Harnessing emerging technologies to reduce Gulf hypoxia

Precision farming enabled by big data and gene-editing technologies are accelerating progress toward increasing nitrogen-use efficiency. However, farmer engagement, public–private partnerships and sound public policies are critical to harness the potential of such technologies to reduce hypoxia in the Gulf of Mexico.

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The dramatic increase in the yield of maize in the US Midwest, beginning in the mid-twentieth century, is one of the most remarkable achievements of modern agriculture. Although this increase in corn yield has been achieved without increasing average nitrogen (N) fertilizer input rates, implying increasing N-use efficiency, only 60–70% of the applied N is harvested in grains[1]. Nitrate loss from maize-based cropping systems flows through artificially drained fields and ultimately, via the Mississippi and Atchafalaya rivers, into the Gulf of Mexico where it causes hypoxia that either kills or causes marine life to flee[2]. It is difficult to evaluate all of the damage caused by freshwater and coastal eutrophication to ecosystem services, drinking water and human health[3], but some cost estimates suggest it is likely to be billions of US dollars each year[4,5]. In 2001, a joint federal–state action plan set a goal to reduce the size of this hypoxic zone to less than 5,000 km^2 through voluntary actions, incentives and education. Instead, the hypoxic zone grew to its largest size ever in 2017, reaching 22,729 km^2 — larger than the state of New Jersey[6].

Recommended application rates of fertilizer for corn production are typically based on average field and weather conditions and generic crop features. The lack of technology to understand in-field variability, together with the underlying belief that yields are constrained by the availability of nutrients in the soil, leads to the over-application of fertilizer on an entire field. This has produced a 'nutrient paradox' — that is, despite the over-use of fertilizer in a field, the resulting level of nutrients is not evenly distributed, with some areas lacking sufficient nutrients while others having excess nutrients that discharge into water bodies. The Environmental Protection Agency Science Advisory Board has recommended a 45% reduction in riverine total N and phosphorus fluxes to reduce the size of the hypoxic zone[5].

Failure of conventional approaches

A number of best management practices (BMPs) have been recommended to reduce nutrient loss. These include edge-of-field practices such as perennial vegetated buffer strips along water bodies and wetlands that slow or drastically reduce the amount of N that reaches water bodies, as well as in-field practices such as changing the rate, timing and method of fertilizer application. Adoption of these practices is low; only 16% of cropped acres are using the appropriate N application rates, timing of application and application method for all crops[7].

Billions of US dollars are spent annually to induce voluntary adoption of BMPs through participation in conservation programs that offer cost-share payments and technical assistance[3]. Given that nutrient pollution is diffuse and that we lack technologies to identify its sources, it is hard to target the selection of farmers in these programs and the payments for participation to improve water quality. Conservation practices alone are ineffective at reducing hypoxia and come at a high cost[5]. Additional challenges for targeting of payments and regulation are represented by the difficulty of establishing a link between local N application and discharges at a distant location, and of quantifying how long nitrogen stays in the soil[8]. A portfolio of approaches across scales from a single field to an entire region (Fig. 1), including new incentives to adopt BMPs as well as emerging technologies, may be necessary to solve this environmental challenge.

Emerging technological advances

New technologies could transform crop management by providing farmers with detailed information about the heterogeneity on their land. Extremely high-resolution airborne and space-borne technologies such as lidar and hyperspectral sensors enable high-precision characterization of landscapes and soils[9]. It is possible to design spatially explicit recommendations (at the metre scale) based on in-field variability in N needs. This can be achieved by optimizing the placement of fertilizer using real-time weather information, crop genetics and planting density, by means of on-board farm-equipment technologies, crop and soil conditions, and knowing how small-scale topographic variations such as depressions control nitrogen residence times[10]. It is also possible to monitor N discharge at the field scale through sensors, crowdsourcing and citizen-science programs.

Precision farming is not new. Global positioning systems, computer-controlled variable-rate application technologies and geo-referenced yield monitors for mapping harvests have been available since the 1990s. However, the agronomic knowledge needed to vary N applications in response to site-specific conditions has lagged behind and prevented effective use for reducing nutrient loss and increasing farm profitability. Recent advances in information and communication technologies are digitalizing agricultural management, including the ability to capture and store massive volumes of data from multiple devices and millions of acres in a single repository, combine it with weather data, market prices and other ambient conditions, and share it with technology and input providers. The use of big data combined with machine-learning and high-performance cloud computing can improve understanding of the complex biophysical processes in agricultural environments, and facilitate 'smart farming' by providing site-specific recommendations in real time to on-board mobile technologies for adaptive and agile nutrient management[11]. Evidence on the economic and environmental benefits of these technologies is still limited because much of the big data being generated from

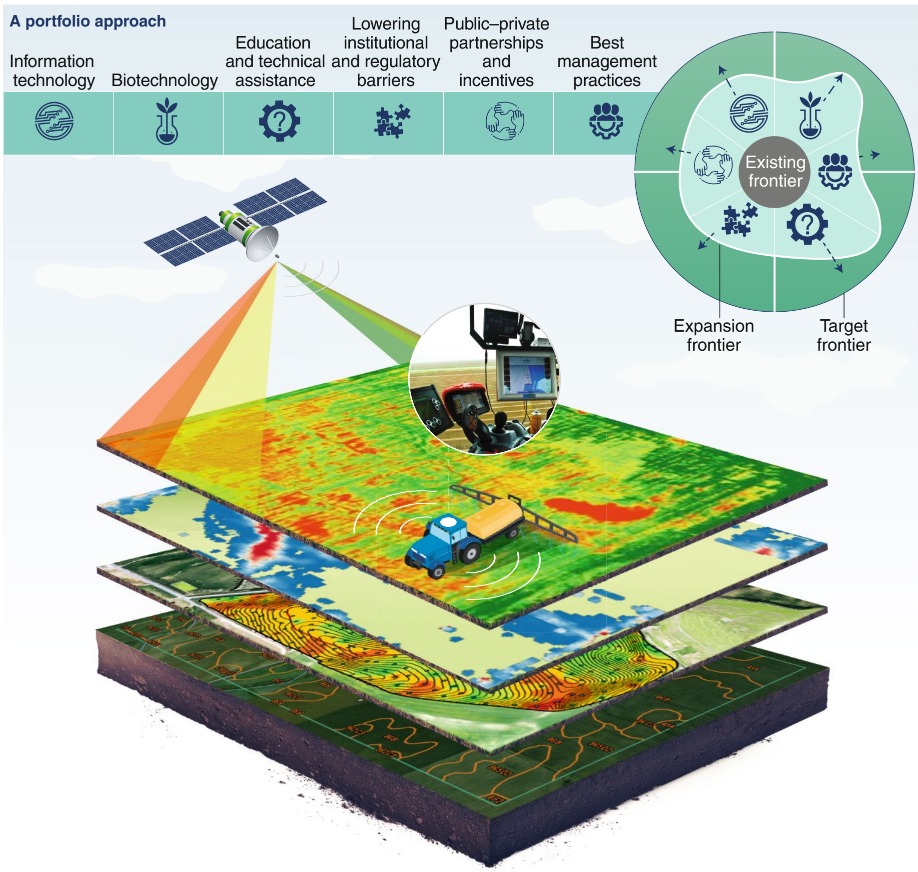

Fig. 1 | Portfolio approach to address the nutrient loading reduction challenge. Data from on-board sensors in tractors, drones or robots as well as satellites can collect information on myriad soil and plant-condition variables and also yield at harvest. These data can be transmitted via satellites or data networks to third-party service providers for analysis, computation and development of tailored variable seeding rates, fertilizer application and irrigation prescriptions specific to the field and plant variety. These technologies have the potential to be harnessed with farmer education and institutional and policy innovations to be part of the portfolio of approaches to reduce Gulf hypoxia.

technology implementation at the farm scale are in private hands and not readily available to researchers. However, a recent study suggests that using remote-sensing technology to identify unproductive land could save US corn and soybean farmers an estimated US$500 million in fertilizer costs, and stop 6.8 million metric tons of carbon dioxide equivalent escaping from unused nitrogen fertilizer into the atmosphere[12].

Additionally, advances in genetic engineering and genome editing have great promise for increasing the efficiency of fertilizer use by modifying plant traits[13]. Unlike first-generation techniques for integrating novel genes into a host plant that are fraught with challenges including random and sometimes ineffective gene placements, second-generation genome-editing methods are rapid and precise[14]. Recent improvements in nitrate uptake and transport and nitrogen-use efficiency made through gene editing[15,16] demonstrate the potential of this technology to help reduce N losses. Additionally, it is becoming possible to develop maize as a nitrogen-fixing plant that would require little, if any, N fertilizer by manipulating symbiotic bacteria in or on plant tissues or living in proximity to root systems.

Call for concerted action

Important research questions about the potential use of these emerging technologies to address the hypoxia problem must be tackled: what combinations of genetics and environmental conditions with management practices would lead to greater agricultural productivity and profitability while reducing N loss? How should data ownership and privacy concerns, as related to big-data technologies, be reconciled with the need to share data among technology providers, researchers and public agencies in order to achieve these outcomes? What economic, behavioural, institutional and policy drivers will induce farmers' adoption of emerging technologies for private benefits and for the public good? What are the unintended consequences of these technologies, such as increased productivity leading to cropland expansion? Can precision farming and gene-editing technologies be adopted synergistically to achieve private and public benefits?

In order to shift the frontier from the status quo to one that is more economically and environmentally sustainable (Fig. 1), we highlight a portfolio of five key areas for concerted action by researchers, the private sector (farmers and agribusinesses), and government agencies to transform agriculture towards meeting growing demands for food, fuel and fibre more sustainably.

Improve scientific understanding of the role of big-data-enabled precision farming in reducing nutrient loss. Publicly funded research is needed to more precisely quantify the linkage between current practices, existing BMPs, nutrient loss and hypoxia, and to demonstrate the benefits of data-driven precision technologies for farmers and for water quality.

Understand the behavioural and institutional barriers to the adoption of existing BMPs and emerging technologies. Studies show that farmer decisions about adopting a technology are driven not only by the return on investment but also by learning costs, risks and uncertainties, and by behavioural factors. This, together with improved understanding of the potential of precision farming, can be used to design more targeted and cost-effective conservation programs.

Provide education and training programs for farmers through neutral third parties. University extension services or independent crop consultants not affiliated with input suppliers can instil confidence and reduce uncertainties while informing farmers about the costs, benefits and possible risks of these technologies. Modern visualization tools, crowdsourcing programs and computational technologies can increase the impact of educational efforts regarding the societal effect of farm management decisions on hypoxia hundreds of miles downstream. Additionally, as consumers become more health- and environment-conscious, these technologies can track food production from the farm to the food table and provide credible certification for healthy, sustainable food supply chains.

Lower the regulatory barriers on genetically engineered technologies to increase nitrogen-use efficiency. Onerous regulations governing genetically modified crops, particularly by the European Union, have delayed their development and release in many countries[17]. Concerns that gene-edited crops could be regulated based on the process used rather than the novel phenotype developed can delay the use of gene-editing tools for crop improvement[18].

Pursue legal and regulatory action as voluntary efforts have not been sufficient. Emerging technologies and changing consumer preferences may bring the interests of farmers, the private sector and the public closer together. In the absence of this convergence, however, it will be necessary to enact regulations to protect water quality. Previous research shows that performance-based policies that harness market incentives, such as tradable permits, can control pollution cost-effectively[19].

Reducing nutrient loss is a wicked problem that has been exacerbated by technological limitations in measuring and monitoring sources of nutrient loss. The technological capability to match the right seed and the right fertilizer application rate with the right soil at the right time, together with recent advances in genetic engineering, have the potential to accelerate progress towards increasing nitrogen-use efficiency. We do not consider these technologies to be a panacea for the hypoxia problem; instead we call for publicly funded research to improve our understanding of the potential of these technologies to reduce nutrient loss and of the economic and institutional drivers to induce their adoption. Such research should also provide a deep evaluation of potential unintended consequences of these technologies. This research can inform the design of effective policies to harness the potential of emerging technologies to mitigate the hypoxia problem. ❐

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References

1. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. *Environ. Res. Lett.* **9**, 105011 (2014).
2. Alexander, R. B. et al. *Environ. Sci. Technol.* **42**, 822–830 (2008).
3. Keiser, D. A., Kling, C. L. & Shapiro, J. S. *Proc. Natl Acad. Sci. USA* **116**, 5262–5269 (2019).
4. Compton, J. E. et al. *Ecol. Lett.* **14**, 804–815 (2011).
5. Rabotyagov, S. S. et al. *Proc. Natl Acad. Sci. USA* **111**, 18530–18535 (2014).
6. Gulf of Mexico 'dead zone' is the largest ever measured. *NOAA* (2 August 2017); https://go.nature.com/2ZcGQh3
7. *Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin* (USDA, 2012); https://go.nature.com/2zaNwO1
8. Van Meter, K. J., Basu, N. B. & Van Cappellen, P. *Glob. Biogeochem. Cy.* **31**, 2–23 (2017).
9. Dutta, D. et al. *IEEE Trans. Geosci. Remote Sens.* **53**, 5133–5147 (2015).
10. Woo, D. K. & Kumar, P. *Water Resour. Res.* **53**, 8404–8422 (2017).
11. Capalbo, S. M., Antle, J. M. & Seavert, C. *Agric. Syst.* **155**, 191–199 (2017).
12. Basso, B., Shuai, G., Xhang, J. & Robertson, G. P. *Sci. Rep.* **9**, 5774 (2019).
13. Xu, G., Fan, X. & Miller, A. J. *Annu. Rev. Plant Biol.* **63**, 153–182 (2012).
14. Jaganathan, D., Ramasamy, K., Sellamuthu, G., Jayabalan, S. & Venkataraman, G. *Front. Plant Sci.* **9**, 985 (2018).
15. Kant, S. *Semin. Cell Dev. Biol.* **74**, 89–96 (2018).
16. Fan, X. et al. *J. Exp. Bot.* **68**, 2463–2475 (2017).
17. Adenle, A. A. et al. *Nat. Biotechnol.* **36**, 137–139 (2018).
18. Wolt, J. D., Wang, K. & Yang, B. *Plant Biotechnol. J.* **14**, 510–518 (2016).
19. Shortle, J. S. & Horan, R. D. *Int. Rev. Environ. Resour. Econ.* **2**, 101–133 (2008).

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Author contributions

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