Science Societies

What's the scope of 4R practices for reducing emissions from fertilizer?

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Measured emissions from research on cropping systems are summarized in meta-analyses to validate 4R practice efficacy.

Fertilizer use has been a key factor in boosting crop yields worldwide. At the same time, the global use of nitrogen fertilizer is associated with greenhouse gas emissions This article reviews the scope for reducing emissions associated with fertilizer use. It addresses the global scale and recent reports focused on Canada, the United States, and sub-Saharan Africa. It concludes with a review of the advantages and limitations of approaches based on managing nitrogen surplus in crop nutrient budgets and shows how a 4R approach both includes and goes beyond reducing surpluses.

Fertilizer use has been a key factor in boosting crop yields worldwide, feeding a growing population, and relieving pressure for land use change. At the same time, the global use of nitrogen fertilizer is associated with greenhouse gas emissions of around 800 million tons of carbon dioxide equivalents (CO_2e) each year. Crop producers and their advisers are under pressure to find ways to reduce those emissions while continuing to increase crop yields and soil health. The principles of 4R nutrient stewardship have much to offer toward this goal.

Much of the effort to reduce greenhouse gas emissions from fertilizer focuses on improvement of nitrogen use efficiency (NUE). Emissions are associated with the manufacture, transport, and use of fertilizers, particularly nitrogen, and thus increasing NUE can dramatically reduce the carbon footprint of crop production. A singular focus on a narrowly defined efficiency, however, can miss other important opportunities to reduce the carbon footprint of crop production and may furtively increase emissions from other sources.

The application of 4R principles aims to produce more crops with fewer emissions while improving soil health. It includes improvement of nutrient use efficiencies and reduction of nitrogen surpluses. It also goes further to include choice of sources that limit the forms of nitrogen susceptible to conversion to nitrous oxide in the soil. A 4R approach also seeks to ensure that nitrogen supply supports the capacity of the cropping sequence to enhance soil capture of carbon.

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Global Scope

The International Fertilizer Association (IFA) and SystemIQ consulted with leading scientists and recently released a report (IFA, 2022) on reducing emissions from fertilizer use. It points out:

- Increasing global NUE from the current 50 to 70% could reduce annual emissions by 240 to 455 million tons CO_2e annually by 2050.
- The United States, with current NUE of 70% has much less opportunity to improve than India and China, where NUE is well below 50%.
- Improving NUE requires more than 4R nitrogen management. It includes management of other nutrient and crop protection inputs, crop genetic improvement, and may involve more labor.
- Inhibitors and controlled-release fertilizers can further reduce emissions by 150 to 260 million tons CO_2e.
- The two strategies, improving NUE and inhibitors, combine to offer a potential 70% reduction in emissions from fertilizer by 2050. Widespread implementation will take time and investment as only 25–30% of the abatement measures would be cost saving to farmers.
- Further reductions will depend on a wider transformation of the food system.

- Soil carbon sequestration on cropland could remove 440 to 7,500 million tons CO_2e per year. While the high end of this range is highly uncertain, stabilizing soil carbon requires nitrogen.
- Manufacturing of mineral fertilizer produced around 450 million tons CO_2e of greenhouse gas emissions in 2019, around 0.8% of total global greenhouse gas emissions. These emissions may be reduced considerably, as soon as 2030, by investments in production of “green” and “blue” ammonia.

Scope in the United States

Programs to reduce greenhouse gas emissions from crop production in the United States, announced in September 2022, focus on climate-smart commodities rather than on fertilizer. The USEPA greenhouse gas inventory, however, attributes 91 million tons of CO_2e emissions to the use of fertilizer, comprising roughly one-quarter of the emissions from agricultural soil management. This inventory does not reflect the effect of 4R practices in reducing emissions, but its Tier 3 methods allow for their inclusion in the future, provided that high-resolution activity data (that is, reporting of farm-specific 4R practices) are made available. The NUE of crop production in the aggregate is already high, driven by the impressive yield increases in corn over the past few decades and the large role of soybeans in the crop nitrogen budget. As legumes, soybeans fix their own nitrogen with a very high use efficiency. In irrigated crops, the potential for nitrous oxide emission is high but can be dramatically reduced by 4R timing and placement in the form of subsurface drip irrigation (Bronson et al., **2018**).

A case study in the System IQ report (IFA, **2022**) noted that nitrogen fertilizers applied in the corn–soybean cropping system of the United States were associated with annual emissions of around 50 million tons CO_2e, mostly as nitrous oxide. It estimated that by moving to more precise split applications to improve NUE, these emissions could be reduced by 7 to 13 million tons CO_2e, and though it could reduce yields by 1%, it would still be cost saving to farmers. Another 9 to 13 million tons CO_2e could be reduced through increased use of nitrification inhibitors though this measure would increase costs to farmers. The cost was estimated at about US$35 to US$85 per ton of CO_2e reduction.

Scope in Canada

In December 2020, the Canadian government set a voluntary target to reduce greenhouse gas emissions from fertilizer use—currently assessed at 13 million tons CO_2e per year—by 30% by 2030. Fertilizer Canada and the Canola Council of Canada (2022) recently released a report assessing the potential adoption of practices that would contribute to this target. The report points out:

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- The current rate of adoption of 4R practices effective in reducing these emissions ranges from 5 to 25%, depending on the practice, the crop, and the region within the country.
- Reducing emissions from fertilizers by 30% by 2030 is an immense challenge and not realistically achievable without imposing significant costs on crop producers.
- Assuming continued increasing trends in crop yields and reasonable adoption of 4R practices, a 14% reduction by 2030 is possible.
- Reaching the 30% reduction target would require 100% adoption of advanced 4R practices, which would require very substantial incentives.

- Government needs to substantially increase investment in high-resolution farm activity data supporting measuring, reporting, and verification of emission reductions.

Recognizing the need for incentives, the Canadian government has made available around CAN$200 million in programs to incentivize practices that include 4R. This cost-share funding is already being delivered for practices adopted in the 2022 crop year. In addition, further funding is promised.

Scope in Sub-Saharan Africa

The global context of fertilizer use is focused on meeting future food demands. These demands will become particularly acute among the rapidly growing populations of sub-Saharan African countries. Opportunities to increase crop yields there are large but will depend on increasing fertilizer use. Increased fertilizer nitrogen use, however, may also raise nitrous oxide emissions. With 4R practices, fertilizer use is optimized and emissions minimized while increasing yields.

A recent scenario analysis of the potential emission reductions that could arise from adoption of 4R practices in concert with increasing fertilizer use was reported in a white paper by Ezui et al. (2022). Using projections from the UN Food and Agriculture Organization for future fertilizer application rates and greenhouse gas (GHG) emissions and applying emission reduction coefficients like those supported by science in Canada, the analysis revealed potential emission reductions of more than 1 million tons CO_2e per year by 2030 and over 3 million tons by 2050.

Development of 4R practices adapted to the farming systems of sub-Saharan Africa will require site-specific research measuring and validating impacts on nitrous oxide emissions. Adoption of such practices has material climate change mitigation potential and should form an essential component of the efforts to sustainably intensify crop production in sub-Saharan Africa.

Reducing Emissions by Reducing Nitrogen Surplus

Many scientists advocate using nitrogen surplus as a proxy for environmental impact. The difference between the amount of nitrogen applied to and removed from a field or farm is much easier to measure than any one of the myriad losses to air and water that impact the environment. And in many situations, for a given farm, those losses are likely to be proportional to the nitrogen surplus.

The tracking of on-farm nutrient balances is an important accountability principle of 4R nutrient stewardship (SPRPN, 2022). A generalized relationship between nitrogen surplus and nitrous oxide emissions, applying to multiple crops and regions in North America, was developed from observations at 286 site-years (Eagle et al., 2020). There are a considerable number of advantages to a focus on surplus reduction.1.

1. Nitrogen surplus is measurable. At the farm and field scale, it is more easily measured than any loss pathway to water or air. All it requires is tracking the nitrogen supplied in applied fertilizers, manures, and other inputs and the nitrogen removed from the field by harvested crops.
2. Nitrogen surplus relates to every loss pathway. Some losses may still occur with a zero surplus, but in general, as surpluses decline, so does opportunity for loss. Thus, other positive impacts on air quality and water quality may be attained.
3. A focus on nitrogen surplus applies no arbitrary limit on increasing inputs commensurate with continuing improvement in yields and productivity. Since higher yields remove more nitrogen, it encourages crop management for higher yields.
4. Reducing nitrogen surplus reduces emissions associated with producing the fertilizer as well as the emissions in field.

A focus on surplus, however, does not capture all possible reductions in emissions associated with fertilizer. Following are some of the limitations of a focus on surplus.

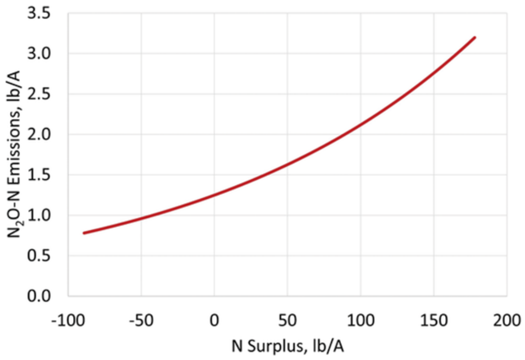

Figure 1, *Generalized relationship between nitrous oxide emissions and nitrogen surplus across 286 sites, mainly in the North American Corn Belt. Adapted from Eagle et al. (2020).*

Limited reductions in nitrous oxide emissions can require substantial reductions in surplus. For example, emissions may be reduced by 28% by reducing surplus nitrogen from 66 lb/ac to zero (Figure 1). However, that's equivalent to growing 200 bu/ac corn with 134 lb/ac of N input instead of 200 lb/ac. Zero surplus implies 100% NUE, which is extremely difficult to achieve. Reducing surpluses from higher levels, however, results in bigger opportunities. Reducing a large nitrogen surplus like 115 lb/ac by just 48 lb/ac yields the same reduction in emission as going from 66 to zero. So, it depends on the opportunity to improve.

Nitrogen surplus neglects independent effects of inhibitors and controlled-release products on nitrous oxide emission. Several products have been demonstrated in global meta-analyses to reduce nitrous oxide emissions, on average, per unit of nitrogen applied. This reduction is larger than their effect on crop yield or nutrient use efficiency. The specific products demonstrated to have such efficacy are nitrification inhibitors and polymer coatings applied to urea. Across a wide range of soils and cropping systems globally, measured nitrous oxide emission reductions averaged 49% for nitrification inhibitors (from 422 observations), 31% for combined urease and nitrification inhibitors (from 118 observations), and 19% for polymer-coated urea (from 89 comparisons) (Fan et al., 2022; Thapa et al., 2016). These reductions in nitrous oxide emissions are larger than the reported effects of these products on crop yield or NUE (7.5 and 12.9%, respectively; Abalos et al., **2014**).

Greenhouse gas emissions are associated with the manufacture, transport, and use of fertilizers, particularly nitrogen. Photos courtesy of Adobe Stock (iamporpla, ????????? ???????, and M. Perfectti).

Nitrogen surplus neglects effects of choice of source on emissions. For example, the application of urea to soil generates 1.6 pounds of actual CO_2 emission per pound of N applied, from the carbon atom in the urea molecule. While this is smaller than the CO_2e of the nitrous oxide emission arising from nitrogen application, it is considerable. Sources may also differ in the carbon footprint of their manufacture (Fertilizers Europe, **2022**).

Nitrogen surplus does not fully consider potential trade-offs with soil carbon storage. Surplus nitrogen does not in itself contribute carbon to the soil. But nitrogen is essential to the process of stabilization of carbon in soil. Surplus nitrogen could potentially enhance the growth of cover crops, and in so doing, support the photosynthetic production of carbon forms that do contribute to increasing soil organic matter (for example, Grove et al., **2009**). On the other hand, when surpluses are small, it's more likely that the crop's total photosynthetic assimilation was limited by available nitrogen. Research in Iowa substantiates the need for nitrogen input levels close to economic optimum to maximize soil carbon storage (Poffenbarger et al., 2017).

Including 4R in Emission Reduction Programs

Crop producers in North America have an opportunity to lead the way toward reducing the carbon footprint of crop production. Programs to do so will include fertilizer since it contributes a substantial proportion of this footprint. Such programs will rightly focus on improvement of NUE and reduction of nitrogen surpluses. They also need to simultaneously consider the factors contributing to buildup and maintenance of soil organic matter through inclusion of cover crops and crop rotations that contribute more carbon to the soil.

Including 4R principles and practices in emission reduction programs and protocols offers opportunity to capture greater reductions in emissions. A program based on 4R builds on the strengths of a nitrogen surplus approach and addresses most of its limitations. Choices of the right sources, timings, and placements have effects on emissions beyond those accounted for in NUE improvement and reductions in nitrogen surplus. Accountability principles for 4R programs encourage the reporting to trusted third parties of tracked data on the specific combinations of source, rate, time, and place for each nutrient application, along with the outcome measure of a crop nutrient balance. These data are essential to document progress in both reducing emissions from fertilizer and improving the carbon footprint of crop production.

Conclusions

The scope for reducing emissions by applying 4R practices is large but may require dramatic and costly changes. In Canada, a 30% reduction by 2030 was found possible only with unrealistically high rates of adoption of advanced 4R practices. Globally, a 70% reduction by 2050 could be achieved, again only with massive improvements in NUE and 4R practice adoption. In both cases, only one-quarter to one-half of those reductions could be achieved in a cost-effective manner for farmers. Farmers on their own do not have the resources to provide all the emission reductions possible. Governments or buyers of crop commodities will need to pay farmers for the value they are providing in adopting practices to achieve reductions in emissions. In Canada's emissions trading system, the projected price for reducing a ton of CO_2e emissions in 2030 is about CAN$150. Farmers, industry, and government will need to work together to develop the monitoring, reporting, and verification needed for the programs to recognize and reward those adopting practices that reduce emissions.

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