 kg/ha from surface runoff. The corn-soybean rotation system, covering 49 % of the watershed, was responsible for 83 % of total nitrogen inputs and significantly contributed to nitrogen losses (64 %) via tile drainage. Merriman et al. (2018) modified the SWAT model to specifically account for dissolved reactive phosphorus losses via tile drainage at finer spatial scales in the Eagle Creek Watershed of Ohio. The enhanced model simulated various BMP scenarios. Under the all-BMP-constructed scenario, average annual nutrient loadings from row crop agricultural areas were 1.44 kg/ha of

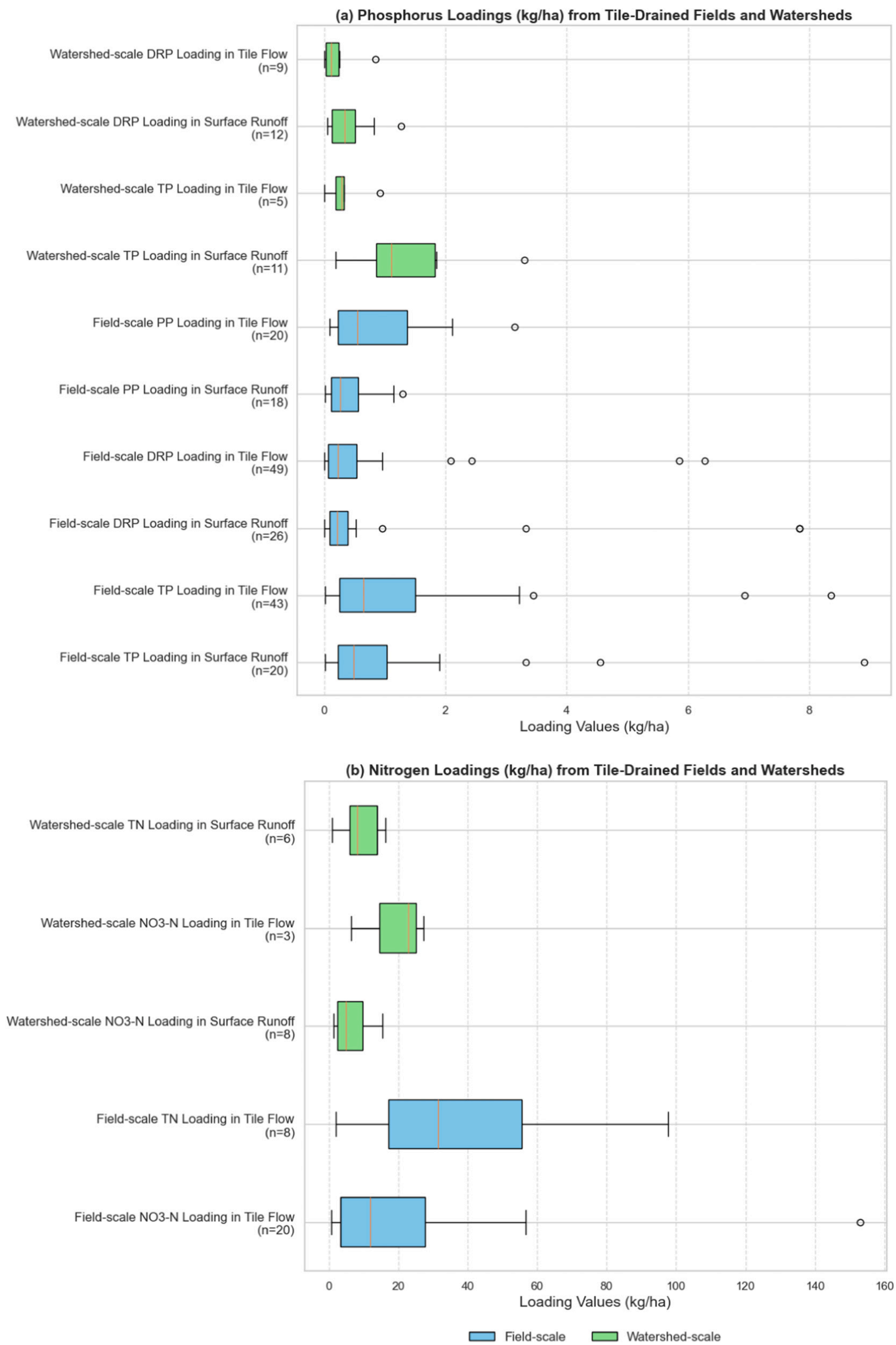

Fig. 4. An overview of (a) phosphorus and (b) nitrogen loadings from tile-drained fields and watersheds. n = sample size. Data sources were Tables 2, 3, Supplementary Tables S7, S8, S9, S10, S11 and S14.

TP, 0.18 kg/ha of DRP, and 4.27 kg/ha of TN. This study highlighted the significance of tile drainage in transporting DRP and the potential of BMPs in mitigating nutrient losses. Kim et al. (2023) revised the SWAT model (SWAT-tile) to examine the effects of varying tile depths on nitrate loadings in the Little Vermillion River watershed, Illinois. They found that nitrate loadings in tile flow increased with deeper tiles, from approximately 9.2 kg/ha at 0.6 m depth to 11.4 kg/ha at 1.2 m depth. This study underscored the importance of tile drainage system configurations on nutrient export. Mehan et al. (2019) used an improved version of the SWAT model to assess the impacts of climate change on hydrology and nutrient loadings in the Matson Ditch watershed in Indiana. Hanke et al. (2024) combined SWAT with an ensemble of climate models in Ontario's Medway Creek watershed, projecting a 23–36 % increase in winter flows through tile drainage system under warmer and wetter conditions, which could increase NO_3-N concentrations by 56–89 %, and TP by 25–47 %. These modeling studies consistently demonstrated that tile drainage contributed substantially to total nutrient loadings entering the Great Lakes, affecting water quality and ecosystem health, highlighting the need for effective management practices to mitigate nutrient losses via tile drainage.

4.3. An overview of nutrient loading from tile-drained landscapes and associated uncertainty

Fig. 4a and b illustrates box-and-whisker comparisons of phosphorus and nitrogen loadings, and supplementary Figs. S1 and S2 represent the associated uncertainty at both field and watershed scales, characterizing nutrient loadings through surface runoff and tile flow pathways. Figs. 4a and S1 reveal that field-scale TP loadings in surface runoff range from 0.01 to 8.91 kg/ha, with a lower quartile (Q1) of 0.22, an upper quartile (Q3) of 1.04, and a median of 0.48. In contrast, field-scale TP loadings in tile flow span 0.01–8.36 kg/ha (Q1 = 0.25 kg/ha, median = 0.64, Q3 = 1.50). Monte Carlo simulations show a geometric mean (GM) of 0.42 kg/ha for TP in surface runoff, with a geometric standard deviation (GSD) of 5.33 and a 95 % CI of (0.02, 11.27). In tile flow, TP has a GM of 0.55 kg/ha (GSD 4.59), within a 95 % CI of (0.03, 10.95). These results indicate that tile flow can produce comparable or even higher TP losses than surface runoff, although both flow pathways remain highly variable. For dissolved reactive phosphorus (DRP) at the field scale, surface-runoff loadings vary from 0.001 to 7.84 kg/ha (Q1 = 0.09, median = 0.22, Q3 = 0.39), whereas tile flow ranges from 0.003 to 6.28 kg/ha (Q1 = 0.06, median = 0.22, Q3 = 0.53). Monte Carlo simulations show a GM of 0.16 kg/ha (GSD 7.92) for DRP in surface runoff (95 % CI: 0.00, 8.87), while tile flow exhibits a GM of 0.18 kg/ha (GSD 5.47), with a 95 % CI of (0.01, 5.03). Particulate phosphorus (PP) also exhibits wide variability at the field scale. Surface-runoff PP loadings range from 0.008 to 1.29 kg/ha (Q1 = 0.112, median = 0.260, Q3 = 0.562), while tile-flow values lie between 0.090 and 3.14 kg/ha (Q1 = 0.220, median = 0.550, Q3 = 1.363). From Monte Carlo simulations, the geometric mean of PP loadings is 0.24 kg/ha (GSD 3.62) in surface runoff (95 % CI: 0.02, 2.94) and 0.54 kg/ha (GSD 3.02) in tile flow (95 % CI: 0.06, 4.77).

At the watershed scale, TP in surface runoff ranges from 0.18 to 3.30 kg/ha (Q1 = 0.86, median = 1.10, Q3 = 1.83), and tile flow spans 0.003–0.92 kg/ha (Q1 = 0.18, median = 0.28, Q3 = 0.32). Monte Carlo simulations reveal a GM of 1.05 kg/ha (GSD 2.12) for TP in surface runoff (95 % CI: 0.24, 4.47), while TP in tile flow shows a GM of 0.13 kg/ha (GSD 7.24) within a 95 % CI of (0.00, 6.27). DRP also shows smaller ranges than at the field level: 0.05–1.26 kg/ha for surface runoff (Q1 = 0.12, median = 0.34, Q3 = 0.51) and 0.002–0.84 kg/ha for tile flow (Q1 = 0.02, median = 0.11, Q3 = 0.23). The Monte Carlo analyses indicate a GM of 0.25 kg/ha (GSD 2.75) for DRP in surface runoff (95 % CI: 0.03, 1.77), whereas DRP in tile flow has a GM of 0.08 kg/ha (GSD 5.65) and a 95 % CI of (0.00, 2.44). These results highlight the substantial variability and uncertainty of phosphorus export via surface runoff and tile drainage. Outliers in the datasets highlight the potential for increased P losses from tile-drained fields under specific site conditions and extreme climatic events.

Figs. 4b and S2 show that field-scale tile flow is often the dominant nitrogen pathway. NO_3–N loadings in tile flow span 0.67 to 153.00 kg/ha (Q1 = 3.48, median = 11.87, Q3 = 27.72). TN loadings in tile flow similarly range from 2.09 to 97.70 kg/ha (Q1 = 17.12, median = 31.52, Q3 = 55.70), indicating that localized management practices, soil properties, and tile drainage contribute substantially to N export. Monte Carlo simulations show that field-scale NO_3–N in tile flow has a GM of 10.06 kg/ha (GSD 4.03), with a 95 % CI of (0.65, 153.88), while TN exhibits a GM of 23.92 kg/ha (GSD 3.27), spanning a 95 % CI of (2.32, 234.24). These findings highlight the significant variability of tile-drain N losses.

At the watershed scale, surface-runoff NO_3–N loadings range from 1.50 to 15.54 kg/ha (Q1 = 2.55, median = 4.97, Q3 = 9.75), whereas tile-flow NO_3–N loadings range from 6.50 to 27.36 kg/ha (Q1 = 14.65, median = 22.80, Q3 = 25.08). TN loadings in surface runoff range from 0.93 to 16.35 kg/ha (Q1 = 6.10, median = 8.15, Q3 = 13.81), indicating a more constrained variability relative to TN loadings in field-scale tile flow. Monte Carlo simulations show that watershed-scale NO_3–N loading in surface runoff has a GM of 5.00 kg/ha (GSD 2.15) with a 95 % CI of (1.11, 22.09), while TN at this scale reaches a GM of 6.72 kg/ha (GSD 2.61) with a 95 % CI of (1.03, 44.08). By comparison, the watershed-scale GM for tile-flow NO_3–N is 15.87 kg/ha (GSD 1.89), with a 95 % CI of (4.55, 55.40), a narrower range than field-scale estimates, indicating tile-drained fields remain critical source areas of nutrient loadings.

These box-and-whisker comparisons and uncertainty analysis underscore the contribution of tile-drained fields to export DRP and NO_3–N. Several field sites exhibit higher nutrient losses through tile flow than surface runoff, although in-stream processes, spatial heterogeneity, and drainage area size moderate these values at the watershed scale. The Monte Carlo simulations in Supplementary Figs. S1 and S2 confirm wide confidence intervals at the field and watershed scale, driven by factors such as crop rotation, fertilizer application, tillage, soil characteristics, drainage configurations, hydrology, and climatic conditions (Williams et al., 2015c; Evenson et al., 2021). These findings highlight the importance of targeted BMPs at the field level, where localized interventions may significantly reduce nutrient losses (Tomer et al., 2013; Bodrud-Doza et al., 2023). At the same time, watershed-scale management strategies can address cumulative impacts and further reduce high loadings (Moriasi et al., 2020; Lintern et al., 2020). Therefore, a comprehensive monitoring and modeling framework encompassing detailed field-scale investigations and aggregated watershed scale analysis is essential to capture nutrient export dynamics and design effective, adaptive management in tile-drained agricultural landscapes.

5. BMP effects on nutrient loading reduction from tile-drained fields and watersheds

Effective implementation of BMPs is crucial for mitigating nutrient losses from tile-drained agricultural fields and watersheds in the GLB. Previous reviews provided valuable insights on BMPs for mitigating nitrogen or phosphorus loss. For example, Dinnes et al. (2002) highlighted strategies for reducing NO_3-N loss by optimizing the timing and rate of nitrogen application, employing soil tests and plant monitoring, diversifying crop rotations, using cover crops, refining fertilizer application techniques, and deploying nitrification inhibitors. Dinnes et al. (2002) also emphasized bioreactors, wetlands, riparian buffers, and drainage control structures in removing nitrate from surface and subsurface flows. In contrast, King et al. (2015a, 2015b) discussed structural, treatment, and management approaches to mitigate subsurface phosphorus transport, such as interrupting flow pathways between surface soils and tile drains, implementing drainage water management, and employing in-stream or end-of-tile treatments, along with strategic ditch design and management. However, these previous reviews focused on mitigating either N or P loss and did not comprehensively address

BMP effectiveness across both nutrients or overall reduction potential at field and watershed scales. Therefore, this section provides a more integrated perspective on BMP effectiveness in reducing nutrient loadings, including phosphorus and nitrogen, based on monitoring and modeling studies and identifies potential strategies for optimizing BMP implementation in tile-drained landscapes.

5.1. BMP effects on nutrient loading reduction from tile-drained fields based on monitoring studies

Various BMPs have been implemented and studied in tile-drained agricultural fields to mitigate nutrient losses. BMP effectiveness from monitoring studies is summarized in Table 4. Cover crop is the most extensively studied BMP in the tile-drained landscape. Cover crops can enhance biological nitrogen uptake during non-crop periods and improve soil hydraulic properties, leading to better water management (Blanco-Canqui et al., 2015; Drury et al., 2014). Hanrahan et al. (2018) conducted a study in the Shatto Ditch Watershed, Indiana, where cover crops like annual ryegrass were planted on 65–68 % of croplands. The study found that median NO_3–N loss from tile-drained fields was reduced by 69–90 % during winter and spring compared to fields without cover crops. At the watershed level, NO_3–N export during high-flow events was 18–22 % lower in years when cover crops were widely planted. Drury et al. (2014) investigated the use of cover crops over five years in Woodslee, Ontario. Plots with cover crops exhibited a 21–38 % decrease in flow-weighted mean NO_3–N concentrations in tile drains and a 14–16 % reduction in cumulative NO_3–N losses compared to plots without cover crops. Similarly, Speir et al. (2022) reported that cover crops reduced tile drain NO_3–N losses by 27–72 % and DRP losses by 7–58 % at the field scale in Indiana. At the watershed scale, NO_3–N and DRP exports were reduced by 2–67 % and 31–88 %, respectively (Speir et al., 2022).

Macrae et al. (2023) compared a No-Till Cover Crop (NTCC) system with a Conventional Conservation-Till (CT) system in the Chatham-Kent region of Ontario. The NTCC system significantly reduced annual NO_3–N losses by 3.425 kg/ha/year compared to the CT system. However, NTCC increased DRP losses by 0.41 kg/ha/year, indicating that cover crops can effectively reduce nitrate losses but may contribute to increased dissolved phosphorus losses under no-till.

Nutrient management strategies and crop diversification can reduce nutrient losses. Gentry et al. (2024) demonstrated that splitting nitrogen fertilizer application in spring and fall with a cereal rye cover crop can reduce tile nitrate loss by 43 % from a tile-drained field near Filson, Illinois, without decreasing crop yield. Oquist et al. (2007) examined the effects of alternative farming practices involving diverse crop rotations with organic management strategies- building soil health, buffer zones, and maintaining biodiversity in the agricultural fields in Minnesota. These practices reduced subsurface drainage discharge by 41 % and decreased NO_3–N losses by 59–62 % compared to conventional farming. The reduction was most pronounced in years with average or above-average precipitation, suggesting that diverse cropping systems and organic management can substantially mitigate agricultural impacts on water quality (Oquist et al., 2007).

Controlled drainage systems, such as Drainage Water Management (DWM) and Controlled Drainage with Sub-Irrigation (CDS), have effectively reduced nutrient losses by managing the water table and reducing drainage outflow. Williams et al. (2015a, 2015b, 2015c) investigated the impact of DWM on nutrient losses in the Upper Big Walnut Creek watershed in Ohio. DWM reduced annual tile discharge by 8–34 % and decreased annual NO_3–N loadings by 8–44 % due to decreased tile discharge. Annual DRP loadings were reduced by 40–68 %. Tan and Zhang (2011) evaluated the impact of CDS on phosphorus losses at the Essex Region Conservation Authority Demonstration Farm in Southern Ontario. The CDS system reported a mean TP loading of 0.70 kg/ha in tile drainage water, significantly lower than the 1.09 kg/ha observed under regular free drainage. Drury et al. (2014) also

Table 4
Major findings from monitoring studies of BMP effects on nutrient reduction in tile-drained fields and watersheds (Supplementary Tables S12 and S14 provide a review of the specific studies that inform this table).

BMP type	BMP effectiveness
Cover crops	• Cover crops reduced tile drain NO_3-N loss by 27–72 % and DRP loss by 7–58 % at the field scale; NO_3-N and DRP export were reduced at the watershed scale by 2–67 % and 31–88 %, respectively, in Indiana (Speir et al., 2022). • Planting cover crops on 65–68 % of croplands led to median NO_3-N losses from tile-drained fields being 69–90 % lower during winter/spring compared to those without cover crops, and watershed-level NO_3–N export during elevated flows was 18–22 % lower in years with watershed-scale cover crop planting in Indiana (Hanrahan et al., 2018). • Cover crops decreased 5-year flow-weighted mean (FWM) NO_3-N concentration in tile drainage by 21 to 38 % and cumulative NO_3-N loss by 14 to 16 % compared to plots without cover crops (NCC) at the filed scale in Ontario (Drury et al., 2014).
No-till cover crop (NTCC)	• Compared to the Conventional Conservation-Till (CT) system, the NTCC system reduced annual NO_3–N losses by 3.43 kg/ha/year and TP losses by 0.56 kg/ha/year but increased DRP losses by 0.41 kg/ha/year at field scale in Ontario (Macrae et al., 2023).
Split nitrogen fertilizer application with cover crop	• Applying 50 % N at spring preplant (before the crop is planted) and 50 % at side-dress (after the crop has emerged and is already growing) with a cover crop reduced tile nitrate (NO_3-N) loss by 43 % over four seasons, compared to 100 % fall-applied N at field scale in Illinois (Gentry et al., 2024).
Alternative farming practices	• Alternative farming practices featuring diverse crops such as oats and alfalfa, combined with organic management and the use of cover crops, reduced tile flow by 41 % compared to conventional methods and decreased NO_3-N losses by 59–62 % at field scale in Minnesota (Oquist et al., 2007).
Controlled drainage with sub-irrigation (CDS)	• The CDS system reported a mean TP loading of 0.70 kg/ha in tile drainage water, significantly lower than the 1.09 kg/ha observed in the Regular Free Drainage (RFD) system at field scale in Ontario (Tan and Zhang, 2011). • Controlled tile drainage–subirrigation (CDS) reduced FWM NO_3-N concentration by 15 to 33 % and cumulative NO_3-N loss by 38 to 39 % relative to traditional unrestricted tile drainage (UTD) at field scale in Ontario (Drury et al., 2014). • Saadat et al. (2018) reported that compared to free draining, controlled drainage significantly reduced annual drain flow by 25–39 % and NO_3-N loading by 26–43 % across different seasons and outlets at field scale, demonstrating that NO_3-N loss reductions were primarily due to decreased flow rates in Indiana.
Controlled drainage with sub-irrigation (CDS) and cover crops (CC)	• P reduction potential in surface water runoff under CDS-CC vs. RFD-NCC: DRP 0.03, PP 0.15, TP 0.22 kg/ha/yr; P reduction potential in tile drainage water runoff under CDS-CC vs. RFD-NCC: DRP 0.07, PP 0.12, TP 0.19 kg/ha/yr; TP loss reduction under CDS-CC treatment compared to

(continued on next page)

Table 4 (*continued*)

BMP type	BMP effectiveness
	RFD-NCC: up to 23 % at field scale in Ontario (Zhang et al., 2017) • Combining cover crops and controlled drainage–subirrigation reduced 5-year cumulative FWM NO_3- concentrations and losses in tile drainage by 47 % (from 102 to 53.6 kg/ha) compared to plots without cover crops and unrestricted drainage (NCC + UTD) at field scale in Ontario (Drury et al., 2014).
Drainage water management (DWM)	• Reduced annual tile discharge by 11 to 178 mm (an 8–34 % decrease), decreased annual NO_3–N loading by 1.3 to 26.8 kg/ha with an average reduction of 9.4 kg/ha (8–44 %), and reduced annual DRP loading by 0.04 to 0.51 kg/ha with an average reduction of 0.19 kg/ha (40–68 %); however, while DWM reduced nutrient loadings in tile flow at field scale, it increased nutrient loadings in surface runoff in Ohio (Williams et al., 2015b). • A review by Ross et al. (2016) found that DWM significantly reduced nutrient losses via tile drainage, decreasing NO_3-N loading by 48 %, TP loading by 55 %, and DRP loading by 57 %.
Wetlands	• Wetlands treating runoff from tile-drained areas—covering 3 % (W1), 6 % (W2), and 9 % (W3) of farmland reduced NO_3-N export by 15–38 % for W1, 39–49 % for W2, and 49–57 % for W3, with NO_3-N mass removal efficiencies ranging from 28 % to 52 %; additionally, over a 12-year period, W1 achieved DRP loading reductions of 53–81 %, while W2 and W3 achieved reductions of 35–91 % and 32–95 %, respectively, with mass removal rates between 71 % and 85 % at field scale in Illinois (Lemke et al., 2022). • Kovacic et al. (2000) found that constructed wetlands (ranging from 0.3 to 0.8 ha in surface area and 1200 to 5400 m^3 in volume) removed 37 % of nitrogen and 2 % of phosphorus from agricultural tile drainage systems. Coupling with a 15.3-m buffer strip increased nitrogen removal to 46 %.
Saturated riparian buffers (SRBs)	• Average annual NO_3-N load removal ranged from 13 to 179 kg N for drainage areas of 3.4 to 40.5 ha in Iowa. Annual removal effectiveness (fraction of total field NO_3-N load removed by the saturated riparian buffers) ranged from 8 % to 84 % (Jaynes and Isenhart, 2019).
Combination of manure lagoons, terraces, buffer strips, sediment control basins, crop rotations, soil testing, optimum fertilization rates, and tillage practices	• At the watershed scale, the most significant reductions were observed, with an average 55.8 % decrease in nutrient loadings following Whole Farm Planning. BMPs proved more effective when integrated into comprehensive whole-farm planning rather than as isolated practices in New York (Makarewicz et al., 2009).

examined the effects of CDS alone and in combination with cover crops. CDS alone reduced NO_3–N concentrations by 15–33 % and cumulative losses by 38–39 % relative to free tile drainage. When combined with cover crops, cumulative NO_3–N concentrations and losses were reduced by 47 %, highlighting the enhanced effectiveness of integrating multiple BMPs. At the Honorable Eugene F. Whelan Research Farm in South Woodslee, Ontario, Zhang et al. (2017) evaluated the effectiveness of combining CDS and overwinter cover crops (CC) on phosphorus reduction. The CDS-CC system reduced DRP, PP, and TP losses in surface runoff by 0.03, 0.15, and 0.22 kg/ha/year, respectively, compared to regular free drainage without cover crops (RFD-NCC). In tile drainage water, the reductions were 0.07 kg/ha/year for DRP, 0.12 kg/ha/year for PP, and 0.19 kg/ha/year for TP. Overall, the CDS-CC treatment achieved up to a 23 % reduction in TP losses, demonstrating the potential of integrating water table management with cover crops. However, by raising the water table and increasing surface soil saturation, CDS may lead to nutrient-rich surface runoff, indicating a trade-off in water quality outcomes. In the saturated soil, excess water flows overland due to limited percolation downward. As a result, CDS can reduce subsurface nutrient export in tile flow but may inadvertently shift nutrient load to overland pathways.

Structural measures such as constructed wetlands and saturated riparian buffers (SRBs) have been employed as edge-of-field BMPs to reduce nutrient loadings from tile-drained fields. Lemke et al. (2022) studied the effectiveness of constructed wetlands in McLean County, Illinois. Wetlands covering 3 %, 6 %, and 9 % of tile-drained areas were monitored. Wetlands occupying 3 % of the tile-drained area reduced NO_3–N export by 15–38 %, while those covering 6 % and 9 % achieved reductions of 39–57 %. For DRP, the wetlands achieved total loading reductions ranging from 32 % to 95 %, with mass removal rates between 71 % and 85 %. Groh et al. (2015) re-evaluated two wetlands established in 1994. This study reported that wetlands continued to remove NO_3-N similar to rates measured shortly after construction, achieving 56 % NO_3-N removal directly in the wetlands and an additional 6.1 % through seepage via riparian buffer strips at wetlands, with relatively low greenhouse gas emissions. Jaynes and Isenhart (2019) showed that saturated riparian buffers are a cost-effective conservation practice that can reduce 8 % to 84 % of NO_3-N loadings from tile drainage water before it enters streams. However, Jaynes et al. (2018) emphasized the installation of SRBs at suitable sites. Key site criteria include the presence of an existing or planned riparian buffer, at least 30 ft wide, with perennial vegetation through which a tile outlet can pass. The soil within the buffer should be loam or clay loam with a minimum of 1.2 % organic matter and a high water table to support denitrification. Additionally, the buffer area should be slightly lower than the adjacent field to prevent crop saturation, and the streambanks must remain stable to ensure long-term functionality. These studies underscored the potential of constructed wetlands and SRBs as effective BMPs for nutrient reduction.

Integrated approaches combining multiple BMPs have shown enhanced effectiveness in reducing nutrient losses. Drury et al. (2014) demonstrated that combining cover crops with CDS resulted in more reductions in NO_3–N losses than either practice alone. Similarly, Makarewicz et al. (2009) studied the effects of structural and non-structural BMPs in the Conesus Lake watershed in New York. Substantial reductions were observed in TP, NO_3–N, total Kjeldahl nitrogen, and total suspended solids. The most notable reduction was an average of 55.8 % decrease in nutrient loadings following the implementation of whole farm planning, which included a combination of structural and non-structural BMP measures, emphasizing that BMPs are more effective when integrated into comprehensive farm management plans rather than applied in isolation.

These monitoring studies demonstrated that BMPs can substantially reduce nutrient losses from tile-drained agricultural fields. Cover crops are particularly effective in reducing NO_3–N losses. Controlled drainage systems can reduce N and P losses by managing drainage outflow, although there are possibilities of increasing surface runoff nutrient loadings under certain conditions. Nutrient management practices and structural BMPs like constructed wetlands also reduce nutrient loading. However, BMP efficacy can vary based on regional and seasonal factors, and no single practice is sufficient. Some BMPs may reduce one nutrient while inadvertently increasing another, as seen with the increase in DRP losses under NTCC systems (Macrae et al., 2023). Integrated approaches combining multiple BMPs are recommended to improve water quality substantially (Sunohara et al., 2015; Fales et al., 2016). Tailoring BMP combinations to specific site conditions offers the greatest potential for mitigating nutrient losses from tile-drained fields.

5.2. BMP effects on nutrient loading reduction in tile-drained fields and watersheds based on modeling studies

Modeling studies complement monitoring efforts by allowing the assessment of BMP impacts under various scenarios, including different climate conditions and management practices. An overview of modeling studies on BMP effectiveness in tile-drained fields and watersheds is summarized in Table 5. Moriasi et al. (2013) used the SWAT model to assess the effects of adjusting tile drain spacing and depth in southern Minnesota. Reducing tile drain depth from 1.5 to 0.9 m led to an 8 % reduction in tile flow and a 14 % reduction in NO_3–N losses. Increasing tile drain spacing from 27 to 60 m resulted in an 11 % reduction in tile flow and a 16 % reduction in NO_3–N losses. Therefore, optimum tile drainage configuration can reduce nutrient losses, as found in other studies by Morrison et al. (2013) at the field scale and Que et al. (2015) at the watershed scale. However, Moriasi et al. (2013) highlighted that reductions in N application rates are more effective than adjustments in tile drain spacing and depth for reducing nutrient loadings at the watershed scale.

Ren et al. (2022a, 2022b) used the SWAT model to assess the effects of crop (corn and soybean) trait improvements to reduce nitrogen losses via tile drainage and percolation and phosphorus losses via surface runoff and tile drainage in the St. Joseph River Watershed located in the U.S. Corn Belt. The modeling results showed that over the past 30 years, crop trait improvements contributed to a 6.8–18.6 % reduction in nitrogen loads (NO_3–N and TN) and a 2.6–3.9 % reduction in phosphorus loads (DRP and TP), while only a modest 0.7–0.9 % increase in evapotranspiration and a 1.5–2.0 % decrease in streamflow annually in an agricultural watershed with approximately 50 % cropland. Pan et al. (2023) applied the RZWQM2-P model to evaluate the impact of tillage intensity and manure application efficiency on phosphorus losses in two neighboring farm fields with tile drainage systems near South Woodslee, southern Ontario. Increasing tillage intensity from no-till to intensive tillage moldboard plow decreased DRP losses by 48.12 % and PP losses by 30.29 %. Enhancing manure/compost mix efficiency reduced DRP losses by 53.98 % and PP losses by 30.95 %, highlighting the effectiveness of specific tillage and nutrient management strategies in reducing nutrient losses. Qi et al. (2018) used the ICECREAM model to assess the effects of tillage timing and fertilizer application methods on phosphorus loss. Shifting autumn tillage to spring resulted in a 10 % reduction in TP losses. Injecting fertilizer rather than surface broadcasting reduced TP losses by 25.4 %, indicating that adjustments in tillage timing and fertilizer application methods can effectively reduce nutrient losses at field scale. Gupta et al. (2022) utilized the decision support system for agrotechnology transfer (DSSAT) model to optimize nitrogen application timings and assess the impact of cereal rye cover crops at a field scale in Illinois. The model predicted substantial reductions in tile drainage volumes and NO_3-N loss with the introduction of cereal rye, demonstrating the effectiveness of cover crops and optimized nitrogen application in nutrient loading reduction. Sadhukhan et al. (2019a, 2019b) evaluated manure injection, controlled drainage, and winter manure application at field scale using the RZWQM2-P model. Manure injection reduced total phosphorus losses by 18 % compared to conventional practices. While controlled drainage reduced TP loss via tile flow, it led to an overall increase in TP loss due to enhanced surface runoff. Moreover, winter manure application increased TP losses, highlighting the risks associated with manure application timing.

Dagnew et al. (2019) applied the SWAT model to evaluate various BMPs in the St. Clair–Detroit River watershed spanning southeastern Michigan and southwestern Ontario. Single practices like fertilizer rate reduction and subsurface placement substantially decreased TP and DRP loadings. However, combinations of cover crops, filter strips, and wetland enhancements achieved loading reductions of up to 80 % with

Table 5
Major findings from modeling studies of BMP effects on nutrient reduction in tile-drained fields and watersheds (Supplementary Tables S13 and S14 provide a review of the specific studies that inform this Table).

BMP type	BMP effectiveness
Adjusting depth of Controlled Tile Drainage (CTD)	Tile drainage depth of approximately 600 mm below the surface can be a good compromise for reducing nutrient loadings; over five growing seasons, CTD at 600 mm depth reduced direct runoff by 6.6 %, TN by 3.5 %, and NO_3-N by 13.7 % compared to CTD at 200 mm depth, although it led to slight increases in TP by 0.96 % and DRP by 1.6 % at watershed scale in Ontario (Que et al., 2015).
Adjusting tile drainage spacing	At Site A, increasing drain spacing from 5 to 70 m reduced TP loading in subsurface drainage from 0.5 to 0.2 kg/ha/year and increased surface runoff TP loading from 0 to 0.4 kg/ha/year. At Site B, the same adjustment in drain spacing reduced subsurface TP loading from 2.3 to 0.1 kg/ha/year and increased surface runoff TP loading from 0 to 4.5 kg/ha/year at field scale in Quebec (Morrison et al., 2013).
Controlled Drainage (CD)	In a meta-analysis of modeling results, Kęsicka et al. (2022) reported that controlled drainage reduced drainage outflow and NO_3-N losses by 30.5 % and 33.61 %, respectively, achieving 71.26 mm and 8.36 kg/ha/year reductions. However, NO_3-N reduction varied widely from 0.88 to 12.32 kg/ha/year, with its effectiveness influenced by study duration and local precipitation, showing more significant reductions in longer studies and areas with lower rainfall.
Reducing nitrogen (N) application rates and adjusting tile drain spacing and depth	Reducing the depth of tile drains from 1.5 to 0.9 m led to an 8 % reduction in tile flow (from 207 to 191 mm) and a 14 % reduction in NO_3-N losses (from 34.0 to 29.4 kg/ha). Increasing tile drain spacing from 27 to 60 m resulted in an 11 % reduction in tile flow (from 205 to 182 mm) and a 16 % reduction in NO_3-N losses (from 33.8 to 28.4 kg/ha). Reducing the nitrogen (N) application rate from 200 to 100 kg/ha led to a 67 % decrease in NO_3-N losses (from 33.8 to 11.1 kg/ha). Significant reductions in NO_3-N losses are more effectively achieved at the watershed scale in Minnesota through reductions in N application rates compared to adjustments in tile drain spacing and depth (Moriasi et al., 2013).
Crop improvement	Crop trait improvements can reduce nitrogen loads (NO_3–N and TN) by 6.8 % to 18.6 % and phosphorus loads (DRP and TP) by 2.6 % to 3.9 % annually (Ren et al., 2022a, 2022b). The efficient use of nutrients by the improved crops during the growing season has a lag effect on nutrient processes. During the non-growing season (from October to April), TN and TP loads can be reduced by approximately 40 % and 10 %, respectively (Ren et al., 2022a, 2022b).
Adjusting tillage timing and fertilizer application methods (injection vs. surface application)	Shifting autumn tillage to spring results in a 10 % reduction in TP losses. Injecting fertilizer rather than broadcasting can reduce TP losses by 25.4 % at field scale. Furthermore, approximately 86.9 % of TP losses through tile drainage occur during the non-growing season in Ontario, highlighting the critical need for targeted

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Table 5 (*continued*)

BMP type	BMP effectiveness
	management strategies to address this significant loss period (Qi et al., 2018).
Adjusting tillage intensity and compost/manure application efficiency	Tillage practices can reduce tile drainage and P loss compared to no-till management. Increasing tillage intensity from no-till to intensive tillage using a moldboard plow leads to a 48.12 % decrease in DRP losses and a 30.29 % reduction in PP losses. Additionally, enhancing the efficiency of manure/compost mix from 0 to 0.5 with moderate soil mixing via a Tandem Disk reduces DRP losses by 53.98 % and PP losses by 30.95 %. These results emphasize the effectiveness of specific tillage and compost management strategies in significantly reducing nutrient losses at field scale in Ontario (Pan et al., 2023).
Adjusting nitrogen application timings (fall and spring) with and without cereal rye cover crop	Cereal rye cover crop significantly reduced NO_3-N loss and tile drainage volumes. Predicted reductions in NO_3-N loss were 43.6 % for fall and 45.4 % for spring nitrogen (N) application treatments, while observed reductions were slightly higher at 48.6 % and 47.8 %, respectively. Regarding tile drainage volume, the predicted reductions were 21.3 % for fall and 21.0 % for spring applications, whereas the observed reductions were 30.2 % and 19.4 %, respectively at field scale in Illinois (Gupta et al., 2022).
Manure injection, controlled drainage, and winter manure application	Manure injection effectively reduced TP losses in subsurface-drained fields by 18 % compared to conventional practices. However, while controlled drainage reduces TP loss via tile flow, it leads to an overall increase in TP loss by 13 % due to enhanced surface runoff. Additionally, winter manure application significantly exacerbated TP losses, showing a 23 % increase. These findings highlight the complex interactions between management practices and their impacts on phosphorus dynamics in agricultural settings at the field scale in Ontario (Sadhukhan et al., 2019a, 2019b).
Fertilizer application rate reduction and sub-surface placement, filter strips, cover crops, and increasing wetland drainage areas	Filter strips achieved 20 to 39 % TP and 18 to 37 % DRP reductions, while subsurface fertilizer placement reduced TP and DRP by 29 to 35 % and 30 to 33 %, respectively. Cover crops resulted in a 30 % TP and 24 % DRP reduction. The most effective combinations, involving cover crops, filter strips, and wetland enhancements, achieved up to 80 % loading reductions at the watershed scale in southeastern Michigan and southwestern Ontario. However, controlled drainage and no-till practices increased TP and DRP loadings, though integrating controlled drainage with cover crops could mitigate this effect (Dagnew et al., 2019).
Management scenarios combined five strategies: fertilizer/manure management, perennial grass conversion, vegetative filter strips, cover crops, and shallower tile drainage.	Conversion of nutrient-loading hotspot areas to perennial grass led to a 47 % reduction in NO_3-N levels. Implementing multiple management practices, including reduced fertilizer/manure application, shallower tile drainage, cover crops, and vegetative filter strips, achieved a 38.5 % reduction in NO_3-N levels. Furthermore, extensive conversion of areas to perennial grass could achieve a 49.7 % reduction in NO_3-N at watershed scale in Iowa. However, projections suggest that climate change may reduce the effectiveness of these practices by up to 65 % for NO_3-N management by the late 21st century (Teshager et al., 2017).
Combination of BMPs	Merriman et al. (2018) highlighted that significant field-scale BMP investments are essential for improving water quality in tile-drained agricultural watersheds, with single BMPs rarely reducing DRP by >10 %, even at high implementation levels. Filter strips were the most effective single BMP, especially when combined with other practices, and cover crops showed efficacy during winter months in Ohio. Merriman et al. (2019) also demonstrated that combining BMPs such as cover crops, crop rotation, nutrient management, reduced tillage, and filter strips was more effective than individual practices in reducing DRP and TP in Wisconsin.

full implementation. Controlled drainage and no-till practices increased TP and DRP loadings at the watershed scale; however, integrating controlled drainage with cover crops could mitigate nutrient loadings. Teshager et al. (2017) used the SWAT model to analyze management scenarios combining BMPs and found that a combination of reduced fertilizer/manure application, shallower tile drainage, cover crops, and vegetative filter strips achieved a 38.5 % nitrate reduction, emphasizing the importance of integrated nutrient management practices. However, Teshager et al. (2017) and Bosch et al. (2014) highlighted that under future climate scenarios with increased precipitation and altered runoff patterns, the effectiveness of BMPs may be reduced. Higher implementation rates of BMPs at the field and watershed scale could substantially offset increases in nutrient yields due to climate change, emphasizing the need for adaptive management strategies considering both surface and subsurface nutrient loadings.

Modeling studies consistently demonstrated that BMPs can reduce nutrient losses from tile-drained watersheds. Nutrient management practices have effectively reduced nitrate and phosphorus losses, including optimized fertilizer application and cover crops. Adjustments to tile drainage configurations based on the soil properties and land use, such as reducing drain depth and increasing spacing, can also reduce nutrient loss. However, some BMPs may have unintended consequences. For example, controlled drainage reduced nutrient loadings in tile flow but increased surface nutrient loadings. Climate change and associated hydrological changes can reduce the effectiveness of specific BMPs like cover crops (Johnson et al., 2022). Integrated BMP approaches combining multiple practices offer the greatest potential for nutrient loading reductions. Modeling studies suggested that bundles of BMPs can achieve higher reductions with full implementation in tandem. However, adaptive management strategies that consider site-specific conditions and future climate scenarios are essential for optimizing BMP effectiveness.

5.3. An overview of BMP effects on nutrient load reduction from tile-drained landscapes and associated uncertainty

Figs. 5 and S3 illustrate the range of nutrient load reduction potentials and associated uncertainty for three tiers of BMPs in tile-drained agricultural landscapes: (i) management at the source, (ii) control at the edge-of-field, and (iii) watershed-level combinations of BMPs. Source-level management strategies include adjusting tile drainage depth and spacing, reducing fertilizer application rates, and refining tillage timing and intensity. Other measures involve cover crops, no-till cover cropping, split nitrogen application, and alternative farming

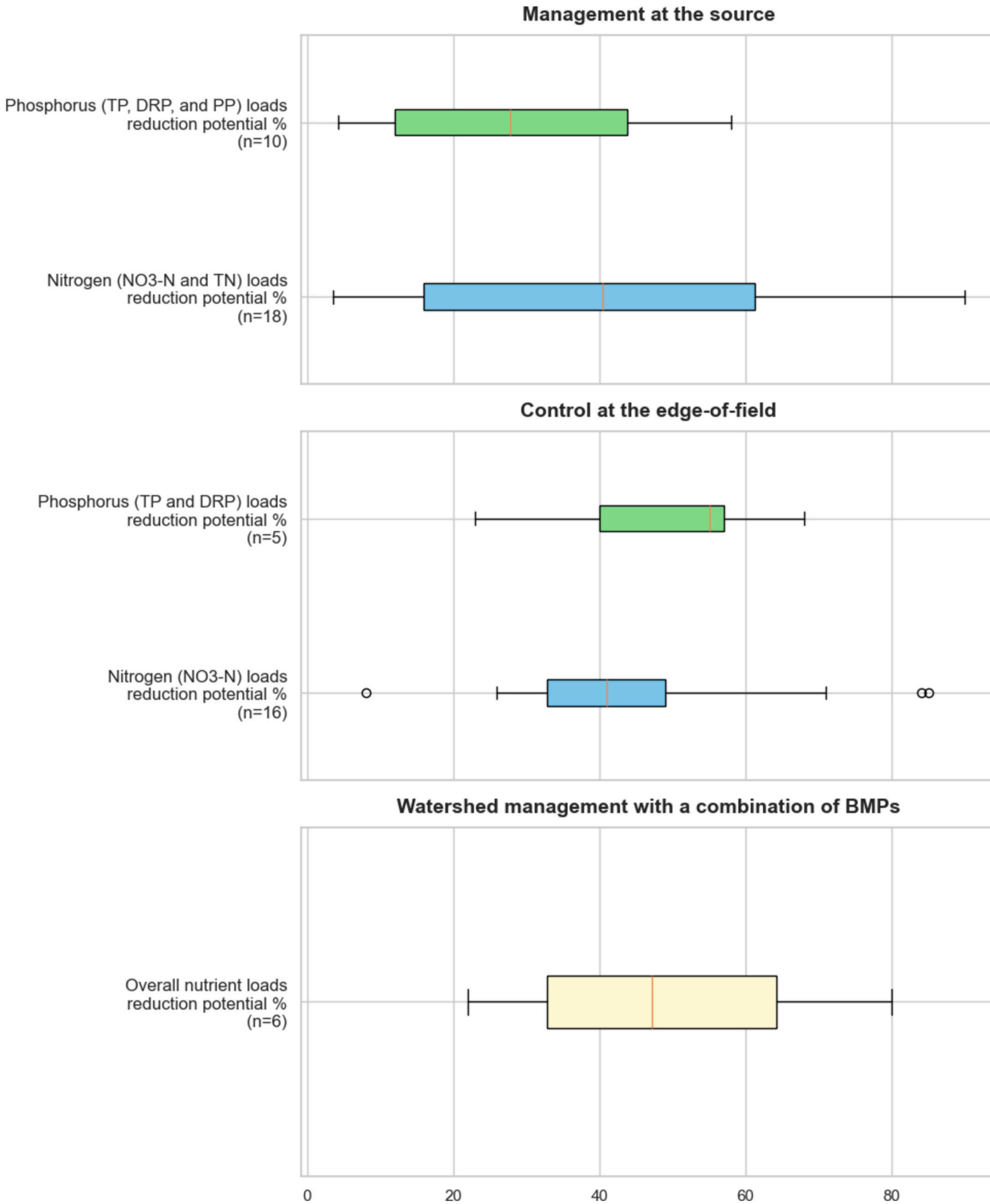

Fig. 5. An overview of BMP effects on nutrient load reduction from tile-drained landscapes. n = sample size. Data sources were Tables 4, 5, Supplementary Tables S12, S13 and S14.

practices. Fig. 5 shows that for BMPs at the source, nitrogen (NO_3–N and TN) reductions range from 3.5 to 90.0 % (Q1 = 16.0, median = 40.5, Q3 = 61.25), while phosphorus (TP, DRP, PP) reductions extend from 4.3 to 58.0 % (Q1 = 12.0, median = 27.7, Q3 = 43.84). Monte Carlo simulations (Supplementary Fig. S3) show mean N reductions of 39.86 % (SD 24.83) within a 95 % CI of (−8.13, 89.89) and mean P reductions of 28.58 % (SD 18.50) within a 95 % CI of (−8.50, 65.19). These broad intervals reflect high uncertainty of BMP effectiveness and sensitivity to crop type, soil properties, management practices, and climatic variabilities.

Edge-of-field BMPs intercept nutrient-rich runoff or drainage water before it enters streams. Key practices include controlled drainage, drainage water management, wetlands, bioreactors, and saturated riparian buffers. Fig. 5 shows that edge-of-field BMPs can reduce NO_3–N load by 8.0 to 85.0 % (Q1 = 32.83, median = 41.0, Q3 = 49.0), while phosphorus (TP, DRP) reductions can be 23.0 to 68.0 % (Q1 = 40.0, median = 55.0, Q3 = 57.0). Monte Carlo simulations estimate mean N reductions of 44.76 % (SD 19.95) within a 95 % CI of (5.42, 83.48) and mean P reductions of 48.60 % (SD 15.60) within a 95 % CI of (17.64, 78.62). Although the median values are high compared to BMPs at the source, BMP performance can drop during extreme flow events or when residence times are inadequate.

Combining source-level and edge-of-field interventions across multiple fields and critical source areas can increase nutrient-load reductions at watershed scale. Fig. 5 shows overall nutrient (P and N) reductions ranging from 22.0 to 80.0 % (Q1 = 32.875, median = 47.15, Q3 = 64.2), while Monte Carlo simulations show mean reductions of 49.05 % (SD 20.39) within a 95 % CI of (8.70, 88.85). These higher reduction potential values suggest synergies when multiple BMPs function at the watershed scale (Wang et al., 2024). However, wide-confidence intervals indicate uncertainties and significant variabilities of BMP performance linked to hydrology, soil properties, climate, land-use patterns, and site-specific BMP performance, highlighting the need for adaptive management (Woznicki and Pouyan Nejadhashemi, 2014; Her et al., 2019; Evenson et al., 2021). Ongoing monitoring, site-specific optimization, and flexibility in BMP selection are essential for sustaining long-term nutrient-load reductions in tile-drained agricultural regions.

Although categorizing BMPs into at-source, edge-of-field, and watershed scales provides a uniform outline and sufficient sample size for statistical analyses, this approach inevitably aggregates diverse practices into broad groups. Therefore, some degree of information is lost, as individual BMPs within the same group may differ in the effectiveness and variability of nutrient load reductions. Certain practices (e.g., specific cover crop species or wetland designs) may exhibit more consistent or higher performance than the overall median reductions of respective categories. Therefore, future studies with expanded datasets or targeted trials of individual BMPs are recommended to refine these broader categories and support feasible site-specific management decisions.

6. Factors affecting hydrologic responses, nutrient loadings, and BMP effectiveness in tile-drained fields and watersheds

Understanding the factors influencing hydrologic responses, nutrient loadings, and the effectiveness of Best Management Practices (BMPs) is crucial for optimizing agricultural productivity while mitigating environmental impacts in tile-drained fields and watersheds of the GLB. Common factors, including tile drainage coverage, soil properties, precipitation patterns, crop types, drainage system design, and climate change, play pivotal roles across these interconnected processes (King et al., 2015a, 2015b). For example, Tedeschi et al. (2024) found that expanding tile drainage areas can result in increased DRP loading to Lake Erie from Canadian tributaries during the thawing season (when the air temperature is between −3.2 and 6.7 °C). Additionally, specific considerations are essential when designing and implementing BMPs to ensure long-term effectiveness under climate change. This section provides a comprehensive overview of these common and specific factors, emphasizing their relationship and implications for BMP design and performance, as represented in Fig. 6.

6.1. Common factors influencing hydrologic responses and nutrient loadings

The hydrologic response of tile-drained fields is governed by a complex interplay of soil characteristics, climatic conditions, agricultural practices, and drainage infrastructure. Soil heterogeneity, particularly variations in texture and structure, considerably affects water infiltration, storage, and movement. For instance, coarse-textured soils promote rapid infiltration but may reduce water retention, while fine-textured soils can lead to slower infiltration rates and more surface runoff (Zhang et al., 2015). These soil properties also influence nutrient dynamics, affecting nitrogen leaching and phosphorus sorption capacity (Hanrahan et al., 2020; Smith et al., 2015).

Soil types affect tile drain flow and nutrient loadings. In a field study in Quebec, Eastman et al. (2010) estimated that tile drainage in clay loam soils resulted in a total outflow four times greater than that from an undrained site with the same soil type. In contrast, a tile-drained sandy loam site discharged 1.8 times more water than a comparable undrained site. Additionally, the form of P in tile flow differed with soil type; 80 % of TP was PP in clay loam soils, whereas only 20 % was PP in sandy loam soils (Eastman et al., 2010). Gaddis and Voinov (2010) estimated higher P loadings from tile flow in clay soils within the St. Albans Bay watershed in Vermont, attributing this to the elevated P concentrations in tile flow from clay soils compared to other soil types.

While soil characteristics can influence tile-drain flow and nutrient export, climate change is an overarching factor substantially affecting hydrologic responses and nutrient loadings in tile-drained fields and watersheds. The GLB has been experiencing climate change, including rising temperatures, reduced snow and ice cover, longer growing seasons, and more frequent intense rainfall events (Bosch et al., 2014). Future projections indicate further increases in temperatures and changes in precipitation patterns, which are expected to impact water quantity and quality in the region (Bosch et al., 2014).

Precipitation patterns, including frequency, intensity, and timing, are primary drivers of hydrologic responses and nutrient transport. Climate change is expected to alter these patterns, with winter and spring precipitation increasing by 20–30 % and a higher percentage of winter precipitation falling as rain (Bosch et al., 2014). High-intensity rainfall events, which are projected to become more frequent, can generate rapid tile drain flows and increase the mobilization of nutrients, mainly when antecedent soil moisture is high (Coelho et al., 2010). Mehan et al. (2019) projected that subsurface drain flow could increase by 11 % to 50 % under RCP 4.5 and up to 67 % under RCP 8.5 by 2070–2099. Similarly, Golmohammadi et al. (2021) found that simulated tile flows are expected to increase by 7 % in the 2071–2100 period compared to 1960–1990. These increased hydrologic flows are likely to cause more nutrient transport.

Moreover, extreme precipitation events are expected to become more frequent and intense due to climate change, exacerbating nutrient losses. Vidon and Cuadra (2011) found that more storms with precipitation exceeding 6 cm had higher phosphorus concentrations in tile-drain flow, with soluble reactive phosphorus accounting for 16.2 % to 22.0 % of total phosphorus fluxes during such events. These events can lead to increased nutrient export via overland flow and macropore flow, reducing infiltration opportunities and increasing the risk of nutrient transport to waterways (Mehan et al., 2019). Seasonal variations in precipitation also affect nutrient loading, with higher losses often occurring during wetter periods (Plach et al., 2019). Climate change projections indicate that wetter springs and winters may further amplify this effect, leading to increased nutrient losses during these seasons. However, Li et al. (2016) reported that water availability will decrease in summer over the Grand River watershed, and adaptation strategies

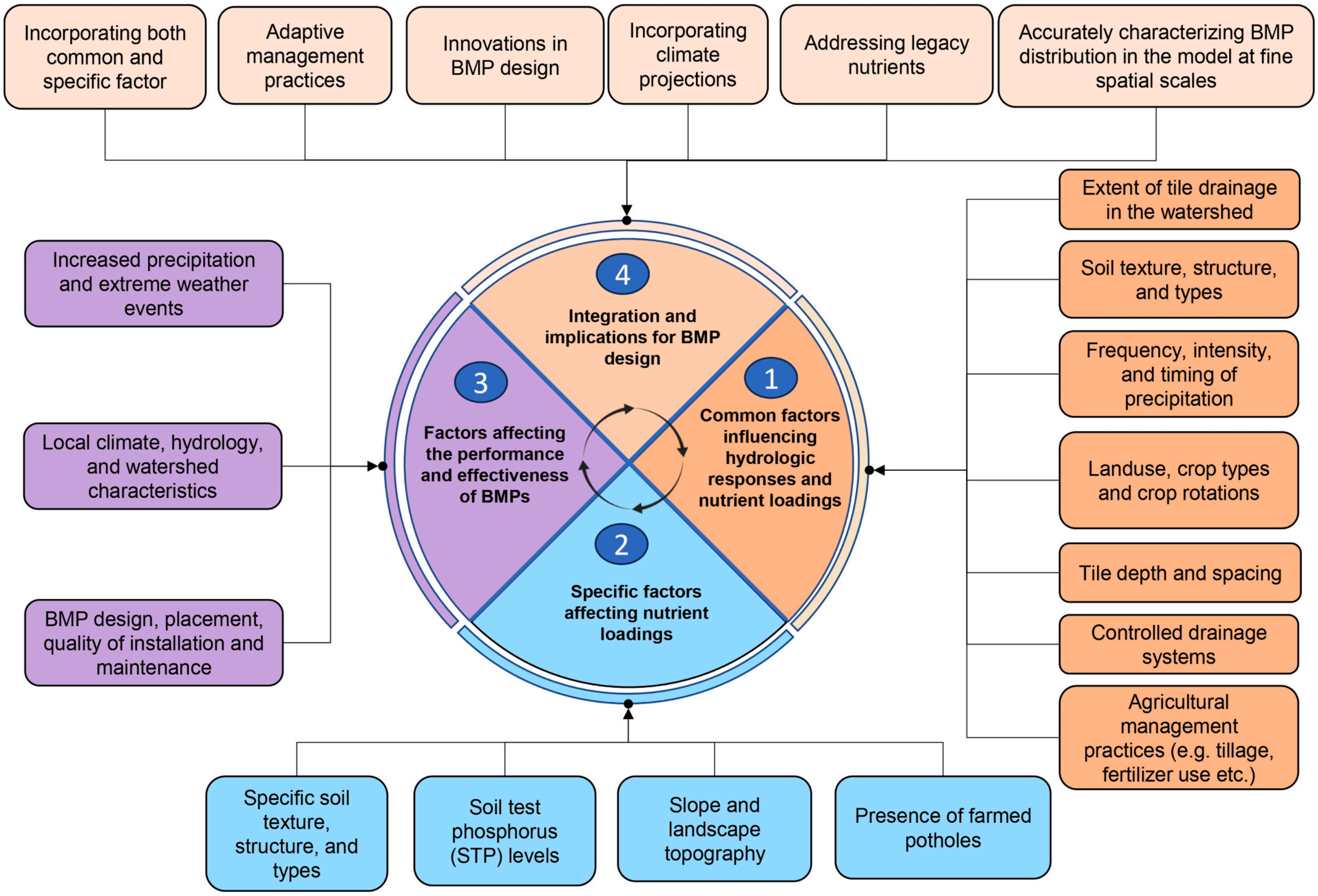

Fig. 6. Categorization of factors affecting hydrologic responses, nutrient loadings, and the effectiveness of Best Management Practices (BMPs) in tile-drained fields and watersheds.

such as subsurface irrigation would be essential to ensure crop growth in a changing climate.

Agricultural practices such as crop type, fertilizer application, and tillage influence water movement and nutrient losses. Crops with extensive root systems, like alfalfa, may reduce tile drain flows by enhancing water uptake and promoting soil structure that impedes rapid drainage (Oquist et al., 2007). Conversely, continuous cropping systems can increase tile drain flows by developing biopores and soil cracks that facilitate preferential flow paths (Askar et al., 2020). Tillage practices impact the formation of macropores and the incorporation of fertilizers, thereby affecting nutrient cycling and transport mechanisms (Sadhukhan et al., 2019a, 2019b).

Furthermore, drainage system design, including tile depth and spacing, directly influences hydrologic responses and nutrient loading. Shallower drains respond more rapidly to precipitation events but may result in lower overall drainage volumes, affecting the timing and magnitude of nutrient export (King et al., 2015a, 2015b). Narrower drain spacing increases drainage volume and can enhance the transport of soluble nutrients like NO_3-N and DRP (Williams et al., 2015a). Moreover, controlled tile drainage (CTD) is recommended for agricultural lands with surface slopes $\leq$1 % (Que et al., 2015). CTD systems can adjust water flow, improving water use efficiency and reducing nutrient losses by retaining water (Zhang et al., 2015).

6.2. *Specific factors affecting nutrient loadings*

Beyond the common factors, specific soil and environmental conditions play critical roles in nutrient loading. Soil texture and structure influence not only hydrologic responses but also soil's denitrification potential and phosphorus sorption capacity (Lam et al., 2016). Fine-textured clay soils with high phosphorus sorption capacity may retain more phosphorus and be prone to forming macropores that facilitate rapid nutrient transport via preferential flow (Plach et al., 2018). King et al. (2015a, 2015b) reported that medium and coarse-textured soils generally exhibit lower P losses than clay-rich soils with macropores. Similarly, Eastman et al. (2010) found that in clay loam soils, preferential flow facilitated higher P transport than in sandy loam soils, attributing the elevated PP in the tile flow.

High soil test phosphorus (STP) levels are directly linked to increased DRP and TP loadings in tile flow (Plach et al., 2018). Excessive fertilizer application without proper incorporation leads to phosphorus accumulation at the soil surface, exacerbating STP (Williams et al., 2018). In waterlogged soils, redox chemical reactions can increase phosphorus solubility and mobility, increasing the risk of phosphorus leaching into tile drains (Lam et al., 2016). Specific landscape features, such as different levels of slope and the presence of potholes and wetlands, influence surface runoff and the potential for nutrient transport to subsurface drainage systems. For example, tile drainage systems in the high slope areas can increase runoff and contribute to more nutrient loading from the fields to streams (Madison et al., 2014; Christianson and Harmel, 2015b).

6.3. *Factors affecting the performance and effectiveness of BMPs*

Designing effective BMPs requires careful consideration of both common and specific factors influencing hydrologic responses and nutrient loadings, including the impacts of climate change. Local soil type, climate, hydrology, and watershed characteristics influence BMP performance. Morrison et al. (2013) found that increasing lateral tile drain spacing decreased subsurface drain flow and increased surface runoff in both sandy and clay loam soils. However, the effectiveness varied by soil type, such as every 5-m increase in drain spacing led to a 6 % decrease in TP loadings in tile flow for sandy loam soils but a more substantial 20 % decrease for clay loam soils (Morrison et al., 2013).

In the context of climate, the projected increases in precipitation and extreme weather events can overwhelm BMPs designed under historical climate conditions (Bosch et al., 2014). For instance, BMPs might be less effective in reducing nutrient loadings during intense rainfall events, which are becoming more frequent due to climate change. BMPs might be overwhelmed more quickly in areas with intense precipitation than regions with moderate precipitation patterns. Variations in sediment loading and water chemistry can affect the nutrient filtration and adsorption capacity of BMPs (Liu et al., 2017; Lintern et al., 2020). Increased hydrologic flows can transport substantial amounts of nutrients, potentially offsetting the benefits of BMPs. Bosch et al. (2014) indicated that climate change could offset runoff reductions achieved from BMP implementation, potentially reducing the effectiveness of management practices by up to 65 % for NO_3-N loadings. These findings highlight the need for BMP designs that are resilient to changing climatic conditions and adapt to increased hydrologic variability.

Beyond the impact of climate change, BMP performance also depends on field management practices such as tillage intensity. Many BMPs were historically designed to minimize soil losses through reduced or no-tillage strategies. However, minimal disturbance practices can promote the development and retention of soil macropores, increasing surface-subsurface connectivity and allowing preferential flow (Askar et al., 2020). This can enhance phosphorus transport from enriched surface soils to subsurface drainage, bypassing potential biogeochemical filtering mechanisms within the soil matrix. Alternatively, deep tillage disrupts these preferential flow paths, potentially reducing P concentrations in subsurface drainage (King et al., 2014).

Beyond adjusting management practices, the initial structural design and quality of construction play critical roles in BMP effectiveness. Poorly designed or implemented structural BMPs may fail prematurely or never perform to their theoretical capacity. Factors such as appropriate sizing, correct installation practices, and selection of suitable locations are essential for maximizing BMP effectiveness (Liu et al., 2017; Lintern et al., 2020). Under changing climate conditions, BMPs may need to be re-evaluated and possibly re-designed to handle increased flows and nutrient loadings.

Assessing BMP effectiveness is challenging due to many factors influencing nutrient transport, including scale, agricultural activity, and landscape interactions. For example, Lavaire et al. (2017) reported that water and nutrients may bypass or seep around control structures of DWM and eventually enter nearby free drainage or groundwater. As a result, the overall reduction in nutrient loads may be lower than the values reported based on tile outflow. This highlights the importance of considering the ultimate fate of water and nutrients while assessing the effectiveness of DWM in reducing nutrient losses. Moreover, BMP effectiveness does not easily translate from field to watershed scale because complex processes such as nutrient routing and in-stream dynamics control nutrient transport from the edge-of-field to watershed outlets (Merriman et al., 2018). Moreover, regular maintenance is critical for sustaining BMP performance over time. Without routine maintenance, the efficiency of BMPs in reducing pollutant loadings can decrease due to structural degradation, clogging, or changes in surrounding land use. This temporal variability is often underestimated in field studies and modeling efforts, leading to potential overestimations of long-term effectiveness (Liu et al., 2017; Lintern et al., 2020).

Accurately characterizing the distribution and abundance of BMPs at a fine spatial scale in the models is difficult. Improving input data requires coordinated, local-scale agricultural management data and post-BMP monitoring programs (Kerr et al., 2016). There is a noted gap in long-term empirical data for BMP performance, which challenges the accuracy of models used to predict BMP effectiveness over time. Current models often assume constant efficiency without accounting for natural deterioration or potential improvements through reconstructive efforts (Liu et al., 2017; Lintern et al., 2020). Improving our understanding requires collecting long-term empirical data to enhance models and improve predictions of BMP performance under varying conditions, including those influenced by climate change.

6.4. Integration and implications for BMP design

Given the interconnected nature of the factors influencing hydrologic responses, nutrient loadings, and BMP effectiveness, adopting a holistic approach to BMP design and implementation is essential under climate change. Tailoring BMPs to specific soil and land-use conditions can enhance BMP effectiveness in reducing nutrient losses while maintaining agricultural productivity (Kim et al., 2023; Morrison et al., 2013). Consideration of common factors such as soil properties, precipitation patterns, agricultural practices, and projected climate change ensures that BMPs address the primary drivers of nutrient transport.

Specific factors, such as the potential for preferential flow paths and the soil's phosphorus sorption capacity, should inform BMP selection and design. In areas prone to macropore development, practices that disrupt preferential flow or enhance soil matrix interactions may be more effective. Similarly, in soils with high STP levels, strategies that reduce phosphorus application or promote its incorporation into the soil can mitigate phosphorus losses. Furthermore, the historical extensive use of fertilizers can lead to the accumulation of legacy nutrients in soils, wetlands, and water bodies, which may persist for years or even decades. These legacy nutrients continue contributing to nutrient loadings to water bodies, exacerbating water quality issues even after BMP implementation (Basu et al., 2023). For example, Osterholz et al. (2024) found that preexisting soil phosphorus dominated the tile flow, with only 14 % of DRP and 5 % of TP originating from new applications of fertilizer and manure. Therefore, understanding the impact of legacy nutrients is crucial in assessing the effectiveness of BMPs and achieving nutrient loading targets (Basu et al., 2023).

Incorporating adaptive management practices that account for the temporal variability of environmental changes is essential. For example, Dohleman et al. (2024) reported that yield-scaled NO_3-N losses decreased by 74 % when comparing 1990s-era (Old) corn systems to 2010s-era (Current) systems and by 91 % when projected to the 2030s (Future). Ren et al. (2022a, 2022b) also documented that improved crop varieties of corn and soybeans can efficiently use nutrients and reduce nitrogen loads. Therefore, updated crop genetic information should be incorporated into the modeling and monitoring studies to estimate current and future nutrient losses and BMP effectiveness. Moreover, regular monitoring and maintenance can improve BMP performance over time, while flexibility in management allows for adjustments based on observed conditions and outcomes.

Given the anticipated impacts of climate change on hydrologic responses and nutrient loadings, BMP design and implementation must account for future climatic conditions to remain effective. Integrating climate projections into watershed models can help predict future conditions and guide the selection and placement of BMPs (Kerr et al., 2016). For instance, Niroula et al. (2023) projected wetter springs and drier summers in the U.S. Midwest (2031–2059), which may damage crop production via increased nutrient leaching and root-zone saturation. This study reported that extending tile drainage coverage and increasing fertilizer rates can maintain baseline corn yields but nearly doubling NO_3–N loadings to waterbodies. However, shifting to spring-only fertilizer application can reduce this increase of NO_3-N loadings to about 1.25 times from the baseline, and adopting cover crops or switchgrass may even improve water quality compared to current levels. Therefore, adaptive strategies for tile-drained landscapes under changing climatic conditions should focus on increasing resilience to more frequent intense precipitation, extended growing seasons, and shifting temperature patterns. For instance, Johnson et al. (2022) reported that adjusting the timing and height of water control structures in controlled drainage systems can mitigate excess flows during peak precipitation events or store water for drier periods. Retrofitting edge-of-field practices (e.g., constructed wetlands and grassed waterways) with increased capacity or overflow features adapt better to intense precipitation. Integrating climate-resilient cover crops and perennial rotations may enhance soil structure and nutrient uptake, reducing runoff and tile drain nutrient loads under high-flow scenarios. These strategies can be combined with advanced nutrient management plans (e.g., subsurface injection and flexible fertilizer timing) to ensure that BMPs remain effective despite evolving hydrological patterns driven by climate change (Johnson et al., 2022).

Innovations in management practices include disconnecting flow pathways between surface soils and subsurface drainage through occasional deep tillage, utilizing rock and blind inlets, and adjusting the outlet height of drainage systems with control structures such as stackable boards or stop logs, which can effectively reduce nutrient loadings. Filters can be used in the tile outlets to improve tile outflow management, including cartridges and structures filled with materials like blast furnace slag, zeolite, and dolomite sand (King et al., 2014). Ditch design and management, such as two-stage ditches which are small constructed floodplains adjacent to the stream channel, can be implemented to intercept nutrients and slow water velocity, thereby promoting in-stream denitrification processes (Speir et al., 2022) and reducing nutrient runoff (Williams et al., 2015b; King et al., 2014).

Moreover, specific agricultural drainage water treatment technologies such as free water surface constructed wetlands with sedimentation ponds (FWS), denitrifying bioreactors (DBR), and saturated and integrated buffer zones (SBZ and IBZ) are effective management practices as highlighted by Carstensen et al. (2020) in a meta-analysis. A conceptual representation of these mitigation measures is presented in Fig. 7. According to a meta-analysis by Carstensen et al., 2020, on average, FWS can reduce NO_3-N by 41 % and TP by 33 %; DBR can reduce NO_3-N by 40 %; controlled drainage can reduce NO3-N by 50 % and TP loss by 34 %; SBZ can remove NO_3-N by 37 %; and IBZ can remove NO_3-N by 26 % and TP by 48 %. Specific studies such as Moorman et al. (2015) reported that DBR can effectively reduce NO_3-N losses by at least 20 % to 30 %, requiring only up to 0.27 % of the watershed area for a cumulative volume with a half-day hydraulic retention time. Woodchips are extensively used as porous materials to fill the DBR bed. Fan et al. (2022) identified optimal abiotic conditions (media age, hydraulic retention time, and temperature) for maximizing NO_3-N removal rates and the efficiency of the woodchip bioreactor. Expanding on this, Fan et al. (2023a) reported that adding biochar and silage leachate can enhance DBR performance, while Fan et al. (2023b) suggested using mixed substrates (e.g., woodchips and agricultural byproducts) can also increase denitrification and optimize the design of DBR. Moreover, Fan et al. (2023c) proposed nonlinear models (e.g., Mitscherlich) for optimizing the relationship between retention time and nitrate removal in denitrifying bioreactors, advancing design improvements under diverse field conditions. Zak et al. (2018) conducted a study on the IBZ system that is distinct from traditional riparian buffer strips, incorporates a combination of a pond and a flow-through filter bed. This IBZ system can remove 10–67 % of TN and 31–69 % of TP loadings. However, Carstensen et al. (2020) also reported substantial variabilities in the reported nutrient reduction rate efficiencies, underscoring the influence of critical factors and inherent uncertainties on BMP effectiveness.

Beyond drainage design, refining soil health scoring and understanding the relationship between soil depth and agricultural productivity can inform BMP selection for different soil types and climates (Amgain et al., 2022; Bai et al., 2024). Furthermore, considering the impact of climate change, BMPs can be modified, designed, or managed differently in response to increased surface and subsurface runoff and nutrient loadings resulting from more frequent and intense precipitation events. During the dry periods, subsurface irrigation and recycling of drainage water from the controlled drainage system can be introduced for optimum crop growth.

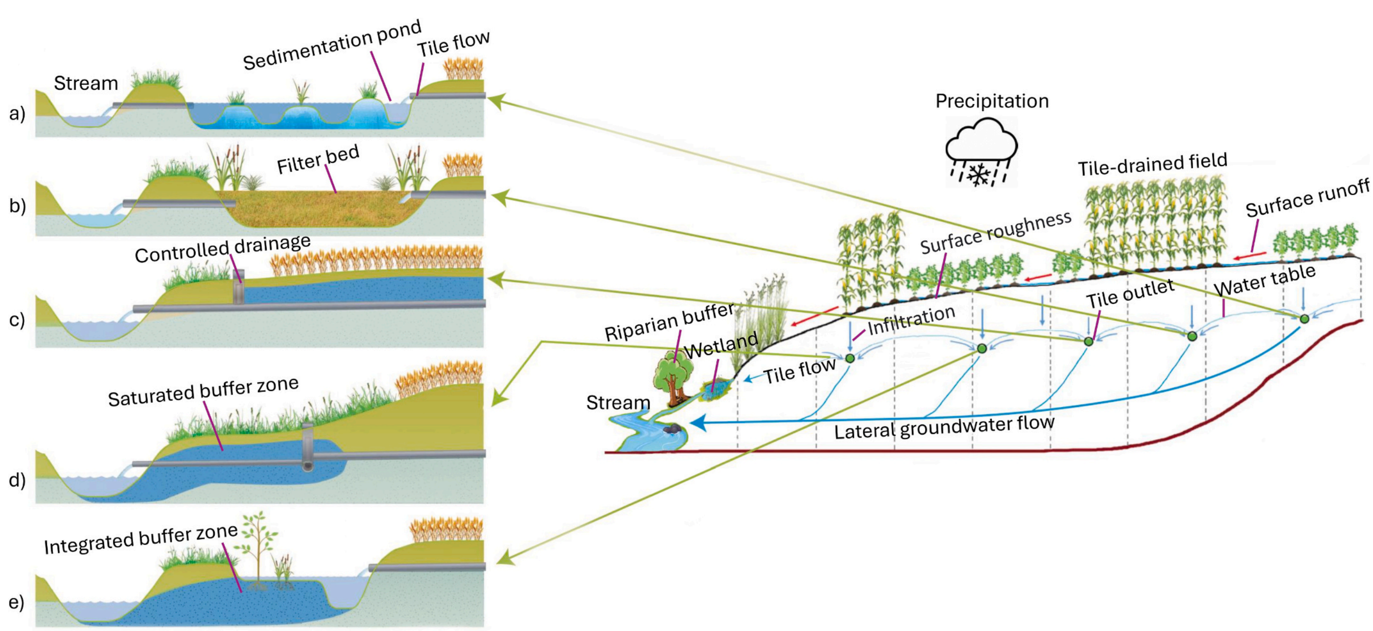

Fig. 7. A conceptual representation of tile outlet management using different mitigation measures such as a) free water surface constructed wetlands with sedimentation ponds, b) denitrifying bioreactors, c) controlled drainage, d) saturated buffer zone, and e) integrated buffer zone.
Adapted from Carstensen et al. (2020) and Cao et al. (2023).

7. A framework for developing potential BMP scenarios in the tile-drained watershed

BMP effectiveness varies between non-tile and tile-drained fields due to differences in water flow pathways and nutrient transport mechanisms. BMPs such as conservation tillage and vegetative filter strips in non-tile drained landscapes primarily address surface runoff. These BMPs effectively reduce nutrient loadings by intercepting and filtering runoff before it reaches water bodies (Plach et al., 2019; King et al., 2015a, 2015b). Conversely, subsurface drainage systems in tile-drained fields alter the hydrological regime, redirecting a substantial portion of surface runoff and associated nutrient loadings through subsurface pathways. This change reduces the efficacy of BMPs targeting surface runoff, necessitating modifications or integrations of practices to target nutrient losses from tile flows (Blanco-Canqui et al., 2015; Drury et al., 2014). Moreover, climate change exacerbates these challenges by influencing precipitation patterns and extreme weather events, all of which affect the performance of BMPs. Developing comprehensive BMP scenarios for tile-drained watersheds requires an integrated approach that considers these variations and the potential impacts of climate change on agricultural conservation practices. Therefore, understanding the interplay between tile drainage, BMP effectiveness, and climate change is essential for developing resilient conservation strategies.

To enhance BMP effectiveness in tile-drained landscapes under climate change, it is crucial to integrate practices that address nutrient transformation and retention within the soil profile and at the drainage outlet. Nutrient management strategies that precisely match fertilizer application with crop uptake can minimize leaching. Techniques such as subsurface banding of phosphorus fertilizers reduce the risk of nutrient losses in tile flow (Qi et al., 2018; King et al., 2015a, 2015b). Implementing controlled drainage systems can further reduce nutrient losses by managing the water table and decreasing drainage outflow (Williams et al., 2015b; Sunohara et al., 2015). These systems can be adapted to account for climate-induced hydrological changes by modifying control structure elevations and timings to manage shifts in water dynamics (Johnson et al., 2022). Additionally, edge-of-field practices like bioreactors and constructed wetlands designed to treat tile drainage water have shown promise in reducing nutrient loadings (Lemke et al., 2022). Adapting these practices to handle increased flow volumes due to more intense rainfall involves retrofitting systems to enhance capacity and resilience to climatic variations. Cover crops are another effective BMP, but their performance can be sensitive to climate change. Warmer autumns may extend the growing season of primary crops (corn-soybean-wheat), potentially delaying cover crop establishment. To adapt, farmers can select cover crop species and varieties better suited to new climatic conditions, adjust planting and termination schedules, and use species that reduce nutrient loading during nongrowing season (Johnson et al., 2022). These adaptations help maintain the efficacy of cover crops in reducing nutrient loading and enhancing soil health under changing climate.

An optimal BMP scenario for a tile-drained agricultural landscape would involve a multilayer approach that addresses nutrient losses at multiple points: field or source, edge-of-field, and watershed outlet (Fig. 8). Moreover, integrating climate change adaptation strategies into BMP planning ensures the long-term effectiveness and sustainability of conservation efforts in tile-drained landscapes. At the field or source level, precision nutrient management, tillage adjustment, crop trait improvement, and climate-resilient cover crops can optimize nutrient use efficiency and reduce leaching during nongrowing seasons (Hanrahan et al., 2018). Adjusting nutrient application timing and considering regular soil and crop testing can improve application accuracy, minimizing the risk of nutrient runoff due to intense rainfall events (Johnson et al., 2022). Structural BMPs such as water and sediment control basins (WASCOB) within the field and constructed wetlands (tile wetlands) at the edge of the field can be implemented to handle larger volumes of water resulting from increased precipitation intensity. Retrofitting these systems and incorporating flow diversion structures help manage intense events and optimize performance

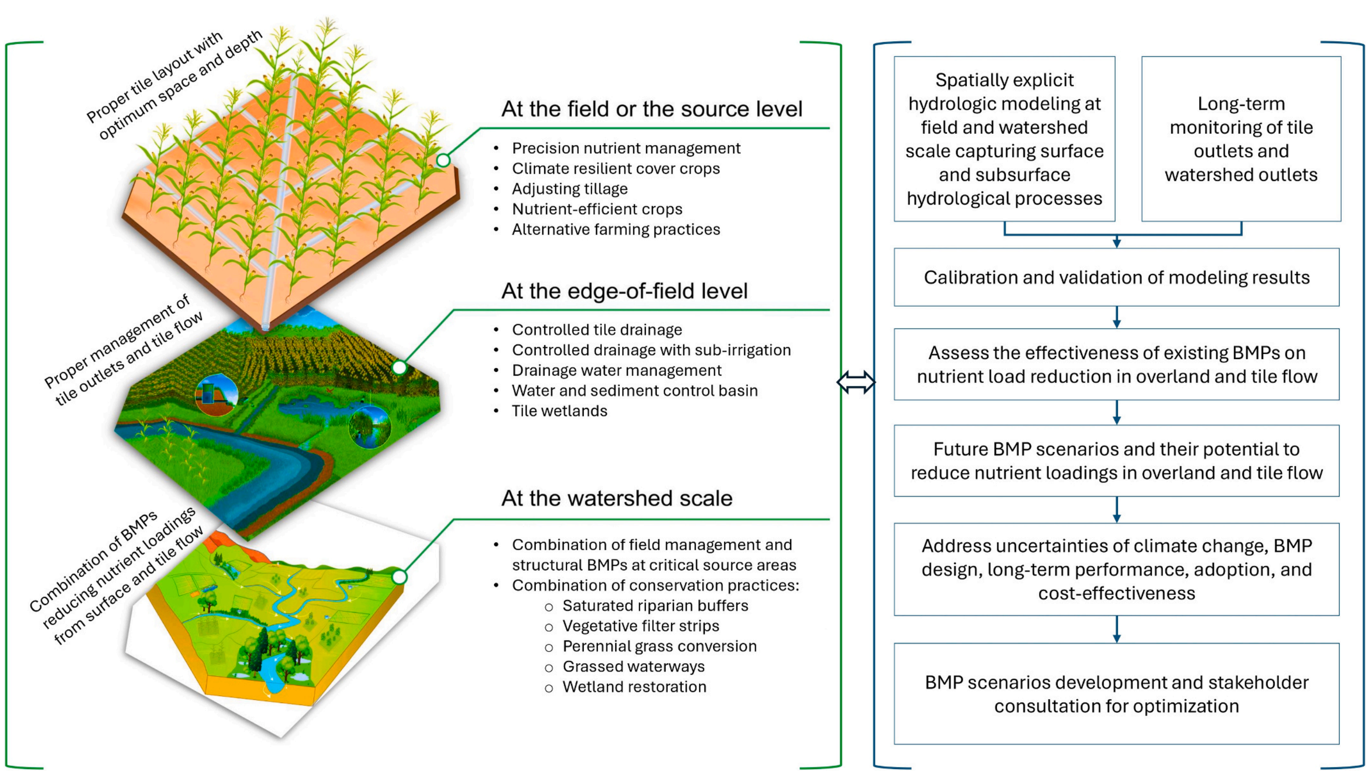

Fig. 8. A multilayer BMP design and scenario development framework for reducing nutrient loadings from the tile-drain dominated landscapes.
Adapted from Carstensen et al. (2020) and The Nature Conservancy (2021).

(Dagnew et al., 2019). Integrating controlled drainage with these structural BMPs enhances nutrient retention and allows for adjustments in control structures to manage shifts in hydrology due to climate change (Williams et al., 2015b; Johnson et al., 2022). Controlled drainage systems can also be modified for warmer winters by adjusting control structure heights to regulate water flow and timings of height adjustments (Johnson et al., 2022). At the watershed scale, larger-scale interventions such as saturated riparian buffers, vegetative filter strips, and wetland restorations serve as final barriers to nutrient transport. Expanding riparian buffer widths and adjusting species composition to include plants resilient to higher temperatures and altered precipitation patterns can maintain the effectiveness of these BMPs under changing climatic conditions (Macrae et al., 2023; Johnson et al., 2022). Restoring or constructing wetlands can further reduce nutrient loadings, but careful design is necessary to ensure effectiveness and avoid unintended nutrients and greenhouse gas release (Dagnew et al., 2019; Lemke et al., 2022). This multilayered BMP approach can ensure comprehensive nutrient management across different hydrological pathways and maximizes the potential for nutrient loading reductions in tile-drained agricultural landscapes under climate change. Integrating these practices requires careful consideration of local soil conditions, topography, crop types, and hydrological regimes to optimize their effectiveness (Sunohara et al., 2015; Fales et al., 2016).

Watershed modeling and monitoring are essential to support the development of these multilayer BMP scenarios for sustainable watershed management under a changing climate. As illustrated in Fig. 8, spatially explicit hydrologic modeling at field and watershed scales can capture both surface and subsurface hydrological processes, facilitating the scaling-up of BMP effects from individual fields to the broader watershed. One example is the use of modular-based Integrated Modeling for Watershed Evaluation of BMPs (IMWEBs) tool, which can delineate the watershed into spatially connected cells, sub-areas, and sub-basins, thereby enabling a detailed characterization of land use and hydrological pathways (Liu et al., 2018; Asgari et al., 2023; Bodrud-Doza et al., 2023). However, further improvements are needed in the tile drainage module and related BMP modules (e.g., WASCOBs and controlled drainage) to represent the hydrological processes in tile-drained landscapes properly (Kompanizare et al., 2024). Moreover, the calibration and validation of model outputs depend on the long-term flow and water quality monitoring data at the field and watershed scales, especially at tile outlets, which remain limited in the GLB watersheds (Chen et al., 2023; Wan et al., 2024). Establishing or expanding such monitoring networks can improve the accuracy and reliability of hydrologic modeling and BMP scenario assessments.

It is also important to consider existing BMPs on the ground during scenario development and ensure continued functionality of the existing BMPs. Future BMP scenarios should account for uncertainties considering climate change projections, crop improvements, BMP design, long-term performance of BMPs, willingness to adopt BMPs by the farmers, and cost-effectiveness to mitigate overestimated or underestimated predictions and address real-world complexities. Therefore, a pragmatic approach should combine monitoring and modeling data to generate evidence-based BMP scenarios, subsequently refined in collaboration with farmers, watershed managers, conservation practitioners, and researchers. This collaborative strategy allows the selection of cost-effective and climate-resilient BMP suites that enhance ecosystem services at field and watershed scales. As depicted in Fig. 8, this multilayered framework can guide watershed modelers and managers in designing and refining BMP strategies for tile-drained landscapes while informing education and outreach efforts for the farmers and students.

8. Challenges and research priorities

The long-term monitoring of tile-drained fields and watersheds reveals substantial challenges in assessing the effectiveness of BMPs in reducing nutrient loadings in the Great Lakes region. As studies like those by Lintern et al. (2020) and Liu et al. (2023) suggested, the effectiveness of BMPs can vary widely due to spatial and temporal variability, including differences in soil type, crop type, and climate conditions. This variability complicates the scaling of results from individual fields to watershed levels, leading to uncertainties in the estimates of BMP effectiveness. Continuous and long-term monitoring is essential for calibrating hydrologic models that predict future changes in water quality and evaluating BMP performance under varying hydroclimatic conditions. Therefore, expanding and supporting long-term monitoring programs across diverse conditions is crucial for improving the reliability of BMP assessments and informing BMP placement and maintenance.

Improvement in modeling techniques is critical to represent subsurface parameters such as groundwater, soil water, and tile flow (Rixon et al., 2024), nutrient dynamics in tile-drain dominated landscapes, and to analyze the effectiveness of BMPs under changing climatic conditions. The ideal model, as outlined by Askar et al. (2020) and Radcliffe et al. (2015), should incorporate detailed simulations of surface and subsurface hydrological processes, including groundwater-surface water interactions, tile drainage and nutrient transport mechanisms, preferential flow pathways, and dynamically represent nutrient forms (e.g., TP, DRP, PP, TN, and NO_3-N) and transformations to capture the impacts of BMPs.

Moreover, improved crop varieties of corn and soybean are more nutrient-efficient than older varieties, resulting in reduced nitrogen losses per unit of grain produced (Dohleman et al., 2024; Ren et al., 2022a, 2022b). Consequently, hydrologic models calibrated with older crop parameters may not accurately estimate the effectiveness of BMPs. Integrating updated corn genetic and agronomic improvements into watershed models is critical for evaluating the effectiveness of BMPs. Additionally, models like SWAT need to overcome issues like semi-distributed spatially disconnected hydrologic response units, model parameter equifinality, and high parameter interaction, which introduce uncertainties in BMP effectiveness evaluations (Neumann et al., 2021; Yuan and Koropeckyj-Cox, 2022). Thus, enhancing models to include updated crop parameters according to genetic information, detailed biogeochemical process characterizations, and improving calibration and validation of the model at the tile outlet, field, and watershed scale is essential to ensuring that models can effectively guide BMP scenario development and optimize BMP configurations under projected climate scenarios. Continuing research on the applications of fine-scale geospatial data, process-based and machine-learning models, and decision support tools is essential for advancing BMP strategies and ensuring adaptability to changing environmental conditions.

Future research should focus on transforming BMP design to enhance cost-effective adoption in tile-drained landscapes under a changing climate, balancing agricultural productivity with environmental protection. According to Lintern et al. (2020), optimizing BMP placement and configuration to target critical source areas can improve BMP effectiveness. Developing an integrated economic-hydrologic modeling approach that combines field and watershed models, on-farm economic models, farmer behavior models, and non-market valuation models can help evaluate the trade-offs between the economic costs of BMP implementation in tile-drained landscapes, nonpoint source pollution reduction, water quality enhancement, and the social value of water quality improvement under different climate change scenarios (Yang et al., 2007; Bodrud-Doza et al., 2023). This approach would also allow for estimating cost-benefit ratios based on environmental benefits and total conservation costs. Moreover, addressing socio-economic and political challenges, such as creating incentive structures and promoting stakeholder engagement, is crucial for ensuring the sustained effectiveness and broader adoption of BMPs. Furthermore, environmental impact assessments of tile drainage should be conducted in accordance with existing regulations such as the Agricultural Tile Drainage Installation Act in Ontario, government programs such as the Tile Loan Program by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), or similar programs that financially support farmers for tile drainage implementation (Tedeschi et al., 2024). These assessments can contribute to informing policy on whether to allow further expansion of the tile drainage coverage and stipulate or incentivize the implementation of tile drainage BMPs.

9. Conclusion

Tile drainage in the GLB enhanced agricultural productivity but caused increased nutrient transport, leading to water quality degradation in the Great Lakes. This review demonstrated that tile drainage altered hydrological pathways in agricultural landscapes, contributing substantial water flow and nutrient loads via subsurface flow. Tile drainage can account for 78 to 97 % of annual total flow at the field scale (median ≈ 86.50) and 40 to 80 % at the watershed scale (median ≈ 46). Field-scale TP and DRP losses vary from 0.01 to 8.36 kg/ha (median ≈ 0.64) and 0.003 to 6.28 kg/ha (median ≈ 0.22) in tile flow, respectively. Field-scale NO_3–N in tile flow can span 0.67–153.0 kg/ha (median ≈ 11.87). At the watershed scale, these values are moderate but can still be substantial, underscoring the importance of considering field and watershed processes when designing land management interventions. Monte Carlo simulations confirmed large confidence intervals of nutrient exports through tile drainage, reflecting the influence of soil properties, cropping practices, drainage designs, and climate variability.

Our synthesis of field and watershed scale studies demonstrated that the effectiveness of BMPs varies widely. At the source level, nitrogen reductions of BMPs can range from 3.5 to 90 % (median ≈ 40.50), while phosphorus reductions span 4.3 to 58 % (median ≈ 28). Edge-of-field BMPs can reduce nitrogen and phosphorus loadings by 8 to 85 % (medians ≈ 41) and 23 to 68 % (medians ≈ 55). Combining BMPs at the watershed scale can collectively reduce nutrient loadings by 22 to 80 % (median ≈ 47), demonstrating the synergistic potential of multi-tiered interventions. However, Monte Carlo simulations demonstrated large confidence intervals, reflecting high uncertainty of the effectiveness of these BMPs, which is influenced by the location-specific factors (e.g., soil type, topography, land use, climate conditions) and land management practices (e.g., fertilizer application, tillage intensity, cover crop, drainage configuration). This variability of BMP effectiveness can be addressed using spatially explicit hydrologic modeling supported by long-term monitoring databases and climate change projections.

Our review reveals that integrating BMPs is a better approach to reducing nutrient loading. In the tile-drained landscape, achieving meaningful load reductions needs tailored strategies at multiple scales (field/source, edge-of-field, and watershed). However, climate change poses additional challenges by potentially increasing the frequency and intensity of precipitation events, thereby influencing BMP efficacy. Furthermore, limited knowledge exists regarding the long-term performance and maintenance of BMPs in tile-drained landscapes under a changing climate. Future research should focus on developing climate-resilient BMPs and improving monitoring and modeling techniques to simulate nutrient transport and BMP effectiveness under diverse land management and climate change scenarios. Mitigating nutrient pollution in tile-drained agricultural watersheds of the GLB requires multifaceted adaptive strategies tailored to local conditions, supported by robust monitoring and modeling efforts, and strengthened through collaborative engagement among stakeholders. The active involvement of farmers, policymakers, researchers, and local communities can ensure the effective implementation and sustained performance of BMPs to balance agricultural productivity with the ecological health of the Great Lakes.

CRediT authorship contribution statement

Md. Bodrud-Doza: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Wanhong Yang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Yongbo Liu:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Ram Yerubandi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Prasad Daggupati:** Writing – review & editing, Validation, Supervision, Conceptualization. **Ben DeVries:** Writing – review & editing, Validation, Supervision, Resources. **Evan D.G. Fraser:** Writing – review & editing, Validation, Supervision, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178657.

Data availability

Data will be made available on request.

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