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A hybrid machine learning–process-based model approach of simulating ammonia volatilization in rice paddies

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Abstract: Ammonia (NH_3) volatilization from rice paddies is a major pathway of nitrogen (N) loss, with strong implications for both fertilizer efficiency and environmental sustainability. However, existing process-based models (PBMs) face challenges in generalizing across diverse agroecosystems due to their complexity and reliance on site-specific calibration. In this study, we developed a hybrid modeling framework that integrates machine learning (ML) with PBMs to reduce complexity while improving predictive generalization. In our framework, PBMs are used to explicitly characterize ammonia loss responses to driving factors, whereas the ML component captures, distills, and generalizes factor–response relationships. This hybrid approach enables the model to preserve mechanistic interpretability while extending predictive power across global rice paddy regions.

Beyond methodological innovation, the framework reveals new insights into the spatial heterogeneity of factor–response relationships that govern NH_3 volatilization in rice paddies. By systematically analyzing climate, soil, and management drivers, we demonstrate that response curves differ significantly across regions, highlighting why mitigation strategies effective in one location may fail in another. Our results suggest that the hybrid approach not only advances the generalization of PBMs but also serves as a diagnostic tool to identify spatially explicit drivers of NH_3 loss in rice paddy systems.

This work demonstrates the potential of hybrid modeling as both a predictive and diagnostic tool, offering practical pathways to design region-specific mitigation strategies for sustainable rice production.

Keywords: *Decision-making support, Ammonia volatilization, Rice paddy, Process-based models, Machine learning models.*