Challenges and Potential Solutions to Reduce Fertilizer Application Rates and Agricultural GHG Emissions

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Introduction

Producing greater yields, through increasingly efficient input use, has long been a main goal of agriculture. The OECD reports that since 1960, yield increases were decoupled from increased land, with yields increasing 390%, while land used to produce food has only increased 10%

(OECD, 2021). Continued yield increases, coupled with efficient input use, results in increasingly sustainable food production, which contributes to the second of the UN's Sustainable Development Goals – to end hunger, achieve food security and improved nutrition and promote sustainable agriculture. Canada has played, and will continue to play, a vital role in successfully achieving this SDG goal through the production of food crops that are exported around the globe. To ensure that Canada continues to make a leading contribution to achieving the SDGs, continued access to crop inputs, such as fertilizer, will be of fundamental importance.

Fertilizer, particularly nitrogen (N), availability is the primary limiting nutrient to sustain crop yield and quality after carbon, hydrogen and oxygen. It plays a fundamental role in the biochemical and physiological functions of the plant.[1,2] Consequently, nitrogen fertilizer application has become an indispensable and unavoidable part of crop production systems, helping to provide adequate food and nutritional security for the world's growing population. In the last six decades, crop yield increases were mainly possible due to fertilizer applications, particularly nitrogen fertilizers. Moreover, high-yielding potential of genetic improved cultivars would not be realized without the application of fertilizer (Blaise, 2021; Chivenge et al., 2021). During recent decades, a tremendous amount of N fertilizers has been applied to agricultural lands to promote crop production worldwide. Globally, the amount of nitrogen use increased by more than 80% over the period 1980 to 2018 (FAO, 2021). This increase is expected to continue as a result of the growing demand for food, feed, and fibre (Tian et al., 2020).

Despite its many benefits, N application comes at an environmental cost. The release of N from agriculture has resulted in a major deleterious environmental impact, including an increase in nitrous oxide (N_2O) – a greenhouse gas (GHG) and important catalyst of stratospheric ozone depletion – soil acidification and fertility deficiency, as large-scale, long-term fertilizer use significantly alters soil nutrient balance. N_2O is primarily produced as a result of biotic processes, namely nitrification and denitrification, which are impacted by the rate of N fertilizer applied, the type of soil, soil moisture, crop activities, and the placement of nitrogen fertilizer into the soil. Moreover, N utilization can result in off-site pollution of the air, groundwater and waterways (Kumar, 2001; Yang, 2006).[3] Over the past 150 years, increasing N_2O emissions have contributed to stratospheric ozone depletion at 2 percent per decade. While little of the nitrogen applied is converted to N_2O emission (typically, 0.5% to 3% of nitrogen added to soil is released as N_2O emission), this emission generally represents a large percentage of the total GHG emissions in the crops sector, since N_2O has 310 times the global warming potential of CO_2 (IPCC, 2007; Bouwman et al., 2002).

On the Canadian Prairies, N_2O emissions from fertilizer application increased by more than 100% between 1985 and 2016 – in Alberta, N_2O emissions increase by 61%, in Saskatchewan nearly

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[1] Among the different types of N fertilizer, anhydrous ammonia contains the highest concentration of N (N>80%) (Kaag and Krishnamurthy, 2010).

[2] Compared to other fertilizers such as phosphorus and potassium, nitrogen is widely used in the Canadian Prairies as it is considered the most important nutrient to improve a plant's biochemical and physiological functions, proper plant growth and development and improvement in yield quantity and quality. Therefore, Due to its importance, this study focuses only on the use of fertilizer nitrogen.

[3] To mitigate the environment consequences of fertilizers, energy efficient innovations and less CO_2 emitting methods to manufacture fertilizers are needed.

threefold, and in Manitoba by 71% (Awada et al., 2021).[4] Total Canadian Prairie emissions from fertilizer application increased from 2.52 Mt CO_2eq in 1985 to 3.16 Mt in 2005 and 5.16 Mt CO_2eq in 2016 (Awada et al., 2021). This increase was driven by intensified crop production by means of increased crop rotation and reduced summerfallow, which required the greater use of fertilizer. In Alberta, the amount of nitrogen used increased by 91% over the period of 1985 to 2016, while crop production increased by 117% over the same period. In Saskatchewan, the use of fertilizer increased 98%, while crop production increased by 61% over the same period. In Manitoba, fertilizer use increased 77% and crop production increased by 26% (Statistics Canada Fertilizer Shipments, CANSIM 001-0068; Statistics Canada CANSIM 001-0017 (1985–2016)). In aggregate, crop production value in the Prairies has risen by more than 450% or $24 billions in the past 30 years (Statistics Canada, (1985-2021), Table: 32-10-0045-01). It has been widely reported that fertilizer nutrient use efficiency (NUE) by crops is low, ranging between 25% and 50% depending on the crop, environmental conditions, and management practices (Hofmann et al., 2020; Herrera et al., 2016). The low NUE leads to high production costs and a threat to the environment. The NUE is the product of two main components: nutrient uptake efficiency and utilization efficiency. The nutrient uptake efficiency is the ability of plants to take up nutrient from the soil, while nutrient utilization efficiency describes the capability of plants to assimilate and remobilize nutrients within the plant (Anas et al., 2020). Excessive and inefficient use of N fertilizer causes a significant amount of the applied N to be lost to the environment via nitrification, denitrification, leaching, and volatilization (Chien et al., 2016; Bowman et al., 2008). Inefficient fertilizer use in the Prairies has consistently been reduced as the price of fertilizer has increased and farmers have adopted soil testing and farmers only applying required amounts of soil nutrients.

Potential solutions to improve nutrient use efficiency and reduce agricultural emissions

The development of new technologies/approaches to optimize NUE and reduce fertilizer application to mitigate environmental consequences while maintaining or improving crop productivity and farmers' income has been a core focus of Canadian agriculture over the past 20 years. In the last few years, advancements in agronomy, breeding and molecular approaches have been promising to realize improvement in NUE (Javed et al., 2022). In what follows, we briefly discuss some examples on improving NUE and reducing N application.

Advancements in fertilizers such as, controlled-release and slow N release fertilizers (e.g., urease inhibitors, urea-triazone) have been commercially used in some countries and are identified as promising tools to increase the recovery of applied N fertilizer, while mitigating the negative impacts of N_2O (Upadhyay, 2012; Bedmar et al., 2005; Shaviv, 2000). However, due to the high costs of these fertilizer formulations, their application tends to be limited to high value crops (Chien et al., 2009). Nitrogen stabilizer, which is a substance added to a fertilizer, has been tested and shown to work successfully in holding the time of fertilizer nitrogen in the soil in the

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[4] Here, we focus on N_2O emissions calculation. Other forms of emissions from fertilizer nitrogen may also be released into the environment, (e.g., NH_4, NH3, and NO3), referred to as indirect N_2O emissions, that can be transferred into N_2O in downwind or downstream ecosystems (IPCC, 2007). These emissions have been well documented, albeit the quantity of N lost through these mechanisms remains difficult to measure (Davidson et al. 2012).

ammoniacal form by delaying the process of nitrification, denitrification, ammonia volatilization, or urease production through action upon soil bacteria (USDA, 2015). Some of the nitrogen stabilizer that are available in the market include, Nitrophos and NovaTec produced by Compo-Expert, ENTEC by Eurochem, Vizura by BASF and N-serve by Dow AgroSciences (Dapeng, 2016). In recent years, research on alternative fertilizer options, such as, bio-fertilizers has been increasing. Bio-fertilizers are microorganism-containing formulations that, when added to soil enhance microbial activity and soil fertility. Bio-fertilizer causes minimal harm to the environment and could be integrated into fertilization management to reduce nutrient inputs and improve plant growth (Javed et al., 2022). Although there is evidence that the use of bio-fertilizers can reduce nutrient inputs (Bindraban et al., 2015), there is still doubts about these fertilizers and more research is needed to confirm their efficiency and negative interactions and risks (Herrera et al., 2016). Additionally, the potential of nano-fertilizers is promising. Nanoscale-enabled fertilizers (e.g., micronutrient form of fertilizer) have been well documented to deliver direct nutrients to crops (Kah et al., 2019) and to also have indirect effects by enhancing macronutrient uptake (Pradhan et al., 2014). Nano carrier-enabled fertilizers use nanomaterials as carriers and targeted applications of nutrients to deliver slow-release mechanisms for micronutrients delivery to improve NUE. Nanomaterials as carriers offer slow fertilizer release to also reduce losses in runoff and infiltration. Cai (2015) indicated that, compared to conventional fertilizer, a large-scale field trial using this fertilizer improved NUE by 20%. Nano-enabled growth enhancers (e.g., coating nanomaterials with guiding biomolecules) also offer the potential to increase nutrient uptake efficiency and enable targeting to plant cell compartments and organelles (e.g., chloroplasts and mitochondria). All these enhance plant protection and nitrogen delivery efficiency to crop while reducing emissions of ammonia and N_2O (Miernicki et al., 2019). Formulations that promote leaf adhesion and precision spraying could further improve the efficiency of foliar delivery and retention. Although, nanomaterials related to crop growth have demonstrated significant results in the laboratory, these technologies have not yet been tested in the field as the current cost of most nanomaterials for crop growth are too high to be viable in the field. Moreover, uncertainty about the potential health and safety hazards of nanomaterials on human and the environment could limit their public acceptance and, consequently, application in the field. The potential for toxicity of various types of nanomaterials and the health and safety are subject of ongoing research.

Advancements in agronomic approaches, such as the 4R nutrient management principles (right source, right rate, right timing, and right placement), represent the best management principles to achieve high NUE (IPNI, 2021). The N source and timing of application determine which method is more suitable for applying fertilizers (detailed reviews about N source, rate, placement and timing are presented in Boswell et al. (1985) and Peterson and Fryre (1989)). A precise synchronization of N availability with N demand – timing N application to match the time with maximum uptake of N by crops – is critical to improving N uptake and reducing N losses (Walters and Malzer, 1990). Crop rotations have shown tremendous impact on improving NUE and reducing N applications, particularly when legume crops are used in rotation and crops are grown under zero-tillage (Dass, 2014). Now precision or digital farming is helping farmers make more precise decisions to increase the efficiency of field itineraries and operations, including optimizing the rate of inputs and machine guidance (Sundmaeker et al. 2016; Poppe et al., 2015). Technologies such as global positioning systems (GPS), geographic information systems (GIS), remote sensing, and variable rate applicators (VRA) have shown evidence to increase the efficiency of fertilizer use. Moreover, different precision technics such as leaf color chart, chlorophyll meter, and green seeker are shown evidence of improving NUE (Javed et al., 2022).

Enhancing NUE in plant breeding: NUE is a polygenic trait, characterized as a quantitative trait locus (QTL), driven by multiple interactions between genetic and environmental factors. Its improvement requires a fundamental understanding of the key steps in plant N metabolism–uptake, assimilation, and remobilization. Several morphological and physiological traits are associated with higher NUE in plants, including root length and architecture, light capture photosynthesis, canopy height, flowering time, carbohydrate partitioning, storage and the remobilization of N (Hawkesford and Griffiths, 2019). Because quantitative traits like NUE are influenced by many genes with minor effects and environmental influence, identifying QTLs for such traits requires a larger mapping population with phenotyping in multiple locations and environmental conditions, as well as a sufficiently large coverage of the genome by the markers. The various investigations that were developed using either transgenic or quantitative genetic approaches to identify key structure and regulatory genes involved in nitrogen uptake, assimilation and recycling remain incomplete. Molecular biology tools can provide information on genes involved in various N stages and can help in identifying the QTLs associated with NUE (Javed et al., 2022). However, an extensive survey of a wide range of genotype covering the genetic diversity of a crop should be performed using the various available omics technologies to identify common and specific elements controlling NUE and crop productivity. Omics datasets that include transcriptomics, proteomics, metabolomics can be integrated with crop phenotype using bioinformatics tools to identify genes involved in N uptake, mobilization and recycling at different plant growth stages.

Conclusion

While fertilizer use in the production of crops in Canada still has a margin for improvement, considerable advances have been made in the application of this input. Increased use of soil testing by farmers, coupled with variable rate application seeding equipment and increasingly improved plant genetics, is contributing to increasingly efficient fertilizer use in Canada. Canada's continued efforts to contribute to meeting the various UN SDGs, particularly #2 to end hunger, will require sufficient access to all crop inputs, but fertilizer in particular, to ensure that yields are sustainable maximized over the coming decades. Arbitrarily reducing fertilizer by a fixed amount will result in reduced crop yields without necessarily changing the GHGs emitted from farms. Canada will optimally contribute to successful achievement of the SDGs if it exercises its full potential to innovate and disseminate its methods worldwide.

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