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Constructed Wetlands as Nature-Based Solutions for Agricultural Runoff Treatment: Nitrogen and Phosphorus Removal Efficiency Under Varying Hydraulic Loading Rates in Temperate Agro-Ecosystems

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Abstract

Agricultural runoff carrying excess nitrogen (N) and phosphorus (P) represents a leading driver of freshwater and coastal eutrophication globally. Constructed wetlands (CWs) offer a nature-based, low-energy solution for intercepting nutrient-laden agricultural drainage before it reaches sensitive receiving waterbodies. This study evaluated the nutrient removal performance of subsurface flow (SSF) and surface flow (SF) constructed wetland systems treating agricultural tile drainage under contrasting hydraulic loading rates (HLRs: 2, 4, 8, and 16 cm d^{-1}) across three growing seasons at a temperate Midwestern United States agricultural watershed. Pilot-scale wetland cells (12 m × 4 m each) were planted with native macrophyte assemblages (Typha latifolia, Phragmites australis, Scirpus acutus, and Carex spp.) and monitored for inflow and outflow nutrient concentrations, hydraulic performance, plant biomass productivity, and associated biodiversity metrics. Results demonstrated that SSF-CW systems achieved superior total nitrogen removal (mean 68.4% ± 8.2%) compared to SF-CW systems (mean 52.1% ± 11.3%) across all HLRs, with optimal performance at HLR = 4 cm d^{-1}. Total phosphorus removal was highest in SSF-CW at low HLR (2 cm d^{-1}), achieving 79.3% removal efficiency, with declining performance at higher flow rates. Plant biomass harvesting in autumn significantly enhanced P removal by 18.6% compared to unharvested controls, implicating biomass P accumulation as an important removal pathway. Macroinvertebrate diversity (Shannon-Wiener index) increased significantly within all wetland types relative to drainage channels, supporting multiple ecosystem service provisioning. Life cycle assessment indicated that CW systems achieved net carbon sequestration of 1.2–2.8 t CO_2-eq ha^{-1} yr^{-1}, partially offsetting agricultural GHG emissions. These findings provide design guidance for optimizing constructed wetland performance as cost-effective, multifunctional agricultural water management infrastructure.

Keywords

constructed wetlands; agricultural runoff; nutrient removal; eutrophication; nature-based solutions; nitrogen; phosphorus; hydraulic loading rate; ecosystem services.

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INTRODUCTION

The intensification of agricultural production systems during the latter half of the twentieth century achieved unprecedented gains in global food output but generated profound environmental externalities, chief among them the accelerated eutrophication of freshwater and coastal marine ecosystems driven by agricultural nutrient pollution (Conley et al., 2009; Strokal et al., 2016). Nitrogen and phosphorus applied as synthetic fertilizers and organic amendments to agricultural lands are mobilized through surface runoff, subsurface tile drainage, and leaching pathways, entering streams, rivers, lakes, and coastal waterbodies where they stimulate excessive algal growth, deplete dissolved oxygen, and fundamentally alter aquatic ecosystem structure and function (Carpenter et al., 2018).

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The Gulf of Mexico hypoxic zone, the Baltic Sea dead zone, and Lake Erie harmful algal bloom events represent emblematic manifestations of agricultural nutrient export at watershed scales, imposing substantial ecological, economic, and human health costs (Diaz & Rosenberg, 2008). Despite decades of agronomic best management practice (BMP) promotion — including precision nutrient application, cover cropping, and riparian buffer strips — achieving the nutrient load reductions required to restore impaired waterbodies demands complementary edge-of-field and landscape-scale treatment approaches (USEPA, 2019).

Constructed wetlands (CWs) have emerged as a particularly promising nature-based solution (NbS) for agricultural nutrient interception, leveraging the coupled physical, chemical, and biological processes of wetland ecosystems — sedimentation, plant uptake, microbial nitrification-denitrification, and phosphorus adsorption — to remove pollutants from agricultural drainage waters (Vymazal, 2014). CWs offer several advantages over conventional engineered treatment approaches: relatively low construction and operating costs, passive operation requiring minimal energy inputs, co-provision of biodiversity habitat and landscape ecosystem services, and compatibility with existing agricultural land management (Mander et al., 2017).

Subsurface flow (SSF) and surface flow (SF) CW configurations represent the two principal design archetypes, each with distinct hydrological, biogeochemical, and ecological characteristics influencing nutrient removal performance (Kadlec & Wallace, 2009). SSF systems, in which water flows horizontally or vertically through a porous gravel or sand media matrix, promote close contact between influent water and both aerobic and anaerobic microbial communities, potentially facilitating coupled nitrification-denitrification and enhanced nitrogen removal. SF systems, where a shallow water column flows over a submerged soil or gravel substrate, support diverse emergent macrophyte communities and extensive open-water surface areas favorable for sedimentation and avifaunal habitat.

Hydraulic loading rate (HLR) — the volume of influent applied per unit wetland surface area per unit time — is recognized as among the most critical design parameters governing CW nutrient removal performance, influencing hydraulic residence time, flow distribution, and the balance between advective and diffusive transport processes (Kadlec & Wallace, 2009). Despite substantial empirical literature on CW nutrient removal, comparative performance data across HLR gradients for temperate agricultural drainage applications remain limited, particularly for native macrophyte assemblages under field conditions characteristic of Midwestern tile-drained agricultural landscapes.

This study addresses these research needs by: (i) comparing nitrogen and phosphorus removal efficiency between SSF and SF constructed wetland configurations under controlled HLR gradients treating actual agricultural tile drainage; (ii) quantifying the contribution of macrophyte biomass uptake to seasonal nutrient removal; (iii) evaluating the effects of autumn biomass harvesting on wetland P removal capacity; (iv) assessing macroinvertebrate biodiversity responses to wetland establishment; and (v) conducting life cycle assessment of the carbon footprint and climate mitigation co-benefits of CW systems in agricultural watersheds.

MATERIALS AND METHODS

Study Site and Constructed Wetland Design

The study was conducted at the Lake Erie Watershed Agricultural Research Station, Ohio, USA (41°32'N, 83°08'W), within a 145-ha tile-drained corn-soybean rotation watershed receiving mean annual precipitation of 870 mm. A pilot-scale CW research facility comprising 16 individual wetland cells (12 m × 4 m each, depth: 0.6 m SSF, 0.3 m SF) was constructed adjacent to the main tile drainage outlet. Eight cells were configured as horizontal SSF systems with 20–40 mm washed river gravel substrate; eight cells were configured as SF systems with 0.3 m topsoil substrate. All cells were planted with native macrophyte assemblages in spring 2020 and allowed one full growing season for establishment before experimental treatments commenced in 2021.

Hydraulic Loading Rate Treatments

Four HLR treatments (2, 4, 8, and 16 cm d^{-1}) were applied to duplicate SSF and SF cells using calibrated peristaltic pumps delivering raw tile drainage from a common collection sump. Actual tile drainage was used as influent to represent realistic agricultural loading conditions including seasonal variation in nutrient concentrations. Flow was maintained continuously through each cell with programmable adjustment to maintain target HLRs regardless of influent flow variability. Hydraulic residence time (HRT) at each HLR was calculated from tracer tests using rhodamine WT dye.

Water Quality Monitoring

Influent and effluent water samples were collected three times per week during the tile drainage season (March–November) and once per week during the dormant season. Samples were analyzed for: total nitrogen (TN), nitrate-nitrogen (NO_3^--N), ammonium-nitrogen (NH_4^+-N), total Kjeldahl nitrogen, total phosphorus (TP), soluble reactive phosphorus (SRP), total suspended solids (TSS), biochemical oxygen demand (BOD_5), dissolved oxygen, pH, electrical conductivity, and water temperature. Analyses followed Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Nutrient removal efficiency was calculated as percent reduction in mass loading between inflow and outflow.

Plant Biomass and Nutrient Uptake

Above-ground plant biomass was harvested from three 0.25 m^2 quadrats per cell in late August (peak standing crop) and early November (post-senescence) using clip-and-dry methodology. Harvested material was dried at 65°C, weighed, and analyzed for total nitrogen and phosphorus content using Kjeldahl digestion and colorimetric methods. Nutrient uptake was calculated as the product of biomass productivity and tissue nutrient concentration. One half of the cells in each CW type × HLR combination were assigned to an autumn biomass harvesting treatment to evaluate the effect on subsequent-season P removal capacity.

Macroinvertebrate Biodiversity Assessment

Aquatic macroinvertebrates were sampled in all wetland cells and adjacent drainage channel reference reaches using standard kick-net sampling (500 μm mesh) in spring and autumn of each study year. Samples were preserved in 70% ethanol, sorted, and identified to family level. Community metrics calculated included: total taxon richness, Shannon-Wiener diversity index (H'), Pielou's evenness index (J'), and EPT (Ephemeroptera, Plecoptera, Trichoptera) richness as a water quality bioindicator.

Life Cycle Assessment

A gate-to-gate LCA was conducted to evaluate the GHG implications of CW construction, operation, and ecosystem service delivery following ISO 14040/14044 standards. The functional unit was defined as treatment of 1 m^3 of agricultural drainage to a 50% TN and 60% TP removal standard. Inventory data included: construction earthworks and materials (concrete, geomembrane, gravel), pump electricity consumption, plant establishment materials, and maintenance activities. Carbon sequestration in wetland soils and plant biomass was quantified through soil coring (0–30 cm) and biomass measurements. GHG emissions from wetland surfaces (CH_4, N_2O) were measured using static chambers to avoid underestimating the climate costs of denitrification byproducts.

Statistical Analysis

Nutrient removal data were analyzed using linear mixed-effects models in R (nlme package) with CW type, HLR, and season as fixed effects, and cell and sampling date as random effects. Relationships between HRT and nutrient removal efficiency were modeled using first-order areal rate constant (k-A) models following Kadlec & Wallace (2009). Macroinvertebrate community composition was analyzed using non-metric multidimensional scaling (NMDS) and permutational ANOVA (PERMANOVA) using the vegan package. All tests were evaluated at $\alpha = 0.05$.

RESULTS

Influent Water Quality Characteristics

Mean influent tile drainage concentrations across the study period were: TN 14.8 ± 3.2 mg L^{-1} (predominantly NO_3^--N: 13.1 ± 2.8 mg L^{-1}), TP 0.38 ± 0.14 mg L^{-1} (predominantly SRP: 0.21 ± 0.09 mg L^{-1}), and TSS 42.3 ± 18.6 mg L^{-1}. Concentration variability was high, particularly during spring snowmelt and post-application events, reflecting typical agricultural tile drainage dynamics in the region.

Nitrogen Removal Performance

SSF-CW systems demonstrated consistently superior TN removal efficiency compared to SF-CW across all HLR treatments and seasons ($p < 0.001$). At the optimal HLR of 4 cm d^{-1} (HRT ≈ 5.2 days), SSF-CW achieved mean TN removal of 68.4% ± 8.2%, compared to 52.1% ± 11.3% in SF-CW. Performance declined markedly at HLR = 16 cm d^{-1} in both system types (SSF: 34.2%; SF: 24.6%), consistent with reduced HRT limiting denitrification reaction completion. NO_3^--N removal (the dominant N fraction) closely mirrored TN removal patterns, confirming microbial denitrification as the primary mechanism. NH_4^+-N was present in low concentrations in influent drainage and showed modest increases in SSF effluent during warmer months, potentially indicating incomplete nitrification under anaerobic media conditions.

Phosphorus Removal Performance

Total phosphorus removal was highest at the lowest HLR for both system types, with SSF-CW at HLR = 2 cm d^{-1} achieving 79.3% TP removal. At HLR = 4 cm d^{-1}, SSF-CW removed 61.4% TP and SF-CW removed 54.8% TP. The decline in P removal with increasing HLR was steeper than for TN, consistent with P removal's greater dependence on sedimentation and substrate adsorption processes sensitive to contact time and flow velocity. Autumn biomass harvesting significantly enhanced TP removal in the subsequent spring by 18.6% ($p < 0.01$) in harvested versus unharvested cells, attributed to removal of P stored in senescing plant tissues that would otherwise be returned to the water column during decomposition.

Macroinvertebrate Biodiversity

Macroinvertebrate assemblages in CW cells were significantly more diverse than drainage channel reference reaches after two growing seasons. Shannon-Wiener diversity (H') was 2.14 ± 0.28 in SF-CW, 1.87 ± 0.31 in SSF-CW, and 0.83 ± 0.19 in drainage channels ($p < 0.001$). SF-CW systems supported greater taxonomic richness (34.2 families mean) than SSF-CW (22.8 families) due to the availability of open water and emergent vegetation habitats. EPT richness, indicative of improved water quality, was significantly elevated in SF-CW cells at low HLR, suggesting water quality improvement sufficient to support pollution-sensitive taxa.

Life Cycle Assessment

The LCA revealed net carbon sequestration advantages for CW systems despite GHG emissions from wetland surfaces. Annual soil carbon sequestration averaged 1.8–3.4 t C ha^{-1} yr^{-1} across system types. After accounting for CH_4 and N_2O emissions from wetland surfaces (CH_4 0.8–2.1 g m^{-2} d^{-1}; N_2O 0.12–0.34 mg N_2O-N m^{-2} h^{-1}) and construction and operational GHG inputs, SSF-CW systems achieved net carbon sequestration of 1.2–2.8 t CO_2-eq ha^{-1} yr^{-1}, while SF-CW systems ranged from a slight net source to modest sink depending on CH_4 emission intensity.

DISCUSSION

The results establish clear performance advantages for SSF over SF constructed wetland configurations for nitrogen removal from temperate agricultural tile drainage, while identifying HLR = 4 cm d^{-1} as an optimal design point balancing treatment performance with land area requirements. The first-order denitrification rate constants derived (k-N = 0.042–0.087 m d^{-1} for SSF-CW) align with values reported for horizontal SSF systems in comparable cold-climate applications (Vymazal, 2014; Kadlec & Wallace, 2009), providing confidence in the broader applicability of these findings for design scaling.

The superior P removal at low HLR (2 cm d^{-1}) in SSF systems is consistent with the importance of sedimentation and media adsorption as P removal pathways requiring extended contact time.

However, the practical land area implications of HLR = 2 cm d^{-1} (requiring approximately 3–5% of the contributing watershed area) may constrain adoption in intensively cultivated agricultural landscapes. The demonstrated benefit of autumn biomass harvesting for P retention capacity underscores the importance of active management in maximizing long-term P removal, particularly as gravel media approach P sorption saturation after several years of operation.

The macroinvertebrate biodiversity findings confirm that CWs function as functional habitat patches within agriculturally dominated landscapes, supporting aquatic biodiversity values that extend well beyond their primary water quality treatment function. The significantly higher diversity in SF-CW systems relative to SSF-CW suggests that open water surface flow configurations should be prioritized in landscape designs where biodiversity co-benefits are a primary objective alongside nutrient removal.

CONCLUSION

This study provides robust, experimentally grounded design guidance for constructed wetland systems treating agricultural tile drainage in temperate Midwestern landscapes. SSF-CW systems at HLR = 4 cm d^{-1} are recommended as the optimal configuration for combined nitrogen and phosphorus removal, achieving 68% TN and 61% TP removal efficiency while supporting significant macroinvertebrate biodiversity recovery. Autumn biomass harvesting is identified as a low-cost management intervention with meaningful P removal benefits. Life cycle assessment supports CW systems as net carbon sequestering agricultural BMPs with multiple co-benefits for water quality, biodiversity, and climate mitigation. Widespread adoption of CW systems at watershed scales, supported by appropriate policy mechanisms and farmer incentive programs, holds substantial potential for addressing agricultural nutrient pollution in the Midwest and comparable temperate agricultural regions globally.

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