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Optimizing Nitrate Removal from Agricultural Drainage using Real-Time Control of Redox Conditions in Denitrifying Woodchip Bioreactors

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Denitrifying woodchip bioreactors (WBRs) are nature-based treatment systems designed to remove nitrate (NO_3^-) from agricultural tile drainage. Denitrification in WBRs is frequently carbon-limited because lignocellulosic woodchips decompose slowly under the flooded, hypoxic-to-anoxic conditions required for efficient nitrate reduction. Periodic drainage followed by re-flooding of the woodchip bed has been shown to increase denitrification rates by a factor of two to three. Transient oxygen exposure stimulates aerobic microbial degradation of wood, generating more bioavailable carbon substrates that enhance denitrification upon re-saturation. However, deliberate drainage introduces two key management challenges: (i) Balancing the short-term loss of treatment capacity while the reactor is drained against future gains in denitrification rates, and (ii) Determining the optimal frequency of drainage events, given that the stimulation of denitrification decays over time following re-flooding.

To address these tradeoffs, we used a Markov Decision Process (MDP)—a mathematical framework for sequential decision-making under uncertainty—to dynamically control the saturation state and associated redox conditions of woodchip beds in order to maximize cumulative NO_3^- load reductions over weekly to monthly time scales. The MDP was parameterized using first-order denitrification kinetic constants derived from laboratory batch and flow-through column experiments that quantified the effect of oxygen exposure duration on post-reflooding kinetics. Under steady-state conditions with environmentally relevant temperatures and flow rates, model simulations indicated that optimized drainage–reflooding strategies increased NO_3^- load reductions by up to 45% relative to a continuously saturated baseline. The framework was also evaluated under non-steady-state conditions using 100 years of synthetic tile drainage discharge and temperature generated with a stochastic discharge model calibrated with data from a Central New York State WBR. In this dynamic context, the MDP increased median NO_3^- load reductions from 35.1% (interquartile range 25.7 to 42.9%) to 43.1% (interquartile range 33.0 to 51.7%). However, performance was highly sensitive to discharge forecast accuracy, underscoring the importance of improved prediction of tile drainage flows. These results demonstrate that real-time control of drainage–reflooding cycles in WBRs can substantially enhance nitrate removal from nonpoint agricultural sources with minimal retrofits to existing systems and without needs for exogenous chemical inputs.