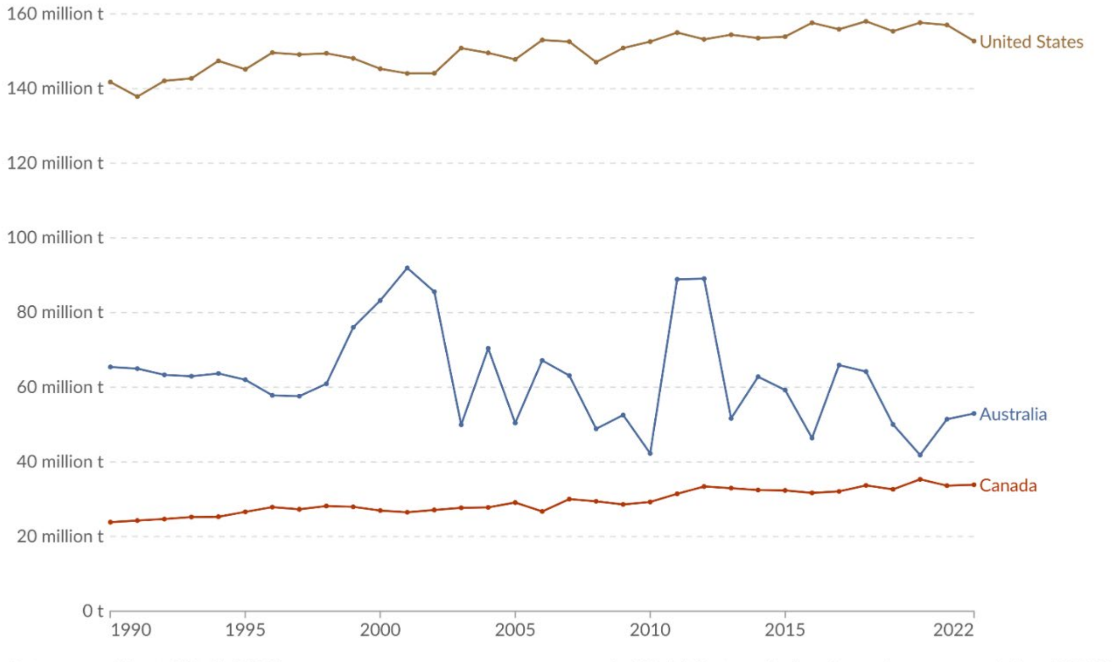
FERTILITY OPTIMIZATION

Climate change caused by greenhouse gas (GHG) emissions has risen to the forefront of many government policies around the world, and emissions caused by agriculture have received their share of attention. The positive side of this attention, though, is funding and research initiatives into better understanding emissions from cropping systems and how to reduce them. The research has reinforced how valuable the 4R nutrient stewardship guidelines are, and that there are opportunities to not just reduce GHG emissions but reduce N losses in all forms to improve nitrogen use efficiency (NUE) and economic return from applied N (Norton, Gourley, & Grace, 2023).

4R Nutrient stewardship is a framework developed to guide farmers toward responsible use of nutrients for economic, environmental, and social benefit (The Fertilizer Institute, 2021; Bruulsema, 2022). This framework guides nutrient applications to be applied at the right time, right place, right rate, and with the right source. Historically these 4R principles have been applied at a field scale; in other words, the whole field has been treated the same based on an average soil type. But 4R nutrient guidelines should not be applied using arbitrary field boundaries. *4R practices are governed by properties like soil texture, soil moisture, crop yield potential, pH, mineralization potential, and soil nutrient levels—all of which vary across a field landscape (Burton, 2018). True 4R nutrient management must acknowledge this variability for full economic, environmental, and social benefit.*

Gaseous Nitrogen Loss

One of the most significant GHG concerns from cropland is nitrous oxide (N_2O). While total emissions of N_2O are typically only 0.5 to 2 kg N_2O-N per ha (Shcherbak et al, 2014), it is a potent greenhouse gas with a global warming potential of approximately 265 times CO_2. Globally, annual emissions from agriculture have increased 28% since 1990, to a total estimate of over 2.07 billion t CO_2eq in 2022 (Climate Watch, 2025). Annual emissions from USA, Australia, and Canada are show in Figure 1. N_2O is produced from fertilizer N as a biproduct of the nitrification process and from soil nitrates through a process called denitrification.



Data source: Climate Watch (2025)   OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

***Figure 1**. N_2O emissions (expressed as tonnes of CO_2eq) from agriculture in Australia, Canada, and USA. Source: Climate Watch, 2025.*

Denitrification is a significant nitrogen loss mechanism in agriculture globally (IPNI, 2021; Stark and Richards 2008). It is largely the result of relatively saturated soil conditions causing a biological reaction to occur via bacteria, converting soil nitrate (NO_3^-) to NO, N_2O, and N_2 releasing these gases to the atmosphere (Maharjan et al., 2024). Under completely flooded, anaerobic conditions nitrate will be reduced completely to N_2, a harmless and abundant atmospheric gas. It is primarily the wet areas surrounding wetlands that have high N_2O emission potential, as depicted in Figure 2. From a farm economics perspective, in what form N is lost does not matter—all lost N results in lower productivity or increased expenses to replace it in the future. Figure 3 shows productivity loss due to N loss in low landscape positions.

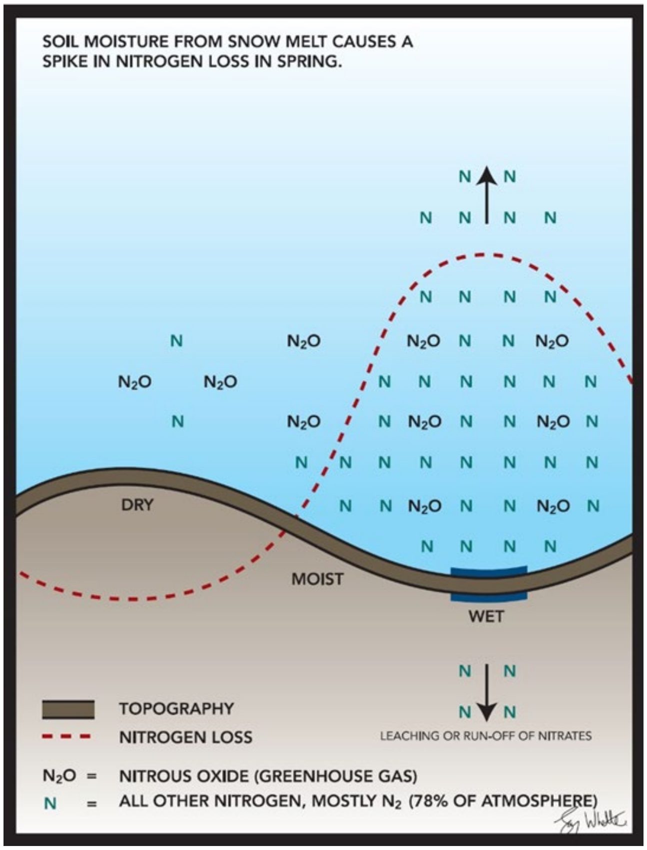


***Figure 2**. Diagram of N loss variability by landscape position. Source: Jay Whetter, Canola Council of Canada*

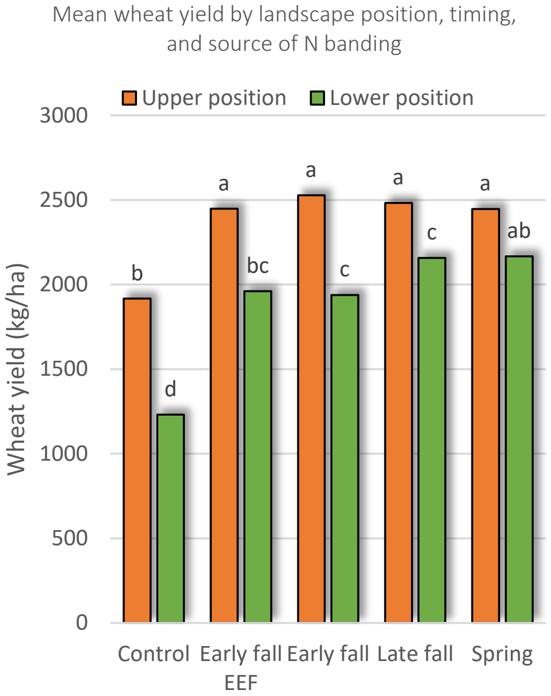


***Figure 3**. Evidence of N loss due to denitrification in low landscape positions. Source: Tiessen et al. 2005.*

The significance of organic matter and subsequent mineralization of nitrogen in-season should also be considered. Many hummocky landscapes characteristic of the USA northern great plains and western Canada have significant organic matter variability (and variable depth of A horizon or topsoil) that result in variable mineralization and soil nitrates (Beckie et al., 1997; Malo and Worcester, 1975; Pennock et al., 1987). This difference can lead to N_2O "hotspots" in high organic carbon soils in lower landscape positions, as reported by Dunmola et al. (2010). Therefore, proper nitrogen rates need to consider mineralization potential along with crop uptake requirements and available soil nitrate at sowing. Figure 4 shows mean topsoil nitrate levels from thousands of fields in western Canada, showing a distinct trend of increased nitrate in SWAT zones 9-10, often due to poor production and/or high organic matter mineralization rates. These are also the wettest areas of the landscape and therefore, without using VR to lower rates in those areas, they would unfortunately be prone to high N_2O emissions.

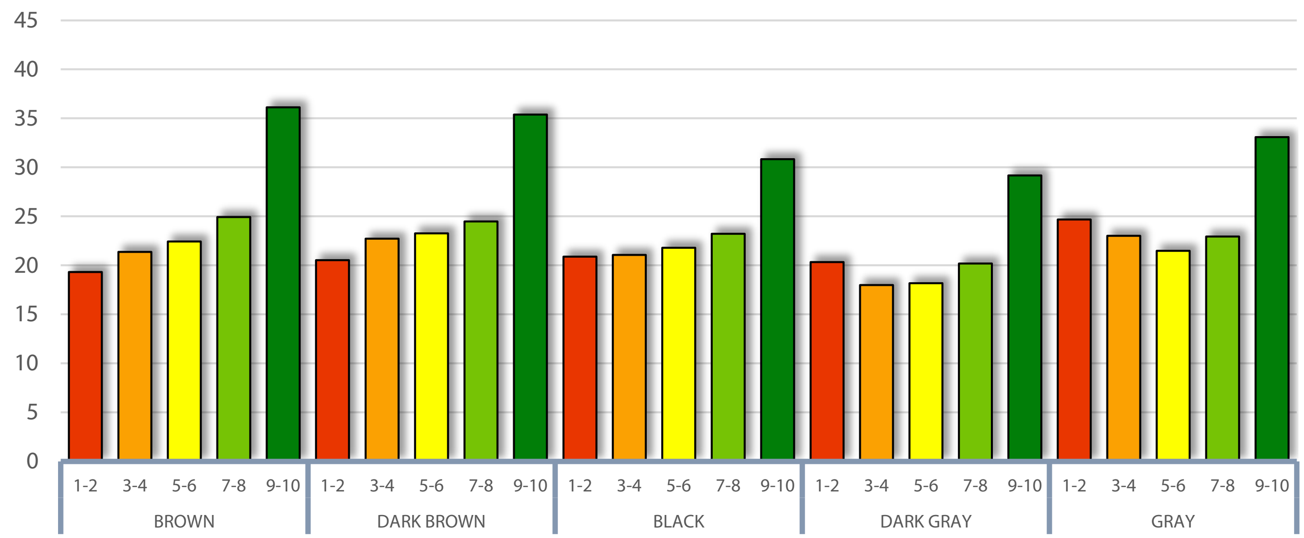


***Figure 4**. Soil nitrate (lbs/ac, 0-20 cm) by SWAT zone and major soil zone in western Canada (mean of 52,000 samples).*

Glenn et al. (2021) concluded that using VR can mitigate N_2O emissions from soils. In this study, the “high yield zones” had the lowest emission factors (N_2O per kg fertilizer N) despite having 50% more nitrogen applied, while the low yield zones had higher emission factors despite receiving 50% less nitrogen than field average. In other words, *N_2O emissions are not directly correlated to the nitrogen fertilizer rate applied, but rather how much of that N is needed (or not needed) for crop growth*. **That difference—the ideal rate of N needed—is what varies across the landscape, and is what we can measure and manage with SWAT MAPS.** *It is also why simply reducing total N applied but maintaining flat rates will not necessarily meet emission reduction goals. That strategy could not only hurt output by limiting yields in areas of the field that need high N rates but may also not be enough reduction to address the “hot spots” that have high emissions. VR N may be the only way to address this scenario.*

In another recent study by Hangs et al. (2024) on VR feedlot manure in Saskatchewan, Canada, VR manure resulted in a 23.7% lower N_2O emissions factor than flat rate manure. The study cited higher soil moisture, SOC, and nitrogen supply in large depressional catchment areas as significant influences on large N_2O fluxes. This reinforces that 4R nutrient stewardship applies to all sources of nutrients, whether they are organic or synthetic.

Use of nitrification inhibitors and polymer coated urea have significantly reduced N_2O emissions in many studies (Calderon et al., 2005; Chen et al., 2008; Chen et al., 2010; Hargreaves et al., 2021; Lin and Hernandez-Ramirez, 2020; Maaz & Snyder, 2018; Misselbrook et al., 2014; Raza et al., 2019; Snyder, 2017; Zebarth et al., 2019), and are no doubt a useful tool to mitigate losses. However, the high upfront cost has held back adoption of these products and, to date, do not make up a large percentage of nitrogen sources used in most regions. Regardless, from a broad perspective, any agronomic practice that delays the availability of nitrate to better match timing of crop uptake will theoretically minimize nitrogen losses—including the use of enhanced efficiency fertilizers (EEFs), timing of application, and VR nitrogen application.

While there are currently no formal guidelines for other inputs such as lime, gypsum, manure, and pesticides—we could apply similar 4R principles of time, place, rate, and source to these products as well. For example, basic 4R practices for lime could be:

- Right time: Several months prior to pH change needed.
- Right place: Areas of field that are acidic, and to the depth acidity occurs.
- Right rate: The rate needed to adjust soil pH to the desired pH based on soil buffer pH and quality of lime.
- Right source: A material with sufficient calcium carbonate equivalence and fineness to adjust pH within the desired timeframe.

Advanced 4R practices would simply take the above considerations and apply them spatially within a field based on mapping of soil properties using SWAT MAPS, to potentially utilize VR applications where it makes sense to do so and reduce the amount of lime needed. This supports a stronger return on investment as well as a reduction in GHG emissions related to production of lime and its reactions in soil that emit carbon dioxide.

While there is not one simple solution to mitigating nitrogen losses and N_2O emissions, a better understanding of where losses are most likely to occur within a field is an important first step in managing the problem. Because water potential, organic matter differences, and crop N uptake are so closely linked to field areas delineated by SWAT MAPS, they offer a valuable PA tool to better manage N and reduce emissions through a variety of stacked agronomic strategies.

Nitrogen Loss via Leaching

Nitrogen can also be lost from cropland via leaching. Texture variation has a substantial effect on nitrogen losses and thus leaching is a well-known problem in sandy soils (Gurevich et al., 2021; IPNI, 2021; Sandercock et al., 1993; Spackman et al., 2019) and is a significant environmental concern in many agricultural regions of the world (Cameron et al., 2002; Shukla and Saxena., 2018; Wang et al., 2015; Nakagawa et al., 2021; Zhou et al., 2015). Excess nitrites (caused by reduction of nitrates) that have leached into aquifers or surface waters used for drinking water can cause what is commonly known as blue baby syndrome (methemoglobinemia), a symptom of nitrite toxicity. High nitrate levels in drinking water can also be fatal to ruminant livestock (Government of Canada, 2020). Nitrates in these water sources are typically caused by over-application of fertilizer or manures to soils that are susceptible to leaching—particularly coarser textured, sandier soils.

There are several solutions to manage nitrate leaching. Timing of application has demonstrated value in some studies (Spackman et al., 2019; Davies et al., 2020), utilizing in-season application of a portion of nitrogen to match crop uptake demand and improve NUE. Organic nitrogen and ammonium are relatively immobile in the soil. They can be moved through soil erosion but largely do not move with the soil solution. Nitrate, being an anion, is present in the soil solution and cannot be bound to the cation exchange complex. Therefore, it is highly mobile and will easily travel with water passing through the soil towards the groundwater. If the availability of nitrate is matched to plant uptake there is little leaching that occurs even if there are large stores of nitrogen in ammonium and organic forms. The impact that split nitrogen applications and EEFs have on reducing nitrate leaching depends on leaching potential, primarily driven by soil texture, crop water use, and rainfall or irrigation.

Nitrogen losses are not just based on soil nitrate levels; excess water is also needed to saturate the soil and move down through the profile carrying nitrate with it. While there is no way to control rainfall, irrigation can be managed to reduce this problem (McDowell, 2017). Irrigated production systems are particularly susceptible to nitrogen losses through leaching and denitrification. Crop water requirements, and the soil's ability to hold water, can vary across the landscape significantly and as a result variable rate irrigation (VRI) systems are slowly being adopted in many regions (Lo et al., 2017). The concept of VRI is simple, yet like soil fertility requirements, can be complex to put into practice (Barker et al., 2017). Regardless, studies have reported opportunity for 8 to 20% in water savings using VRI technology (Sadler et al., 2005).

Use of SWAT MAPS to Optimize Fertility and Reduce Nitrogen Losses

SWAT MAPS allow farms to spatially apply several best practices at once to reduce nitrogen losses. SWAT MAPS consider the spatial variability of water flow and accumulation, differences in soil texture, and crop yield potential across a landscape. With this information a farm can use several different strategies (or combinations of strategies) to reduce nitrogen losses:

1. *Target proper nitrogen rates* based on crop yield potential, soil nitrogen supply, and estimated in-season nitrogen soil supply rate (mineralization).
2. *Utilize protected nitrogen sources* (i.e. nitrification inhibitors or polymer coated urea), especially in parts of the field at highest risk of loss such as coarse textured soils and poorly drained depressions.
3. *Top-dress nitrogen in-season* based on current soil moisture variability across the landscape, yield potential, and expected nitrogen loss. The accuracy of this application can be enhanced even further utilizing soil moisture probes and detailed texture data to make SWAT WATER maps – spatial soil water maps that model the soil water content across a landscape.
4. *Use SWAT WATER maps and VRI technology* to more accurately apply water based on WHC and landscape position in different parts of the field.

Nutrient balance also plays a role in managing nitrate accumulation and leaching by promoting crop health, which increases yield and nitrogen uptake in the crop. This has been demonstrated in wheat and canola

(Malhi et al., 2009) and in corn and rice (Duan et al., 2014). This reinforces the complexity of soil and plant nutrition and interactions that exist between nutrients to maximize their use and uptake. Liebig's Law of the Minimum will come into effect, where nitrogen response and uptake can be limited by other nutrients such as phosphorus, potassium, sulfur, micronutrients, or available water. Therefore, a holistic approach based on soils and water is needed to manage nitrogen rates and minimize environmental impact from leaching.

Metrics

The easiest way to assess the efficacy of a fertility prescription is to look at the crop yield and residual nutrients. Did the crop yield achieve its target (assuming no major pests, disease or extreme weather)? If so, are there large amounts of residual nutrients. An underperforming crop can be indicative of under-fertilization, especially if there are little residual nutrients. Excessive residual nutrients means the crop was over fertilized. For more in depth analysis tissue testing can be done to assess for sufficiency, deficiency, or luxury consumption.

Recommended Metrics:

- **Crop yield (compared to target)**
- **Nutrient use efficiency (compared to target)**
- **Regular soil testing to monitor soil nutrient levels, pH, organic matter, and salts**
- **Tissue testing to measure plant nutrient uptake**
- **Use of soil moisture probes to measure soil water for guiding nutrient application decisions**

Figure 5. *Example of a saline area (SWAT zone 10) in a wheat field in southeast Queensland, Australia. This area tested excessively high in soil nitrates and presented an opportunity for using VR technology to reduce fertilizer cost and environmental loss.*

References

Barker, J. B., Franz, T. E., Heeren, D. M., Neale, C. M., & Luck, J. D. (2017). Soil water content monitoring for irrigation management: A geostatistical analysis. *Agricultural Water Management*, *188*, 36-49.

Beckie, H. J., Moulin, A. P., & Pennock, D. J. (1997). Strategies for variable rate nitrogen fertilization in hummocky terrain. *Canadian Journal of Soil Science*, *77*(4), 589-595.

Bruulsema, T. (2022), Nutrient Stewardship: Taking 4R Further. Crops & Soils Mag., 55: 34-40. https://doi.org/10.1002/crso.20165

Burton, D. (2018). A Review of the Recent Scientific Literature Documenting the Impact of 4R Management on N_2O Emissions Relevant to a Canadian Context.

Calderón, F. J., McCarty, G. W., & Reeves III, J. B. (2005). Nitrapyrin delays denitrification on manured soils. *Soil science*, *170*(5), 350-359.

Cameron, K. C., Di, H. J., & Condron, L. M. (2002). 17 Nutrient and Pesticide Transfer from Agricultural Soils to Water in New Zealand. *Agriculture, hydrology and water quality*, 373.

Chen, D., Suter, H., Islam, A., Edis, R., Freney, J. R., & Walker, C. N. (2008). Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. *Soil Research*, *46*(4), 289-301.

Chen, D., Suter, H. C., Islam, A., & Edis, R. (2010). Influence of nitrification inhibitors on nitrification and nitrous oxide (N_2O) emission from a clay loam soil fertilized with urea. *Soil Biology and Biochemistry*, *42*(4), 660-664.

Climate Watch (2025) – with major processing by Our World in Data. “Agriculture” [dataset]. Climate Watch, “Greenhouse gas emissions by sector” [original data].

Davies, B., Coulter, J. A., & Pagliari, P. H. (2020). Timing and rate of nitrogen fertilization influence maize yield and nitrogen use efficiency. *Plos one*, *15*(5), e0233674.

DUAN, Y. H., SHI, X. J., LI, S. L., SUN, X. F., & HE, X. H. (2014). Nitrogen use efficiency as affected by phosphorus and potassium in long-term rice and wheat experiments. *Journal of Integrative Agriculture*, *13*(3), 588-596.

Dunmola, A. S., Tenuta, M., Moulin, A. P., Yapa, P., & Lobb, D. A. (2010). Pattern of greenhouse gas emission from a Prairie Pothole agricultural landscape in Manitoba, Canada. *Canadian Journal of Soil Science*, *90*(2), 243-256.

Glenn, A. J., Moulin, A. P., Roy, A. K., & Wilson, H. F. (2021). Soil nitrous oxide emissions from no-till canola production under variable rate nitrogen fertilizer management. *Geoderma*, 385, 114857.

Government of Canada. (2020, January 24). Agriculture and Water Quality. Retrieved from Agriculture and Water Quality: https://www.agr.gc.ca/eng/agriculture-and-the-environment/agriculture-and-water/watershed-protection/agriculture-and-water-quality/?id=1371491033072

Gurevich, H., Baram, S., & Harter, T. (2021). Measuring nitrate leaching across the critical zone at the field to farm scale. *Vadose Zone Journal*, *20*(2), e20094.

Hangs, R., Schoenau, J. J., Knight, J. D., & Farrell, R. E. 2024 (Preprint). Using Variable Rate Precision Application of Feedlot Cattle Manure to Mitigate Soil Greenhouse Gas Emissions. *Available at SSRN 4701022*.

Hargreaves, P. R., Baker, K. L., Graceson, A., Bonnett, S. A. F., Ball, B. C., & Cloy, J. M. (2021). Use of a nitrification inhibitor reduces nitrous oxide (N_2O) emissions from compacted grassland with different soil textures and climatic conditions. *Agriculture, Ecosystems & Environment*, *310*, 107307.

International Plant Nutrition Institute (IPNI) (2021). Nitrogen Notes. Number 5 – Denitrification. www.ipni.net/publications.

Lin, S., & Hernandez-Ramirez, G. (2020). Nitrous oxide emissions from manured soils as a function of various nitrification inhibitor rates and soil moisture contents. *Science of the Total Environment*, *738*, 139669.

Lo, T. H., Heeren, D. M., Mateos, L., Luck, J. D., Martin, D. L., Miller, K. A., ... & Shaver, T. M. (2017). Field characterization of field capacity and root zone available water capacity for VRI. *Applied Engineering in Agriculture*, 33(4), 559-572.

Maaz, T. M., & Snyder, C. (2018). The Identification of Management Strategies that Target Multiple Nitrogen Loss Pathways (Part 3 of 3). *Better Crops with Plant Food*, *102*(4), 16-19.

Maharjan, B., Jin, V., Puntel, L., Iqbal, J., Williams, T., Blanco, H., and Wortmann, C. S. (2024). Crop Management to Reduce Soil Nitrous Oxide Emissions in Nebraska. University of Nebraska-Lincoln. Nebraska Extension Publications. Accessed at: https://extensionpubs.unl.edu/publication/g2322/html/view.

Malhi, S. S., Schoenau, J. J., & Leach, D. (2009, February). Maximizing N fertilizer use efficiency and minimizing the potential for nitrate-N accumulation and leaching in soil by balanced fertilization. In *Soils and Crops Workshop*.

Malo, D. D., & Worcester, B. K. (1975). Soil Fertility and Crop Responses at Selected Landscape Positions 1. *Agronomy Journal, 67*(3), 397-401.

McDowell, R. W. (2017). Does variable rate irrigation decrease nutrient leaching losses from grazed dairy farming?. *Soil Use and Management*, *33*(4), 530-537.

Misselbrook, T. H., Cardenas, L. M., Camp, V., Thorman, R. E., Williams, J. R., Rollett, A. J., & Chambers, B. J. (2014). An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. *Environmental Research Letters*, *9*(11), 115006.

Norton, R., Gourley, C., & Grace, P. (2023). *Nitrogen Fertiliser Use and Greenhouse Gases. An Australian Assessment: Challenges and Opportunities*. Kingston: Fertilizer Australia

Pennock, D. J., Zebarth, B. J., & De Jong, E. (1987). Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma*, *40*(3-4), 297-315.

Raza, S., Chen, Z., Ahmed, M., Afzal, M. R., Aziz, T., & Zhou, J. (2019). Dicyandiamide application improved nitrogen use efficiency and decreased nitrogen losses in wheat-maize crop rotation in Loess Plateau. *Archives of Agronomy and Soil Science*, *65*(4), 450-464.

Sadler, E. J., Evans, R., Stone, K. C., & Camp, C. R. (2005). Opportunities for conservation with precision irrigation. *Journal of Soil and Water Conservation*, *60*(6), 371-378.

Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences*, *111*(25), 9199-9204.

Shukla, S., & Saxena, A. (2018). Global status of nitrate contamination in groundwater: its occurrence, health impacts, and mitigation measures. *Handbook of environmental materials management*, 869-888.

Snyder, C. S. (2017). Enhanced nitrogen fertiliser technologies support the ‘4R’concept to optimise crop production and minimise environmental losses. *Soil Research*, *55*(6), 463-472.

Spackman, J. A., Fernandez, F. G., Coulter, J. A., Kaiser, D. E., & Paiao, G. (2019). Soil texture and precipitation influence optimal time of nitrogen fertilization for corn. *Agronomy Journal*, *111*(4), 2018-2030.

Stark, C. H., & Richards, K. G. (2008). The continuing challenge of agricultural nitrogen loss to the environment in the context of global change and advancing research. *Dynamic Soil, Dynamic Plant*, *2*(1), 1-12.

The Fertilizer Institute. (2021). 4R Nutrient Stewardship. Retrieved from https://nutrientstewardship.org/4rs/

Tiessen, K. H. D., Flaten, D. N., Grant, C. A., Karamanos, R. E., & Entz, M. H. (2005). Efficiency of fall-banded urea for spring wheat production in Manitoba: Influence of application date, landscape position and fertilizer additives. Canadian Journal of Soil Science, 85(5), 649-666.

Wang, H., Gao, J. E., Li, X. H., Zhang, S. L., & Wang, H. J. (2015). Nitrate accumulation and leaching in surface and ground water based on simulated rainfall experiments. *PLoS One*, *10*(8), e0136274.

Zebarth, B. J., Burton, D. L., Spence, J., & Khosa, M. K. (2019). Simultaneous measurement of net nitrogen mineralization and denitrification rates in soil using nitrification inhibitor 3, 5-dimethylpyrazole. *Canadian Journal of Soil Science*, *100*(1), 1-10.

Zhou, Z., Ansems, N., & Torfs, P. (2015). A global assessment of nitrate contamination in groundwater. International Groundwater Resources Assessment Center; Internship report; Wageningen University: Wageningen, The Netherlands.

Acronym & Abbreviation Guide

4R — Right Source, Right Rate, Right Time, Right Place
Nutrient stewardship framework to optimize nutrient use efficiency and reduce losses.

CO_2 — Carbon Dioxide
Discussed in relation to soil carbon sequestration and lime-related emissions.

EC — Electrical Conductivity
Measure of soluble salts in soil; used to infer salinity, texture variability, and water movement.

EEF — Enhanced Efficiency Fertilizer
Nitrogen fertilizers with inhibitors or coatings reducing loss through volatilization, leaching, and denitrification.

GHG — Greenhouse Gas
Gases whose emissions contribute to climate change (e.g., CO_2, N_2O, CH_4). Frequently discussed in relation to fertilizer and soil management.

N_2O — Nitrous Oxide
Potent GHG (265× CO_2) emitted from soils through nitrification/denitrification, especially in wet zones.

NUE — Nitrogen Use Efficiency
Fraction of applied nitrogen taken up by crops; used to evaluate the effectiveness of fertility programs.

SOC — Soil Organic Carbon
Carbon component of SOM (~58% of SOM mass); key indicator of carbon sequestration potential.

SOM — Soil Organic Matter
Decomposed biological material in soil essential for fertility, structure, water retention, and long-term soil health.

SWAT — Soil, Water, and Topography
A spatial soil landscape framework for mapping stable properties that drive yield potential and environmental interactions.

SWAT MAPS
High-resolution soil, water, and topography maps forming the foundation of precision agronomy within the SWAT ECOSYSTEM.

VR — Variable Rate
Varying seed, fertilizer, or pesticide applications within a field based on mapped variability.

VRI — Variable Rate Irrigation
Irrigation water applied at different rates across a field based on soil water holding capacity and moisture demand.

WHC — Water Holding Capacity
Volume of plant-available water stored between field capacity and wilting point across soil profiles.