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VIEWPOINT

Advancing circular nutrient economy to achieve benefits beyond nutrient loss reduction in the Mississippi/Atchafalaya River basin

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Since the establishment of the US Hypoxia Task Force (HTF) in 1997, billions of dollars have been invested in Nutrient Reduction Strategy (NRS) implementation in the Mississippi and Atchafalaya River basins (MARB) to reduce the Gulf of Mexico hypoxic zone size to less than 5,000 km^2 (1,930 mi^2) by 2035 (USEPA 2022). However, after 25 years of continuous efforts, substantial improvement in water quality has yet to be achieved. The largest hypoxic zone measured was 22,730 km^2 (8,776 mi^2) in 2017, more than four times the targeted goal (NOAA 2022). Farmers' adoption of best management practices proposed by state NRS and collaboration among diverse stakeholders are vital to achieving the HTF goals because the majority of nutrient pollution is from agricultural sources (USEPA 2022; Robertson and Saad 2021). Therefore, reorienting the strategy to implement NRS more effectively and motivate farmers' involvement has been a top priority at the scientific and policy levels.

A circular nutrient economy encompasses responsible nutrient management practices for the reduction of nutrient losses and increased recovery of nutrients from waste streams for reuse in agricultural production. The concept is based on the principles of the circular economy, which seeks to decouple economic growth from resource consumption and environmental degradation. Some countries (e.g., Netherlands and Singapore) have been pioneers in implementing circular nutrient economy practices to close nutrient loops, such as the Phosphate Platform and Singapore's NEWater program. In this viewpoint, we suggest that a circular nutrient economy in the MARB could accelerate NRS implementation and achieve benefits beyond nutrient loss reduction.

ADVANCING A CIRCULAR NUTRIENT ECONOMY COULD MOTIVATE NUTRIENT REDUCTION STRATEGY ADOPTION

A significant emphasis in the current NRS of MARB states has been placed on preventing off-field nutrient loss to achieve environmental benefits. In contrast, less attention has been paid to the potential economic benefits to farmers. A 2019 comprehensive review on the adoption of conservation practices illuminated a range of significant social, economic, and operational factors influencing adoption (Prokopy et al. 2019). The study highlighted that the farmers whose primary operational motivation was financial were less likely to adopt conservation practices than those with noneconomic primary motivations. Apart from some cost-share programs supported by governments to implement conservation practices (USEPA 2022), many practices may not result in immediate and/or direct agriculture-related economic benefits, such as an increase in crop yield or a reduction in fertilizer cost (Robertson and Saad 2021), and may even decrease yields (e.g., cover crops) (Deines et al. 2022). Even with cost-share programs, many practices may still incur net or opportunity costs.

Advancing a circular nutrient economy in the MARB would achieve multiple benefits in terms of the economy, ecology, efficiency, and long-term sustainability. The MARB rivers discharged 90,500 t (99,759 tn) of nitrate (NO_3^-) and 15,600 t (17,196 tn) of phosphorus (P) into the Gulf of Mexico in May of 2021 alone (NOAA 2021). A recent study indicated that the midwestern United States has a large potential for nutrient recovery and reuse due to extensive centralized wastewater and maize (*Zea mays* L.) ethanol infrastructure with a high degree of co-location with agricultural nutrient consumption, highlighting the untapped potential for a circular nutrient economy in this globally significant grain-producing region (Ruffatto et al. 2022). Nutrient recycling as a strategy to meet the NRS goals can generate income for farmers and partially offset reliance on inputs, leading to greater profitability. Shifting to a systems perspective, recovering lost nutrients offers an excellent opportunity for more effective sharing and implementation of NRS to deliver direct cost recovery from nutrients' fertilizer value and indirect cost recoveries by mitigating the nutrient clean-up or damage costs. Indeed, systems thinking has been associated with the adoption of cover crops by individual farmers (Church et al. 2020).

TECHNOLOGICAL AND SYSTEM APPROACH INNOVATIONS AT LOCAL, REGIONAL, AND NATIONAL SCALES

Technological and system approach innovations are needed to advance the circular nutrient economy in NRS at local, regional, and national scales. The development of new methods has shifted the scope from nutrient removal to nutrient recycling, offering technological solu-

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tions to achieve nutrient loss reduction at the local scale. There are two notable examples worth mentioning here: (1) the establishment of municipal-agricultural partnerships between wastewater utilities and farmers, where the wastewater treatment plants have partnered with farmers to apply wastewater treatment residuals and biosolids to agricultural fields rather than sending them to landfills, and (2) the development of nutrient-recycling-based edge-of-field techniques like biochar-sorption-channel treatment systems (Yang et al. 2021) and drainage water recycling in the artificially drained basin, which has the potential to reduce nutrient losses to our streams significantly.

Figure 1a presents a typical nutrient loss recovery system deployed in Illinois, where excess nutrients are prone to be lost from the field via surface runoff or drainage water. In this new edge-of-field nutrient treatment system, a woodchip bioreactor is employed to remove nitrate-nitrogen/nitrite-nitrogen (NO_3-N/NO_2-N) via a denitrification process, and biochar is used to capture P from drainage water through precipitation reactions. The P-loaded biochar can be applied as a soil amendment to retain nutrients in the colocated farmland and offset the costs of implementing NRS to prevent nutrient loss (Yang et al. 2021). Adding nutrient capture reconciles the long-standing disadvantage of edge-of-field approaches relative to in-field approaches to keep nutrients in the agroecosystem to facilitate nutrient recovery and address water quality issues. Standard protocols should be developed based on field research, and feedback from agricultural producers should be considered prominent to develop translatable, real-world feasible solutions. This means new NRSs toward nutrient recycling need to be closely integrated with realities of agricultural production, such as management constraints and the cost of nutrient inputs via fertilizers.

Collaboration among HTF states is critical in achieving a robust circular economy at regional and national scales (Wardropper et al. 2023). There is a need for structural pathway articulation to integrate nutrient recycling systems as a key component of nutrient reduction strategies, as it is vastly underutilized. Each HTF state, based on its economic consideration, can contribute to the transformative development of centralized and decentralized nutrient recycling systems for decision-making at a broader scale. Meanwhile, it is critical to acknowledge that recovering nutrients from millions of hectares (acres) in the United States is an extraordinary challenge. In some cases, nutrient loss reductions may drive nutrient recycling, whereas, in others, comparable or lower costs of nutrients relative to off-farm inputs may drive incentivization in the future, especially given projected fertilizer price volatility. The identification of nutrient loss sources has always been a key HTF metric for NRS implementation (figure 1b). We, therefore, call for a greater emphasis on integrating accessible data and monitoring approaches effectively by identifying the magnitude of recycling potential from nutrient losses relative to agronomic needs from multifield to the regional scale. To this end, the synthesis benefit of large-scale water quality data integration and localized nutrient recycling solutions would provide the foundation for reorienting the circular nutrient economy to meet NRS goals and achieve benefits that go beyond nutrient loss reduction.

DISCLAIMER

The authors declare no competing financial interest.

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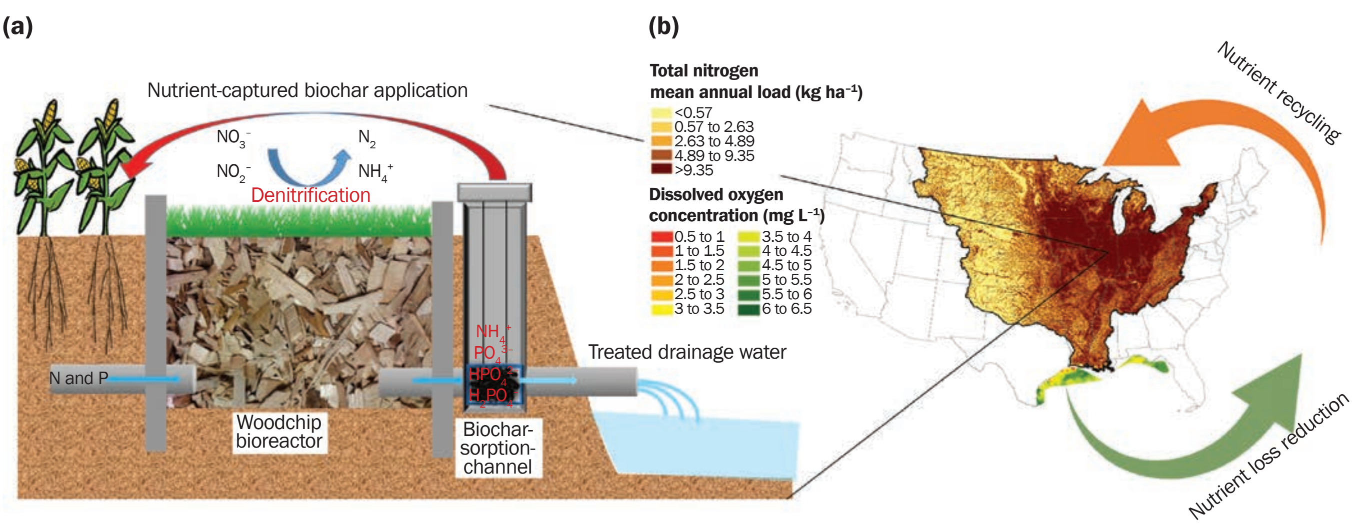
Figure 1
(a) A typical nutrient loss recovery system at the local scale: biochar-sorption-channel treatment systems; (b) total mean annual nitrogen load delivered from the Mississippi and Atchafalaya River basins to the Gulf of Mexico (US Geological Survey based on 1999 to 2014) (Robertson and Saad 2021) and 2017 hypoxia zone data from the US National Oceanic and Atmospheric Administration (NOAA 2022).



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