# Key Findings of the Canadian 4R Research Network

## Increasing Profitability and Improving Environmental Sustainability

Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada
nutrient stewardship
FERTILIZER CANADA

# Key Findings of the Canadian 4R Research Network

**Fertilizer Canada** represents manufacturers, wholesale and retail distributors of nitrogen, phosphate, potash and sulphur fertilizers. The fertilizer industry plays an essential role in Canada's economy, contributing $23 billion annually and over 76,000 jobs. The association is committed to supporting the fertilizer industry with innovative research and programming while advocating sustainability, stewardship, safety and security through standards and Codes of Practice. Please visit **fertilizercanada.ca**.

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Electronic versions of the final reports are available on the Internet at **fertilizercanada.ca**.


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# Abstract


We live in an important juncture in world history. At the same time as we face the challenges of climate change and environmental degradation, we also face the challenges of global food security and feeding the world's growing population.

For Canadians, it is important to show leadership in meeting both challenges. On the one hand, whether it is our commitment to the UN Sustainable Development Goals or our plan to meet our responsibilities to the 2015 Paris Agreement through the Pan-Canadian Framework on Clean Growth and Climate Change, Canada is committed to environmental sustainability. On the other hand, as outlined in the Barton report, *Unleashing the Growth Potential of Key Sectors*, Canada has the potential to move from the world's fifth to its second largest agriculture exporter and assume its position as a global leader in the production of safe, nutritious, and sustainable food well into the 21st century.

In order to achieve both objectives, Fertilizer Canada has worked with its partners in the federal government, provincial governments, industry, and academia to establish suites of sustainable best management practices (BMPs) for fertilizer application—known as 4R Nutrient Stewardship (Right Source @ Right Rate, Right Time, Right Place®). From Prince Edward Island potatoes to Prairie wheat, these practices relate to the production of major crops in regions across Canada. This Canadian-made innovation has also become recognized internationally, including the United Nations' Food and Agricultural Organization, for its potential in meeting the dual challenge of reducing the environmental footprint of farms everywhere while also increasing productivity.

The purpose of this report is to present the findings of the Canadian 4R Research Network (also referred to as the '4R Research Network'). After a three-year independent research project engaging nine researchers across the country, the 4R Research Network has provided much needed scientific evidence to support the efficacy of the BMPs associated with 4R Nutrient Stewardship. As outlined in the subsequent pages, 4R Nutrient Stewardship enables Canadian growers from regions across the country to increase the profitability of their farms through higher yields or enhanced economic efficiencies while also improving their environmental sustainability by reducing greenhouse gas emissions, leaching of nutrients through the soil or harmful impacts on surrounding water resources.


> "The evidence is clear: we can improve both the quality and quantity of food for feeding the global population – but we can't do it without taking care of our valuable water and soil."
>
> **Honourable Lawrence MacAulay**
> Minister of Agriculture and Agri-Food

# 4R Nutrient Stewardship

To fertilize properly and achieve the benefits of an abundant and healthy crop, professionals should follow 4R Nutrient Stewardship: **Right Source @ Right Rate, Right Time, Right Place®**. This science-based nutrient management framework is universally adaptable yet locally-focused, allowing growers to tailor fertilizer needs to their specific fields and crops.

By applying the right source of fertilizer at the right rate, the right time and in the right place, growers can ensure nutrients from fertilizer – Nitrogen, Phosphorus, Potassium and Sulphur – are taken up efficiently by their crops and not lost to water or air.

Developed in Canada, this innovative nutrient management framework allows growers to increase crop production on existing farmland while minimizing unwanted environmental impacts – creating a truly sustainable way to feed the world. The principles underpinning the 4R Nutrient Stewardship framework can be applied in any geographical location and farming system. Cost-effective and environmentally responsible soil management and enhancement is crucial to increasing food production and sustainability for small-holder growers and large-scale farms.

4R Nutrient Stewardship has been recognized by both decision makers in Canada and around the world as a leading BMP system for nutrient management and environmental protection.

RIGHT SOURCE | RIGHT RATE | RIGHT TIME | RIGHT PLACE


The **Right Source** means ensuring a balanced supply of essential plant nutrients including granular fertilizers, liquid fertilizers and/or manures.

The **Right Rate** is applying just enough fertilizer to meet the needs of the plant while accounting for the nutrients already in the soil.

The **Right Time** means applying fertilizer when the plant will get the most benefit and avoiding times when fertilizer can be lost to the environment.

The **Right Place** is where the plants can easily use fertilizer and where it is less likely to be lost to the water or air.

"There is a delicate balance between reducing nutrient losses through nutrient management while maintaining or improving soil carbon and thus soil health. The fertilizer industry is partnering with universities, watershed stakeholders, and government agencies to expand the data linking agronomic and environmental performance of 4R practices."

**Terry Roberts**
IPNI President

# 4R Research Network

The 4R Research Network is composed of nine leading Canadian researchers quantifying the economic, social, and environmental benefits resulting from advanced fertilizer management systems under 4R Nutrient Stewardship. The project emphasizes collaboration with university researchers, professional advisors, growers, provincial agriculture departments, and Agriculture and Agri-Food Canada researchers.

Their research covers many areas of environmental focus including reducing greenhouse gas and ammonia emissions, losses of phosphorus to surface waters, and nitrate leaching to groundwater. Activities cover key field crops across Canada and were selected to overcome gaps in adoption, such as: limited knowledge on BMPs; evaluation of multiple nutrient loss pathways of nitrogen and phosphorus; evaluation of BMPs under diverse soils, weather and cropping systems in Canada; and decision-making tools for tailoring BMPs to local needs and conditions.

The 4R Nutrient Stewardship framework delivers to Canadian growers the information they need to enhance competitiveness and increase productivity and adaptability to market needs, while addressing the sustainable intensification of agriculture. This research initiative strengthens the science behind 4R Nutrient Stewardship principles. The result leads to science-based demonstration of the benefits of the 4Rs for grower decisions that can improve on-farm economics, feed a growing global population, and protect the environment.

# Highlights

## 4R Nutrient Stewardship:

- Science-based, made-in-Canada and internationally recognized fertilizer management framework.
- The 4R Nutrient Stewardship program is on track to securing 20 million acres, or 25 per cent, of Canadian crop production by 2020.
- Nitrogen-specific BMPs under 4R Nutrient Stewardship have already been proven to reduce greenhouse gas emissions (GHG) by at least 25 per cent and increase a grower's profits by as much as $87 per acre [‡].
- The Food and Agriculture Organization has recognized the 4Rs as a valuable BMP framework for farming communities around the world.

## 4R Research Network:

- Engages nine Canadian researchers situated at universities, institutes and governmental agencies across Canada whose research has already produced 11 academic manuscripts, eight published articles, 108 oral presentations and 24 workshops. Overall, the 4R Research Network has reached over 10,000 professionals.
- Three-year independent research emphasizes collaboration with over 80 university researchers, professional advisors, growers, provincial agriculture departments, and Agriculture and Agri-Food Canada (AAFC) researchers combined.
- Awarded a combined funding of $2.2 million from AAFC, and from Fertilizer Canada's member company contributors to the Science Cluster and the North American 4R Research funds.
- Research covers areas of environmental focus including reducing GHG and ammonia emissions, losses of phosphorus to surface waters, and nitrate leaching to groundwater.
- Identified 10 BMPs, to enable growers to improve profitability while increasing environmental sustainability.

> "The 4R program – the right fertilizer source, right rate, right time and right place – provides a useful framework for guiding fertilizer application in the Lake Erie Basin and beyond. The 4Rs can be effective in reducing nutrient export from fields, while meeting plant nutrition needs and therefore maximizing crop yields."
>
> IJC 2014 report - *A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms* & 2016 Progress Report of the Parties

‡ Mussell, A. and Heaney, D. "An Economic Analysis of Farming 4R Land program in Alberta". May 2013. (Available for download at **www.fertilizercanada.ca**)

## Global and National Context

**Food security and the global population:**

- As the world's population continues to grow, expected to reach nine billion by 2050, the agricultural sector must double current production levels to meet demand.
- In developing countries, 75 per cent of growth in food production must come from increased yields, which can only be achieved with the help of fertilizers, and Canada, which is the world's top exporter of potash fertilizer, will be increasingly relied upon to meet growing demand.

**Agriculture and climate change:**

- The agriculture sector contributes to approximately 14 per cent of the world's GHGs with concerns that this may rise as food production grows to meet global demand.
- In the context of the 2015 Paris Climate Conference (COP21), the UN Sustainable Development Goals, and the 2017 Pan-Canadian Framework on Clean Growth and Climate Change, the 4Rs can help Canada achieve its environmental sustainability objectives without compromising food security, by making agriculture more sustainable, more productive, and more resilient.

## Key Findings of the 4R Research Network

**The scientific findings of the 4R Research Network provides further evidence that the BMPs of the 4Rs increase both profitability and environmental sustainability:**

- Applying the 4Rs in corn production in Ontario can increase yields by nearly 20 per cent, reduce GHG emissions by as much as 75 per cent and reduce P losses to runoff by 60 per cent.
- Applying the 4Rs in wheat production in Manitoba can reduce GHG emissions by as much as much as 55 per cent.
- Applying the 4Rs in potato production in Prince Edward Island can reduce nitrate leaching into the soil by as much as 32 per cent.
- Applying the 4Rs over time can offset initial costs to adoption.

## Alberta – Wheat and Canola Crop Production

**Applying nitrogen fertilizer in the Right Place reduces GHG emissions while increasing profitability:**

- Regardless of fertilizer source, growers can reduce GHG emissions and increase crop yields by applying fertilizer bands as close to the seed row as possible and deeper than the seed row to ensure that the crop accesses applied nitrogen early in the growing season.

**Applying the Right Rate at the Right Time increases profitability and reduces GHG emissions:**

- Farms will be more efficient economically and environmentally sustainable if growers avoid excessive nitrogen fertilizer rates at the time of seeding because it exceeds the needs of an early plant and only increases the risk of higher GHG emissions.
- At intermediate rates of nitrogen, split fertigation lowered cumulative $N_2O$ emissions compared to all N fertilizer being applied before planting.
- Using sulphur as part of long-term balanced NPK treatments is effective at increasing yield and crop N uptake and lowering nitrous oxide ($N_2O$) emissions per unit of crop yield. In this case nitrous oxide was reduced as much as 50 per cent and resulted in seeing the greatest yields. N balances are also driven by crop rotation.

## Saskatchewan – Wheat, Canola and Soybean Production

**Applying phosphorus fertilizer at the Right Rate and in the Right Place reduces runoff while increasing profitability:**

- Broadcasting without incorporation can greatly increase the risk of phosphorus in snowmelt run-off. This is an especially important observation for large acre Prairie producers who may be trending towards broadcast methods.
- By using in-soil placement to apply phosphorus fertilizer at appropriate rates, growers can significantly lower phosphorus runoff (as much as 75 per cent) into surface and sub-surface water bodies while also increasing the economic efficiency of their farms.

## Manitoba – Wheat Production

**Applying the Right Source of nitrogen fertilizer reduces GHG emissions:**

- Applying enhanced efficiency fertilizers (in a mid-row band) can help growers reduce GHG emissions by as much as 55 per cent.

**Applying nitrogen fertilizer at the Right Time reduces GHG emissions:**

- Regardless of fertilizer source, growers can reduce GHG emissions by 20 per cent if nitrogen fertilizer is applied in the spring as opposed to fall.

## Ontario – Corn Production

**Applying the Right Source of nitrogen fertilizer at the Right Time reduces GHG emissions:**

- Combining the use of urea-ammonium nitrate (UAN) with nitrification and urease inhibitors at the eighth-leaf growth stage of corn allows growers to reduce GHG emissions by as much as 75 per cent.
- The application of combined sources (either urea or UAN, with urease inhibitors) can allow growers to reduce GHG emissions anywhere between 40 and 60 per cent depending on weather conditions.

**Applying the Right Source of nitrogen fertilizer in the Right Place improves environmental sustainability and increases profitability:**

- Injecting nitrogen fertilizer into the soil allows growers to increase corn yields by as much as seven per cent and totally eliminates harmful ammonia loss to the soil.
- Combining this type of placement with UAN fertilizer can improve corn yields by nearly 20 per cent when compared to broadcasting.

**Applying phosphorus fertilizer at the Right Time and in the Right Place reduces water contamination:**

- Subsurface banding of phosphorus fertilizer as opposed to broadcasting enables growers to reduce runoff by 60 per cent.

## Prince Edward Island – Potato Production

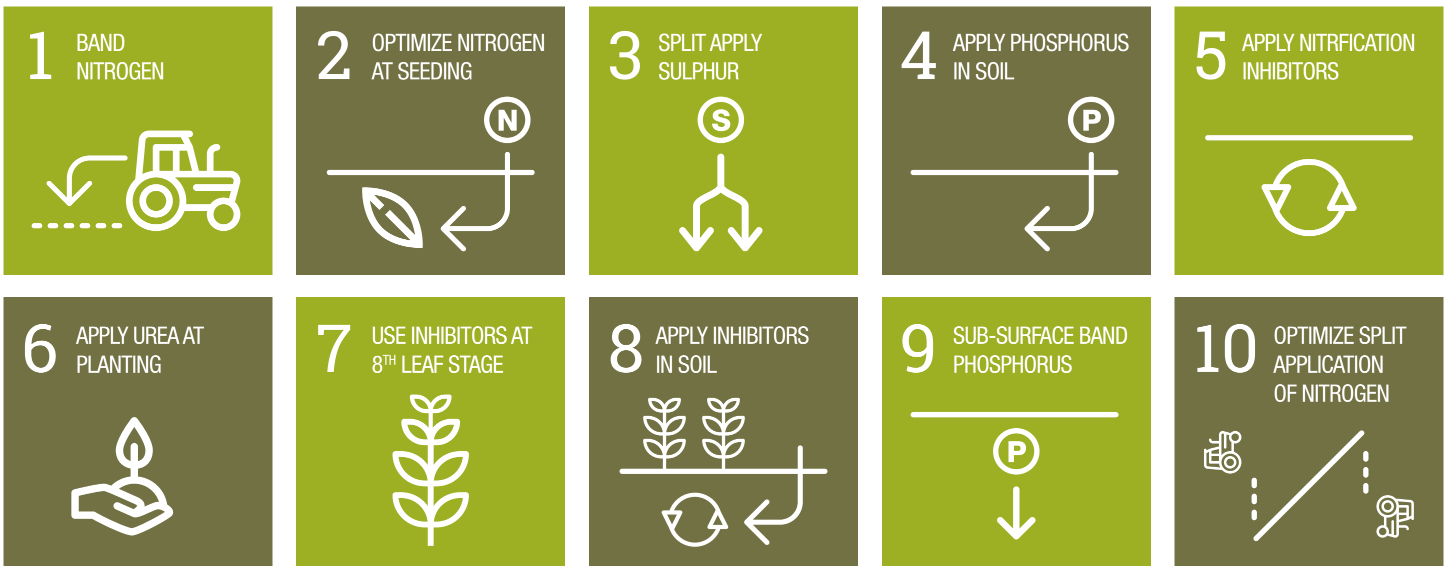
**Applying the Right Rate of nitrogen fertilizer at the Right Time reduces GHG emissions and nitrate leaching into the soil while also increasing profitability:**

- Splitting nitrogen fertilizer, 60 per cent at planting and 40 per cent as in-season foliar urea, produces the same crop yield with optimized rates and reduces GHG emissions, thereby increasing both economic efficiency and environmental sustainability.
- Implementing 4R practices also reduces nitrate leaching into the soil by as much as 32 per cent.
- Soil testing is important in determining the Right Rate of nitrogen fertilizer application. Nitrogen fertilizer rates can be optimized (in this particular case, 25 per cent less nitrogen was required) without reducing yields by accounting for soil nitrogen supply.

## 10 4R BMPs spanning the Canadian landscape

The 4R framework is a universally applicable, yet locally focused framework of interdependent principles that encourages growers to consider not only their source of fertilizer, but how much to apply at what time and in what place on the field. 4R BMPs are not stand alone solutions to nutrient management, but should be considered a suite of practices that work in tandem toward the goal of improving nutrient use efficiency and reducing nutrient losses.

The following 10 BMPs have been scientifically proven to increase crop production for growers while minimizing nutrient losses to the environment. Over three years, nine leading researchers of the Canadian 4R Research Network conducted research projects to test various Source, Rate, Time and Place practices for common Canadian crops: wheat, canola, soybean and potatoes.




1. In wheat and canola production in Alberta, applying nitrogen fertilizer as a band that is close to the seed row as possible and deeper than the seed row (**Right Place**) reduces greenhouse gas emissions while increasing profitability.
2. In wheat production in Alberta, optimizing nitrogen application (**Right Rate**) during seeding (**Right Time**) increases profitability and reduces GHG emissions.
3. In wheat production in Alberta, integrating sulphur as part of balanced macronutrient nutrition (**Right Source**) and placed in a split application using in-crop fertigation (**Right Time**) results in greater uptake of nutrients by the plant and lowered GHG emissions.
4. In wheat, canola and soybean crop production in Saskatchewan, applying phosphorus fertilizer as an in-soil placement (**Right Place**) at the recommended rate (**Right Rate**) reduces runoff while increasing profitability.
5. In wheat production in Manitoba, applying nitrification inhibitors with urea (**Right Source**) reduces GHG emissions in wet years.
6. In wheat production in Manitoba, applying urea in the spring at planting (**Right Time**) reduces more GHG emissions than fall application.
7. In corn production in Ontario, applying urea or urea ammonium nitrate with nitrification and urease inhibitors (**Right Source**) at the eighth leaf growth stage (**Right Time**) reduces GHG emissions by 40 to 60 per cent.
8. In corn production in Ontario, combining nitrogen fertilizer with a nitrification and urease inhibitor (**Right Source**) applied as an in-soil injection (**Right Place**) increases corn yields by nearly 20 per cent, reduces nitrous oxide emissions by 40 per cent and virtually eliminates ammonia losses to the atmosphere.
9. In corn production in Ontario, applying phosphorus fertilizer as a sub-surface band (**Right Place**) reduces water runoff by as much as 60 per cent, compared to broadcasting.
10. In potato production on Prince Edward Island, split application (**Right Time**) of nitrogen fertilizer at an optimized rate (**Right Rate**) reduces GHG emissions and harmful nitrate leaching into the soil, while also increasing profitability.

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**Dr. Mario Tenuta**
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University of Guelph

# 4Rs and Nitrogen

### Potato Production in PEI:

Canada is a global leader in potato production and Atlantic Canada makes up nearly 40 per cent of the total national output valued at approximately $1 billion with much of this production in Prince Edward Island—which has earned the nickname "Spud Island."

On a high fertility site at the AAFC Harrington Research Station, 120 kilograms of nitrogen per hectare produced the same level of crop yield as higher nitrogen rates and reduced GHG emissions thereby increasing both economic efficiency and environmental sustainability. On the same site, the use of in-season foliar applications of urea resulted in increased nitrogen use efficiency. Split applications of 60 kilograms of nitrogen per hectare applied at the time of planting with an additional 30 kilograms of nitrogen applied later in multiple foliar urea applications resulted in yields that were not different than 180 kilograms of nitrogen applied at planting.

In side-by-side trials conducted in grower's fields, 4R BMPs were shown to result in as much as a 32 per cent reduction in nitrate leaching—the loss of plant nutrient to the soil—and therefore further increase efficiency.

A survey of the nitrogen supplying capacity of 26 potato fields in PEI showed a range of 30 to 110 kilograms of nitrogen per hectare was supplied from the soil during a 130-day growing season. This demonstrates the importance of assessing inherent soil nitrogen supplying capacity in determining the Right Rate of nitrogen fertilizer application and realizing improved nitrogen use efficiency and reduced environmental impact.

### Corn Production in Ontario:

Canada ranks 11th in the world for corn production and 66 per cent of this output occurs in Ontario. Although weather conditions affect assessments of the impact of the 4Rs, there is evidence that the **Right Source**, in particular, can reduce this sector's environmental footprint.

While the impact on leaching is unclear, the combination of the application of the **Right Source** (in this case, either urea or urea and nitrogen with nitrification and urease inhibitors) with the **Right Time** has a direct impact on reducing nitrous oxide emissions by as much as 75 per cent. Regardless of the time, the application of the **Right Source** mentioned above has a significant impact on reducing nitrous oxide emissions by anywhere between 40 and 60 per cent depending on the weather. These results are consistent with findings from other regions in Canada and the United States.

In a complementary study, when inhibitors were broadcasted with nitrogen sources (urea and UAN), corn yields increased by five to seven per cent. However, when combining injection with inhibitors—in this case urea nitrogen with nitrification and urease inhibitors—they can also increase corn yields by nearly 20 per cent when compared to broadcasting. Furthermore, it reduced nitrous oxide emissions by 40 per cent and virtually eliminated ammonia losses. In other words, this combination of **Right Source** and **Right Place** has a positive environmental impact while improving profitability for growers.

> "Understanding which soils pose a risk of nutrient loss in the province can assist agricultural producers on the Island in managing nutrients more efficiently and in protecting the environment. Adjustments in the crop nutrient source and application rate, timing, and placement method may greatly reduce the risk of nutrient losses."
>
> **Dr. David Burton**
> Dalhousie University

### Wheat Production in Manitoba:

From sunflowers to canola and soybeans to wheat, Manitoba accounts for over 12 per cent of cropland in Canada. Studies show that the application of the **Right Source**—in this case, enhanced efficiency fertilizers (EEF)—allows growers to reduce emissions by as much as 55 per cent. It also lowers the emission intensity by half when compared to the use of urea alone. Regardless of fertilizer source, growers can reduce GHG emissions by 20 per cent if nitrogen fertilizer is applied at the **Right Time**—spring rather than fall.

### Wheat and Canola Production in Alberta:

Canada has earned its reputation as the world's bread basket and Alberta comprises nearly 10 per cent of Canada's wheat production. Alberta is a significant contributor to Canadian oilseed production as well with a record canola harvest in 2017 of nearly seven million acres.

Regardless of fertilizer type, growers can reduce emissions and increase crop yields by applying nitrogen fertilizer in the **Right Place** - banding as close to the seed row as possible and deeper than the seed row to ensure that the crop accesses applied nitrogen early in the growing season. Additionally, split fertigation treatments lowered cumulative $N_2O$ emissions compared to all N fertilizer applied before planting.

When growers apply the **Right Source** at the **Right Time**—integrating sulphur as part of balanced NPK nutrition and split applying nitrogen using in-crop fertigation—they can be effective at lowering GHG emissions under the right weather conditions. In this case, GHG emissions were reduced as much as 50 per cent. Greater yields were also seen in this case. Growers can be more efficient economically and environmentally sustainable if they apply the **Right Rate** (optimizing nitrogen levels), at the **Right Time** (during the seeding period).

"The public is very keen on consuming products that are grown in an environmentally friendly way. We think this type of research addresses these concerns. In the end, not only will we have numbers quantifying the impact of nitrogen loss, but we can then look at what farmers can do to minimize that impact. This increases the confidence of consumers."

**Dr. Claudia Wagner-Riddle**
University of Guelph

**Dr. Jeff Schoenau**
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**Dr. Ivan O'Halloran**
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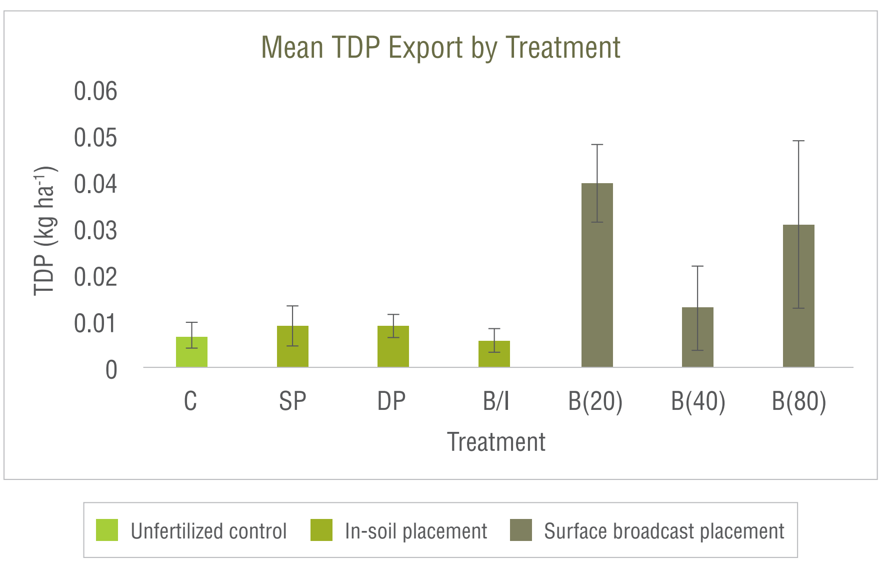
# 4Rs and Phosphorus

## Wheat, Canola and Soybean Production in Saskatchewan:

Saskatchewan is home to some of the largest farms in Canada with the highest acreage producing a majority of Canada's canola, wheat, barley and pulse crops. At the same time, there is increasing concern over the water quality of some of the province's great rivers that traverse across the country.

By applying phosphorus fertilizer in the **Right Place**—in-soil placement—at the recommended **Right Rate**, growers can significantly lower phosphorus runoff into surface and sub-surface water bodies while also increasing the economic efficiency of their farms. As much as a 75 per cent difference in the amount of phosphorus runoff was measured when comparing broadcast and in-soil placement methods.




**In-soil placement prevents P loss in run-off water (Saskatchewan)**

Mean Total Dissolved Phosphorus (TDP) export as a function of fertilizer P application method and rate following a simulated snowmelt runoff experiment. Error bars represent the standard error of the four replicates of each treatment. Means (n=4) with different letters are significantly different (Tukey's HSD, P<0.05). A description the of the treatments is as follows: C: Control (no P); SP: Seed-placed (20 kg P2O5 ha-1); DB: Deep band (20 kg $P_2O_5$ $ha^{-1}$); B/I: Broadcast with incorporation (20 kg $P_2O_5$ $ha^{-1}$); B(20): Broadcast (20 kg $P_2O_5$ $ha^{-1}$); B(40): Broadcast (40 kg $P_2O_5$ $ha^{-1}$); and B(80): Broadcast (80 kg $P_2O_5$ $ha^{-1}$).

## Corn Production in Ontario:

Canada has one of the world's largest sources of renewable freshwater with approximately nine per cent of total resources including the Great Lakes. Agriculture is an important socio-economic element in Ontario's Great Lakes region, yet is also a contributor to environmental issues including phosphorus runoff.

Studies in this region show that when growers use the **Right Place** for phosphorus application — in this case, subsurface banding as opposed to broadcasting—losses to runoff are generally reduced by 60 per cent. At the same time, this more efficient placement results in the same level of crop yield and profitability for their farms. Additionally, most phosphorus loss took place during the first runoff event of the growing season, which has implications for **Right Time** with regards to rainfall effects and understanding how it changes soil nutrient levels.

**Dr. Alison Eagle**
Duke's Nicholas Institute for Environmental Policy Solutions

**Dr. Nicolas Tremblay**
Agriculture and Agri-Food Canada

# Overall Economic, Environmental and Social Effects of 4Rs

## Using 4R Nutrient Stewardship in decision support systems

Agriculture has been at the forefront of recent technological advances, particularly precision agriculture, with respect to automation, use of drones, satellite imagery and other sensing technologies. Currently, it is entering an era of, artificial intelligence, cloud data storage and other big data innovations. Although the 4Rs mark an important innovation in farming practices, they have the potential of making an even bigger impact when combined with other new technologies in computing and data mining software.

Determining an optimum fertilizer application rate can be challenging because it is influenced by growing conditions associated with location, time and farm management systems as well as contemporary market conditions. This challenge is further complicated by the fact that crop response to fertilization remains uncertain due to many unpredictable factors, such as weather anomalies, soil microbiology, and the performance quality of farming tools among others.

With this in mind, a decision support system – a computational program that leverages datasets – was developed to help growers, certified crop advisors and agri-retailers do a better job at predicting and determining the **Right Rate** that minimizes risks associated with fertilizer use, including waste and lost yield opportunities. Known as NumericAg, this prototype framework was developed to improve nitrogen application for corn in Quebec and Eastern Ontario and its early success amongst users demonstrates the potential for the next generation of decision support systems to further improve the sustainability of farming while increasing efficiency and profitability.

The project addresses the risks and opportunities at the field-scale with respect to weather and its interactions with soils and other management factors. The goal of this project was to quantify the influence of economic factors and of soil and weather conditions (i.e., temperature, precipitation, texture and organic matter content) that were experienced during legacy fertility trial setups, in the context of potential crop production scenarios.

The tool assesses expected profitability for different N rates for rainfall prior to and around side dress application time. This tool, combining the **Right Rate** and **Right Time** approaches, was found to enhance profitability of N use on corn. It is expected that the tool could help growers and crop advisers not only to select the most profitable application rate, but also to manage risks associated with over and under application.

## How 4Rs affect sustainability outcomes

4R Nutrient Stewardship reduces losses to the environment, while enhancing profitability for farmers by keeping fertilizer and other added nutrients in the growing crops and in the soil supporting those crops. On the farm, sustainable nutrient management using the 4Rs helps growers to think about whether they are applying the right fertilizer source at the right rate at the right time and in the right place. Management changes that get these "right" help fertilizer investments to go further, by producing more crops per kilogram of fertilizer applied. Scientists across Canada in the 4R Research Network have found that 4R management practices overall reduced nitrogen and phosphorus losses, thus providing water and air quality benefits on the farm and beyond.

### On-farm

By applying the right source and right rate of fertilizer nitrogen (N) and phosphorus (P) that a plant needs, farmers can ensure that every kilogram of fertilizer provides productive value. Placement, timing and source help improve that efficiency; with improved yield or optimized total fertilizer needs. Yield increases of up to 20 per cent (Drury study), 25 per cent lower fertilizer rates to avoid over-application (Burton study), or a five per cent increase in spring wheat protein content (Tenuta study) prove that such changes can be excellent investments. For corn in Ontario, even a 10 per cent yield increase (about 16 bushels/acre over the average yield) would have a farm-gate value of about $76/acre. Fertilizer N cost savings would be approximately $22/acre for potatoes in Eastern Canada by optimizing N fertilizer rates. These on-farm savings could exceed the costs of the improved management, and many economic studies support such a fact.

While these are estimates of the on-farm benefits, the project also identified gaps in full and consistent information about both the monetary costs and the effort needed to make a transition. Farms looking to improve nutrient management vary in terms of size, cropping system, and other characteristics. This translates to variances in the equipment, materials, or labour needed to apply fertilizer while the crop is growing (**Right Time**), to use an enhanced efficiency fertilizer (**Right Source**), or to band/inject the fertilizer below the surface (**Right Place**). Further, the effort needed for change (learning, experimenting, assuming risk, social pressure, management time) also has real costs for which quantification is difficult. Due to this high variability and lack of available data, economic models tend to overlook these costs in favour of partial economic analysis that includes only the fertilizer cost and yield benefit.

Therefore, while improved nitrogen management can increase return on investment for fertilizer inputs and enhance yields or crop quality, on-farm adoption is still limited. This may give outside observers the incorrect perception that farmers do not make holistic nutrient management decisions. Focusing only on the fertilizer savings or yield gains might even lead some to suggest that incentives for change are unnecessary. However, it is those less obvious barriers or costs (social pressure, equipment costs, labour adjustments) that may dominate, and thus need to be addressed, especially in initial transition periods. Help from extension services, program incentive payments, or other initiatives may help in the adjustment period, during which farmers can experiment without taking on risk, learn how to reallocate labour, and see those positive results.

While some new fertilizer sources or additives, or timing and labour changes have on-going costs, other on-farm costs tend to be concentrated in the early stages of a practice change. These include training and education, new equipment, and increased risk of yield loss during the transition period (i.e., when figuring out a new system). After the initial transition period, the continued yield gains and fertilizer cost savings from many of the 4R practices prove sufficient to warrant scaling back or even discontinuation of outside incentives.

### Beyond the farm

Using our designed conceptual models, we documented environmental benefits of 4R practices experienced downstream as well as by the farmer who has changed management practices. While farmers may see lower fertilizer costs, higher crop yield, or other cost savings, some 4R practices involve higher value fertilizer sources, new equipment, or more skilled labour. Therefore, it may be important to find ways for the general public, the downstream town, or others to support farmers in improving environmental outcomes. Adoption of improved practices could increase if initial on-farm costs are covered by incentives or ecosystem services payments from supply-chain actors, local governments, or others who experience the benefits of improved environmental outcomes.

### Nitrous Oxide example

Field research found that 4R practices could reduce nitrous oxide ($N_2O$) emissions in Canadian field crops by 40 to 75 per cent. These practices involved higher value enhanced efficiency fertilizers, and new or different equipment for fertilizer application. Yield gains and optimized rates may not cover all the costs of practice change. This is where the value of emissions reductions could play a role (with incentives to farmers).

For a corn field with typical baseline $N_2O$ emissions of 2.6 kg $N_2O$-N/ha/yr, a reduction of 50 per cent results in emission savings of 1.3 kg $N_2O$-N/ha/yr. This is the equivalent of 2.0 kg $N_2O$ (1 kg N = 1.57 kg $N_2O$), which has 265 times the global warming potential as the same amount of $CO_2$, and is therefore equal to 540.9 kg $CO_2$e/ha/yr. Such emission reductions in a carbon market would be worth almost $10 CAD/ha/yr (if they could be guaranteed, and could be traded in existing carbon markets with low transaction costs). The social value of these GHG emission reductions may even be higher than that, with social cost of carbon estimates double that seen in functioning markets.

### Nitrate example

Field research found that 4R practices could reduce $NO_3$ leaching losses by up to 32 per cent. Again, rate optimization could provide sufficient cost savings for farmers to cover the costs of labour and equipment for splitting fertilizer application into two times instead of one. If not, the downstream users or others in society with interest in improving water quality (e.g. reducing dead zones in oceans) may be able to help provide incentives for change.

For a corn field with typical baseline $NO_3$ leaching losses of 25 kg $NO_3$-N/ha/yr, a 32 per cent reduction means avoided losses of eight kg $NO_3$-N/ha/yr. For downstream water sources, this can reduce the costs of reducing $NO_3$, algae, and toxins from drinking water (algae and toxins resulting from higher nutrient levels in lakes, for example). The cost of removing excess $NO_3$ in drinking water varies a lot, depending on the size of the facility and the starting concentration of $NO_3$ in the water. Using the US-based estimate of $0.16 /kg N for treatment costs, the average value for a reduction of eight kg per year would amount to $1.28/ha/yr. Active water nutrient trading markets in Ontario, North Carolina, Ohio, and elsewhere are evidence that downstream users recognize the value and are willing to compensate farmers for the practice change. Avoided damages to ocean fisheries, drinking water (human health), and recreation would add even more value to abatement of $NO_3$ losses at the field.

Using cover crops also holds some opportunities to better understanding their benefits to reducing nutrient leaching.

For each local region or watershed, the benefits of 4R practices will vary depending on the key environmental issue (e.g., phosphorus in surface water, N in groundwater, climate change). This means that the impetus for encouraging agricultural practice change may also be different from place to place. However, a common set of models and indicators, will support planning, research, and monitoring programs. The consistency in measurement and application can greatly increase credibility of results. In addition, the focus on social and economic outcomes can add new information important to decision makers and society.

# The Path Forward

The work completed by the 4R Research Network clearly shows that the application of Right Source @ Right Rate, Right Time, Right Place® reduces greenhouse gas emissions on cropland. Using locally appropriate 4R BMPs also reduces phosphorus movement to surface water and nitrogen movement to ground and surface water, as well as ammonia losses. These significant environmental benefits were obtained across a range of cropping systems from Atlantic Canada through to the Prairies amply demonstrating the universality of the 4R Nutrient Stewardship approach. While there are still nuances to be worked out, the research results illustrate that it is typically the combination of source, rate, time and place rather than a single R that maximize environmental benefits.

A second and equally important finding of the Canadian 4R Research Network was that best management practices aimed at reducing environmental impacts can also provide economic benefits. With fewer losses, fertilizer nutrients stay where needed by the growing crop, leading to yield gains or equivalent yields, and crop quality improvements, at optimized fertilizer rates. Results suggest that the same or improved yields could be achieved with lower rates of more expensive products. This will be an ongoing question from farmers as they look to meet environmental goals without compromising productivity, profitability and the economic sustainability of their farms.

On-farm economic benefits can offset much of the additional cost associated with 4R BMPs. Why then are advanced 4R BMPs not rapidly replacing current environmentally unfriendly practices on farm? The transition period may require a catalyst for change. Every farm is unique in terms of their equipment, risk tolerance, and available human and financial resources. Often practice improvement requires a change in equipment that must be worked into a farm's equipment replacement schedule. They can also impact what is typically a farmer's scarcest resource, available time during critical periods such as seeding. These barriers can slow adoption even though post-adoption economics are favorable.

Implementing 4R practices also produces environmental benefits for society at large, and these environmental benefits generate off-farm economic benefits as well as healthier ecosystems. However, these off-farm benefits tend to be disconnected from the on-farm challenges of producing a crop in a competitive market with resource limitations. In some regions, water-quality and greenhouse gas mitigation markets work to increase the farm-gate value of a crop produced in a way that provides the optimal off-farm environmental benefits.

Driving 4R adoption will require an integrated effort by the research community, the agriculture and food industry, and the public at large. Continuing research aimed at more fully understanding the complex interactions among practices, crop production, and loss mechanisms will help sort out the combinations of 4Rs that most consistently maximize environmental benefit in different cropping systems. In particular, the incorporation of new digital technologies and tools on environmental outcomes can play a role in future work. Combining these with economic analysis can give growers a better idea of transitional and ongoing costs and benefits. Policy and programs that assist growers with transitional costs are also required. These may take the form of ecosystem goods and services programs such as carbon offsets and/or linkages to sustainable supply chains that help growers with access to new markets. In effect, such programs transfer some of the downstream benefits back to the farm. The just-completed work of the 4R Research Network has created a solid knowledge base from which to deepen our understanding and ensure 4R BMPs are widely adopted on the farm.