SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

FURTHERING 4R NUTRIENT STEWARDSHIP

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KEY POINTS

Future implementations of 4R Nutrient Stewardship need to integrate with changing farming objectives that support a wider range of sustainability outcomes. The new paradigm for Responsible Plant Nutrition provides perspective for such integration. We suggest changes to align it with future farming systems that intensify production, improve human nutrition, protect and enhance biodiversity, shrink environmental and carbon footprints, and make nutrient flows more circular.

While 4R Nutrient Stewardship has achieved global recognition, barriers limit its impact. Beneficial outcomes depend not only on good 4R practices, but also on those for every aspect of the farming system. Priorities among the 12 outcomes shown in Figure 1 vary among regions and countries, as do the specific 4R decisions for nutrient application. In many places, however, opportunities exist to increase use of data-driven digital solutions to support decisions, and to accelerate innovation using on-farm adaptive management. Choices among nutrient sources need to include more circular and climate-smart attributes, and rate, time, and place of application need to become more precise and dynamic.

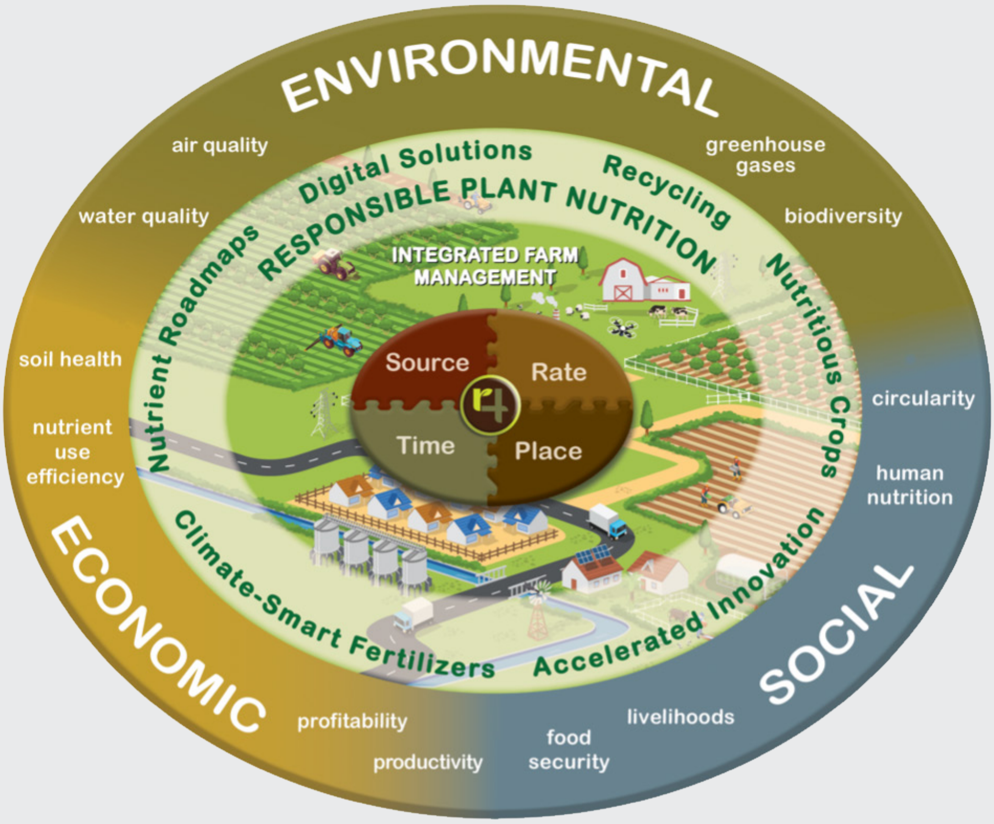

Figure 1. Furthering 4R Nutrient Stewardship will require integration with farming systems to support the six actions of Responsible Plant Nutrition and report sustainability outcomes.

The accountability for performance requires the communication of progress to all players in the agricultural value chain, including end users, environmental agencies, and industry. Advanced performance reporting includes tracking of 4R practices, measurement of farm-level economic outcomes, and assessment of soil, environmental and social benefits. Better ways to monitor adoption and key outcomes are urgently needed, including science-based targets and more profound application of digital technologies. The fertilizer industry needs to further collaborate with the agri-food sector to develop and adopt sustainability standards for farming systems management that include holistic 4R practices and performance metrics.

WHAT IS THE ISSUE?

Nutrient applications comprise a large proportion of the nutrient flows into most agricultural systems, and are directly managed by farmers and their service providers. Hence, the original framework of 4R Nutrient Stewardship presented the 4 "rights" as four globally relevant management objectives for nutrient application practices that require implementation through solutions specific to regions and cropping systems ***(Figure 2)***[1]. For each of the four components of making the right nutrient application decisions, core principles were defined that summarized the underlying scientific understanding.

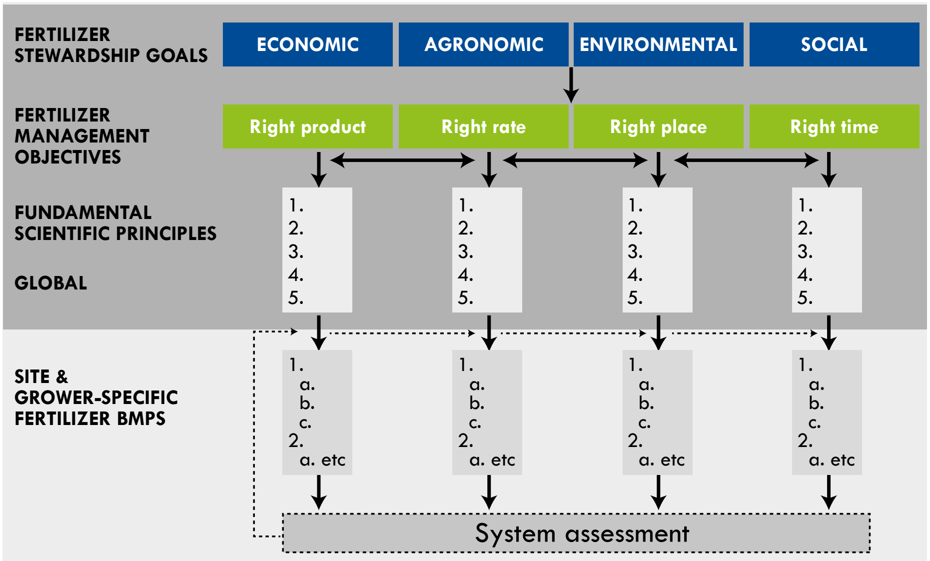

Figure 2. Original framework for 4R Nutrient Stewardship, presented in 2007 (Fixen, 2020).

The new paradigm for Responsible Plant Nutrition has broadened the scope of nutrient stewardship[2]. A focus on source, rate, time and place of nutrient applications remains very relevant to this new paradigm, but 4R as originally designed, and as applied in the past, does not fully connect to all of its aims. The connection can be improved to expand the relevance of 4R within the new paradigm.

The six key actions for the implementation of Responsible Plant Nutrition open up needs and opportunities for programs of implementation of 4R. These include, correspondingly:

1. **Nutrient Roadmaps:** Plugging 4R practices into policies, business models, platforms, and programs verifying sustainability.
2. **Digital Solutions:** Delivering data-driven, more precise and more dynamic 4R nutrition decisions.
3. **Recycling:** Optimizing utilization of renewable nutrient resources requires choices for "right source" to consider recycled forms where feasible.
4. **Nutritious crops:** Crop nutrient applications that improve human nutrition and health.
5. **Climate-Smart Fertilizers:** Considering the carbon footprint of nutrient source, including emissions associated with both its manufacture and its use.
6. **Accelerated Innovation:** Testing 4R components in adaptive management systems for faster translation into practice.

WHAT IS HAPPENING?

The concept of 4R Nutrient Stewardship has achieved global recognition, but its impact remains limited at larger scale. The Food and Agriculture Organization (FAO) of the United Nations includes the principles of 4R Nutrient Stewardship in the International Code of Conduct for the Sustainable Use and Management of fertilizers[3]. The 4R Plant Nutrition Manual (IPNI, 2016)[1], a 130-page document detailing the global principles of 4R Nutrient Stewardship, was translated into eight languages and distributed broadly in the Americas, Asia, Africa, and Oceania.

The many languages of 4R

WHAT OUTCOMES HAS THE 4R CONCEPT PRODUCED IN DIFFERENT REGIONS?

Regional experiences with implementations of 4R and challenges to its furtherance differ considerably around the world. Some of these implementations have run under the 4R brand, whereas others do not but represent similar approaches. A long history of research in soil fertility and plant nutrition continues to inform 4R practice choices, even if the research was not conducted under the 4R brand.

NORTH AMERICA

4R Nutrient Stewardship grew into a highly recognized concept, first within the fertilizer industry, then among agri-environmental scientists working on issues with agricultural nutrients[4]. The use of 4R practices has been recognized to mitigate greenhouse gas emissions. In the first quantification protocol to be implemented for reduction of agricultural nitrous oxide emissions, the provincial government of Alberta in Canada recognized 4R Nutrient Stewardship in 2010[5]. An assessment of natural climate solutions for Canada concluded that increased adoption of 4R practices could reduce greenhouse gas emissions in Canada by an additional 6.3 million tons of carbon dioxide equivalents annually by 2030, contributing 3% of Canada's commitment to the Paris Accord[6]. Within two years of its launch in 2014, the first 4R Nutrient Stewardship Certification Program in the United States grew to influence nutrient applications on nearly 40% of the cropland in the western Lake Erie watershed,[7] limiting phosphorus losses that drive algal blooms . While nutrient use efficiency has been improving over the past few decades, quantification of actual reductions in nitrous oxide emission and phosphorus loss remains a challenge.

SOUTH ASIA

From 2009 to 2019, the 4R Nutrient Stewardship concept was incorporated into national research and extension programs in several countries and became part of the narratives within the fertilizer industry agronomic training and field programs. However, broader on-farm implementation beyond research plots remains a challenge. Defining the fertilizer "rights"—source, rate, time, and place—for the many crops and cropping systems of the sub-continent was beyond the capacity of most smallholder farmers and their advisors, but also many researchers. The need for a simple easy-to-use decision support tool that translates the 4R concept into field-specific fertilizer recommendations led to the development of the Nutrient Expert software[8], which followed a new approach for Site-Specific Nutrient Management first developed in the 1990s[9]. Nutrient Expert uses a robust on-farm information database of attainable yields, fertilizer and manure use, nutrient balance, and other growing conditions. On-farm use of the tool produced sustainability benefits, including impacts on yield, profitability, soil health, nutrient use efficiency, energy and water use efficiency, and greenhouse gas emissions[10].

SOUTHEAST ASIA

Considerable research and extension on field crops (rice, maize) and plantation crops (oil palm, coffee, cocoa) was supported by the International Plant Nutrition Institute until 2019. Field handbooks on 4R principles were published for oil palm, rice, sugarcane, cassava, rubber, mango, watermelon, and grape[a]. Small holder cocoa farmers in Indonesia were found to vary considerably in fertilizer management capability[11]. Fertilizer management research on oil palm found no effect of timing but substantial effects of rate of application on nutrient use efficiency[12]. Fertilizer recommendations based on 4R Nutrient Stewardship helped cassava farmers reap the benefits of their investment in fertilizer[13]. A sustainable production standard for rice was developed in 2011 and includes principles for inorganic and organic fertilizer sources, timing and rate[14].

CHINA

Agriculture in most parts of China is typically smallholder-based. A focus on high yields through high fertilizer inputs has impaired the country's environmental sustainability[15]. Use of the Nutrient Expert digital tool for 4R practices maintained yield and profitability while increasing nutrient use efficiency[16] [17]. Implementation of 4R Nutrient Stewardship along with improvements in agronomic management could improve performance relative to defined nitrogen surplus benchmarks, and thus ensure food security and increasing nitrogen use efficiency, while improving environmental sustainability and economic return[18]. The regional implementation of technologies and management practices following the 4R principles must be carefully designed to fit site-specific biophysical contexts[19]. The use of an Integrated Soil-Crop System Management approach has been demonstrated to improve both nitrogen use efficiency and crop yields of more than 20 million farmers in China, from 2005 to 2015[20].

SUB-SAHARAN AFRICA

Recognizing that crop yields in smallholder farming systems of sub-Saharan Africa need to increase to address the many livelihood challenges those communities are facing, the Abuja Fertilizer Summit of 2006 called for an increase in fertilizer nutrient use. The Alliance for a Green Revolution in Africa integrated this call in their soil strategy, focused around Integrated Soil Fertility Management (ISFM). ISFM is described as *'A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles'*[21]. ISFM thus embraces the 4R principles, but adds good agronomic practices. The use of ISFM practices including hybrid varieties and combinations of organic inputs with fertilizer raised the agronomic efficiency per kg of applied nitrogen to values as high as 40 kg, compared to 17 kg for local practices[22]. Adoption rates of 'complete ISFM' are commonly in the order of 10-25% of the smallholder farming communities engaged[23]. More recently, Nutrient Expert and other tools for site-specific nutrient management in rice, maize and cassava have also been developed and tested in Sub-Saharan Africa[24]. Much opportunity remains to attain larger scale adoption.

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[a] See publication list at http://seap.ipni.net/library/publications

AUSTRALIA-NEW ZEALAND

Several programmes in Australia embrace the principles of 4R but are not necessarily labeled as such. In Queensland concern regarding runoff of nutrients from coastal catchments to the Great Barrier Reef has resulted in the "Six-Easy Steps Toolbox" nutrient management program being developed by the sugar industry[25]. The fertilizer industry's Fertcare program explicitly embraces 4R nutrient stewardship. It has trained almost 4000 professionals on fertilizer management to enhance productivity, minimize environmental issues and ensure food safety. The dairy and grains industries have adopted the 4Rs in their recommendations for fertilizer use. Nutrient management also benefited from coordinated research, under the banner of 'Better Fertiliser Decisions for Crops' producing collated information on crop and pasture responses to fertilisers and providing a documented basis for more tailored nutrient recommendations on farm[26]. In New Zealand, dominated by pastoral systems, the nutrient budgeting supported by OverseerFM is used by over 11,000 farms, driven by environmental legislation regarding the quality of surface and groundwaters[27].

LATIN AMERICA

While inputs of phosphorus to crops in Brazil are currently in considerable surplus to crop offtake, field trials suggest that the combined use of no-tillage, cover crops, and adoption of 4R practices could improve overall phosphorus use efficiency[28]. By contrast, crop nutrient balances are in deficit in Argentina and Bolivia[29]. When integrated with crop rotation, cover cropping, and balanced application of fertilizer nutrients, 4R practices provide not only for agricultural productivity, but also for protection and conservation of soils[30]. Field research on maize in the Pampas of Argentina showed that "ecologically intensive" management practices—which included 4R practices for nitrogen source, rate, and timing—improved maize productivity without increasing the emission of nitrous oxide[31]. Another study in Argentina found lower nitrous oxide emissions per unit of production from soybeans in rotation with cereals as compared with soybean monoculture[32]. A set of conservation agriculture practices that included nitrogen fertilizer management was found to reduce soil erosion, and improve soil health and profitability of crop production in the Andean region of Ecuador[33].

EUROPE

Agri-environmental policy approaches in Europe differ markedly from those in North America, as do trends in agricultural nutrient use. Europe emphasizes more regulatory approaches in comparison to voluntary approaches[34]. Historically, nutrient surpluses in western Europe were larger than in the United States. The cumulative phosphorus surplus over the past century in Europe amounts to 63 years of current crop removal, while the same figure for the United States is 18 years[35]. The regulation-driven changes during the past 25 years in the European Union have reduced agricultural nitrate loads to the aquatic environment and improved nutrient use efficiency, but these issues remain at the forefront of environmental and agricultural policies that drive farming. European water quality, for example, is threatened by increasing N:P ratios[36]. The fertilizer industry in Europe includes 4R within its Infinite Nutrient Stewardship concept[b], and has developed initiatives to comply with national and EU policy goals, including precision farming technologies[c], a tool for estimating the carbon footprint of fertilizer manufacture[37], a circular economy action plan, and support for implementation of a nitrogen use efficiency indicator[38].

Despite the regional differences in the implementations of 4R Nutrient Stewardship described above, commonalities are also evident, particularly the need to better integrate with good practices for agronomy, soil conservation, and environmental management.

WHAT BARRIERS LIMIT ADOPTION AND QUANTIFICATION OF BENEFITS OF 4R?

The original 4R framework included assessment of sustainability outcomes and continuous refinement by adaptive management, as indicated in Figure 2. While metrics for such assessments were described in section 9.3 of the 4R Plant Nutrition Manual[1], progress in reporting has been limited. In some regions, industry organizations are able to tally the area of cropland, and the number of farmers or advisors, practicing some level of 4R nutrient stewardship. But not much more. The main driver for the adoption that has occurred so far is profitability and risk reduction—economic benefits to the farm. There is a need to increase the recognition of the broader environmental and social benefits of 4R by rewarding farmers for adopting 4R practices. Measuring the contribution of 4R practice adoption to these outcomes faces numerous challenges, including:

- Lack of resources available for in-depth monitoring and evaluation;
- Multiple factors governing the "right" choices for a particular farm field;
- Privacy issues limiting willingness and ability of agri-retailers and farmers to share data;
- Insufficient research documenting the impacts of specific 4R practices[4]; and
- Metrics span a range of scales, and trade-offs and synergies are difficult to assess[39].

The combinations of source, rate, time, and place for nutrient applications that enhance the sustainability of cropping systems are site-specific, because:

- Soils differ in their nutrient supplying capacity and other properties;
- Crops differ in nutrient needs;
- Crops respond differently to nutrient applications depending on soil, climate, weather, and the level of management of the farmer;
- The processes affecting nutrient losses, and the magnitude of potential losses, vary with soil, landscape, climate and weather;
- Environmental harm due to nutrient losses varies depending on the form of the nutrient lost and the characteristics of the ecosystem

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[b] See https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Nutrient_Stewardship_Sept_2016_websize.pdf

[c] See for example https://www.yara.com/crop-nutrition/products-and-solutions/precision-farming/

into which they flow;

- Production objectives differ among farmers depending on their scale and socioeconomic condition; and
- Stakeholder priorities for outcomes influenced by nutrient application vary regionally depending on socioeconomic status, cultural values, policies, and perceived and actual risks.

WHAT CAN BE DONE?

HOW CAN THE 4R FRAMEWORK FIT FUTURE FARMING SYSTEMS?

The following considerations should feature prominently in developing future programs to implement 4R Nutrient Stewardship.

Integrate with farming systems in transition

The integrated farming systems of the future will include 4R practices, but management choices for many other components—including agronomy, crop diversity, drainage, livestock, pests, seeds, soil conservation, and water (Figure 1)—also influence the flows of farm nutrients. Soil conservation is particularly important to meet criteria for the still-evolving definition of regenerative agriculture[40], as is integration with livestock systems[41]. Farming systems that exploit biological nitrogen fixation through rotations, intercropping, and cover crops also increase nitrogen use efficiency. At a landscape level, nutrient flows among cropland, pasture and livestock production systems should be integrated and optimized[42]. Rebuilding the links between livestock and croplands provides opportunities for sustainable intensification of agriculture in China[43] and other regions. Mechanization, irrigation, and fertigation offer large opportunities to expand the range of choices available to the farmer for managing nutrient applications, and increasing whole-system productivity and nutrient use efficiencies. This is of particular importance in current smallholder farming systems.

Crop diversity and food systems also need to transition to better address human health and nutrition security needs[44]. Grain buyers, processors and governments need to provide incentives to increase the nutritional value of the crops produced, as has been done, for example, with selenium in Finland[45]. Fertilizing food crops with targeted micronutrients through agronomic approaches may result in diverse benefits for the health of consumers[46]. Foliar application of nitrogen fertilizers during and/or right after anthesis has particular effects on grain protein[47]. Post-anthesis foliar application of micronutrients also affects grain concentrations of zinc, selenium and iodine, and is suggested to be a highly effective strategy to address the hidden hunger problem in human populations in the developing world[48]. It was also shown that adequate nitrogen fertilization is required for a successful biofortification of wheat[49] and silage maize[50] with zinc and iron. The HarvestPlus initiative has already developed new crop cultivars biofortified in zinc, iron and vitamin A that currently reach more than 20 million people, with opportunity to scale to one billion[51]. This requires targeted fertilizer-based fortification solutions at scale too.

Use data-driven digital solutions to support decisions

Fertilizer dealers and other service providers in many countries now offer GPS-guided nutrient applications, and sub-field zone soil sampling and crop monitoring. These technologies provide more precise application, minimal overlap, and high field efficiency. Many agri-businesses also provide services using yield monitor data and satellite or aerial imagery to guide nutrient management decisions. These technologies often focus on rate and timing of nutrient applications, but may require changes to source and placement as well. There are large opportunities to better link these technologies and solutions to utilize all available data in farm-level decisions[52]. Different technologies are appropriate for farming on different scales. The use of Nutrient Expert or similar decision support tools provides an example of a digital solution relevant to smallholder farmers. Model-based decision support for nitrogen management has also been applied with dryland farmers in Australia, using APSIM[d] [53]. Use of digitally supported advisory systems and mechanization with appropriate scale-neutral technologies such as laser land leveling[54] have potential relevance to millions of smallholder farmers.

Innovate using adaptive management

On-farm adaptive management and applied research, participating in open innovation systems, can lead to accelerated development and refinement of practical technologies that provide economic and environmental benefits[55]. For example, recent innovations being refined in North America include the use of weather-driven crop models to predict year-to-year variations in the optimum amount of nitrogen to apply. Climate Fieldview from Bayer, Encirca Premium from Corteva, and Yara's Adapt-N enable growers to use real-time weather data to help fine-tune nitrogen applications to the site- and season-specific crop requirements for their fields[56]. While these can also be considered data-driven digital solutions, the aggregation of data from many producers within a region allows for more rapid innovation and refinement of decision algorithms, supporting adaptive management. Public-private partnerships sharing data on crop response to nutrients can help support these objectives[57].

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d. Commercialized as Yield Prophet https://www.yieldprophet.com.au/yp/Home.aspx

WHAT NEW CORE PRINCIPLES ARE NEEDED FOR SOURCE, RATE, TIME AND PLACE?

Principles for the four components (source, rate, time, place) apply most directly at the field and farm scale. Specific decisions that follow these principles need to be tailored to specific soils, crops, climates, farming systems and even value chains. They should also consider farm types, risk aversion, and financial capital. We propose here new 4R principles that address the previously identified gaps in achieving responsible plant nutrition, with supporting rationale. The remaining original principles are also listed, but described in more detail in IPNI (2016)[1].

PRINCIPLES FOR RIGHT SOURCE

1. **[new] Supply nutrients in quantifiable and available forms.** The form applied may be either immediately or slowly releasing plant-available nutrients, but its nutrient content must be known if crop requirements are to be met. Commercial fertilizers are sold based on standards for grades and solubility; manures and recycled sources can be analyzed for nutrient content and availability, or appropriate nutrient content tables can be used[58].
2. **[new] Use climate-smart forms.** Climate-smart forms of fertilizer need to generate less emission of greenhouse gases, both in their manufacture and post-application. Fertilizers differ widely in their environmental footprint per unit nutrient applied[59]. Industry innovations toward producing solar fertilizers[60], green ammonia and blue urea[61] may lead to smaller future footprints of nitrogen[62]. Inhibitors of nitrification and urea hydrolysis and fertilizer coatings have been available for decades, but their adoption has been limited. A major reason is their cost, relative to their efficacy in terms of improving yields and nutrient use efficiency[63], which is often relatively smaller than the 20 to 40% reduction in nitrous oxide emissions they can achieve[64]. Future innovations include nanoparticulate forms of nutrients, aptamers, and coatings sensitive to plant signals, constituting "Smart Fertilizers" that release nutrients in response to microbial activity and plant demand[65]. Choice of low-emission forms contributes to reducing Scope 3 emissions for the fertilizer sector.
3. **[new] Use recycled forms where feasible.** The land application of manures, biosolids, and composts reduces the need for manufactured fertilizers and serves to lessen agriculture's total environmental footprint. On farms that import livestock feed, however, nutrients in the manures may exceed crop requirements on the land available. Technologies for nutrient recovery from manures in more concentrated forms such as struvite[66] or calcium phosphates[67] allow for nutrients to be transported longer distances. Guidelines and roadmaps for developing such bio-based fertilizer technologies have been proposed[68]. Innovation is advancing to process different waste streams into novel forms of fertilizer that have excellent application potential. For example, the Ostara struvite process now captures phosphorus from wastewater treatment plants in Atlanta, Edmonton, Saskatoon, and a total of 22 systems worldwide, with capacity to produce 25,000 tonnes per year of controlled-release ammonium magnesium phosphate fertilizer. Anuvia from Florida markets organic plant nutrients made from food wastes. Notable others include Ductor, producing bioenergy and a liquid N fertilizer from biogas units, Elemental producing fertilizer from various forms of food waste in the UK, and Grassland Fertilisers, producing low analysis granular forms from cattle feedlot waste.
4. **[new] Consider biological inoculants.** For legume crops, the use of various rhizobial strains is well-known and supported as a method to ensure the biological fixation of very considerable amounts of nitrogen, and its optimization is critical for sustainable intensification[69]. Biofertilizers have been defined as living microbes that enhance plant nutrition by either by mobilizing or increasing nutrient availability in soils[70]. Various beneficial bacteria and fungi are currently used as biofertilizers, and may successfully colonize the rhizosphere, rhizoplane or root interior. Despite their potential, however, biofertilizers have yet to replace conventional chemical fertilizers in commercial agriculture. Growth responses to inoculation with arbuscular mycorrhizal fungi are, on the whole, inconsistent[71].
5. [original] Suit soil physical and chemical properties.
6. [original] Recognize synergisms among nutrient elements and sources.
7. [original] Recognize blend compatibility of materials.
8. [original] Recognize benefits and sensitivities to associated elements.
9. [original] Control effects of non-nutritive elements.

PRINCIPLES FOR RIGHT RATE

1. **[new] Address variability in crop response.** Year to year variation in weather, and spatial variability within and among fields, and their interaction, lead to differences in crop response to applied nutrients[72 73]. Weather is an important driver of crop nutrient requirement, but traditional recommendations often do not vary from year to year. Incorporating weather in the decision process for nitrogen rates has been shown to improve outcomes for maize production in North America[74], for commercial crops in Australia[53], and for a wheat-maize system in North China Plain[75].
2. [original] Assess plant nutrient demand.
3. [original] Assess soil nutrient supply.
4. [original] Predict fertilizer use efficiency.
5. [original] Consider soil resource impacts.
6. [original] Consider economics and the law of diminishing returns.

PRINCIPLES FOR RIGHT TIME

1. **[New] Address changes in nutrient need through the growing season.** Dynamic adjustment of nutrient applications during the growing season has been demonstrated to be feasible in many cropping systems, including oil palm[76], maize[77], fertigated cotton[78], and wheat[79 80]. A machine-learning approach using in-season meteorological data showed promise for predicting nitrogen demand in California almond production[81] and in Eastern Canada canola production[82]. Such dynamic adjustment is also possible using tools as simple as leaf color charts, smartphones or visual deficiency symptoms.
2. [original] Assess timing of plant uptake.
3. [original] Assess dynamics of soil nutrient supply.
4. [original] Recognize dynamics of soil nutrient loss.
5. [original] Evaluate logistics of field operations.

PRINCIPLES FOR RIGHT PLACE

1. **[New] Place nutrients to avoid loss.** Correct spatial placement of nutrients across the landscape can minimize off-site losses of nutrients. Many companies are developing remote or proximal sensing systems to predict where nutrients are best applied using fertilizer variable rate spreading technologies[83]. Variable-rate fertilizer application to wild blueberry based on slope gradient and crop cover reduced runoff losses of phosphorus without reducing yield, compared to uniform-rate application[84]. In an Iowa corn-soybean system, variable rate fertilization was found to reduce phosphorus inputs and spatial variability in soil test levels, thereby reducing potential for phosphorus loss[85]. In soils of high pH, incorporating urea rather than leaving it on the surface can reduce ammonia losses[86 87]. Placing phosphate sources below the soil surface can reduce concentrations and loads of dissolved phosphorus in drainage water[88], particularly in cropping systems with conservation tillage[89].
2. [original] Consider where plant roots are growing.
3. [original] Consider soil chemical reactions.
4. [original] Suit the goals of the tillage system.
5. [original] Manage spatial variability.

Summing it up, nutrient sources need to be made more circular and climate-smart, and rate, time, and place of application need to be more precise and dynamic.

HOW CAN 4R CONTRIBUTE TO SUSTAINABILITY PERFORMANCE REPORTING?

Farmers, industry, civil society and governments have increasing but different needs for monitoring and reporting sustainability performance toward science-based targets. Where 4R implementation has attained any degree of recognition, it has often been driven by focused stakeholder expectations. For example, the Lake Erie 4R Certification Program focused on practices that would reduce losses of phosphorus and algal blooms, while keeping crop production profitable. Integrated Soil Fertility Management focused on increasing crop production and food security by increasing profitability and reducing risks for smallholder farmers. Every region and every cropping system will have different stakeholder priorities.

Ascertaining stakeholder priorities, however, occurs at a level far beyond farm scale, and is essentially the work of sustainability platforms such as Field to Market or other organizations with governance structures suitable to the representation of stakeholder interests. For this reason, we describe instead some core universal accountability components as framework for 4R, and how they might link to any of the existing sustainability platforms. The framework requires tracking of 4R practices and economic performance at the farm level. Reporting of environmental and social impacts, not feasible to measure directly at farm level, would occur at the regional or program level in collaborative programs and initiatives that involve science-based estimation methods and models. Quantifying these impacts often requires detailed data on the farm-specific practices employed and the specific soil properties.

Track 4R practices and economic performance at the farm level

The core framework of 4R implementation at the farm level includes tracking the four practice components, and their immediate farm-level economic outcomes. One approach for tracking 4R practices uses tables, developed with expert input, that describe specific suites of source-rate-time-place practices for specific cropping systems, at basic, intermediate and advanced levels of management[90]. The four performance metrics in Figure 1 measurable at the farm level include productivity, profitability, nutrient use efficiency, and soil health.

- Productivity, defined as yield of marketable product.
- Profitability, the difference between revenues and expenses, supports farmer livelihoods.
- Nutrient use efficiency can be tracked as a ratio of outputs to inputs, or as a surplus or deficit.
- Soil health can be focused on soil fertility but also includes biological and physical aspects of the soil that support productivity, available water holding capacity, and carbon storage.

The information on these four performance areas is for the benefit of the farm manager, but can also contribute to the reporting of environmental and social performance, when shared with an aggregator with appropriate protection of privacy. Several of these metrics have been advocated for their relevance to the delivery of ecosystems services. For example, soil test phosphorus concentration has been proposed as a metric of agricultural impact on biodiversity, soil health, and risk of water contamination associated with pasture productivity in New Zealand[39]. Also, nitrogen surplus has been proposed as an indicator of nitrous oxide emissions, for use by food-supply-chain companies and others to quantify regional-scale aggregated changes in greenhouse gas emissions[91]. Tailored approaches that keep nitrogen balances within safe limits help avoid trade-offs between nitrous oxide emissions and high crop yields[92]. An analysis of over 10,000 field-year combinations of farm data in the Netherlands—shared with a consulting company providing decision support—showed how management and weather effects on yields and nitrogen use efficiencies could be used to assess production, economic, and environmental performance[93].

Share tracked data to report performance

Quantification of key material outcomes provides information important to everyone involved in the value chain, from farmers to consumers. Not all that is tracked needs to be shared and reported, but quantification of these outcomes is linked to key practices. Environmental outcomes associated with 4R in farming systems that may be of importance include biodiversity[94], net greenhouse gas emissions (including soil carbon sinks), and air and water quality, as shown in Figure 1. A 4R plan can contribute an important part of the farm activity information required for relevant sustainability platforms—agri-food industry collaborations that already include many fertilizer manufacturers and retailers—that report environmental outcomes to stakeholders. For example, the Field to Market Alliance for Sustainable Agriculture recognizes specific suites of 4R nitrogen practices for the calculation of nitrous oxide emissions from maize and wheat cropping systems in the United States in its Fieldprint Platform[95]. It requires 4R nutrient practice data in four of its eight metrics: biodiversity, greenhouse gases, energy, and water quality. The Ecosystem Services Market Consortium uses an even greater level of detail on 4R practices to generate marketable credits, using validated models of effectiveness in reducing greenhouse gas emissions. Several other platforms are evolving, including the industry-led, voluntary carbon farming platforms of Indigo Ag, Truterra, Bayer, Nutrien, Yara, and many others. Many food companies and agricultural input suppliers currently seek to define and reduce their "Scope 3" emissions and footprint, which may include all the indicators in this category associated with agricultural production in their supply chain.

A 4R plan—or even a whole-farm management plan—relates less directly to social impacts on food security, human nutrition, livelihoods, and circularity (Figure 1), but such impacts are collective results of activities on individual farms and throughout the supply chain. Therefore, it is critical to make the connections through efforts by collaborative platforms and government inventories. Indicators of food security and human nutrition at global and national levels are published by FAO, national governments and other organizations. Livelihoods reflects the benefit to the incomes of farmers that may be derived from rewarding of practice adoption that supports societal benefits, and also includes the employment created within agribusiness in new innovative activities supporting the furthering of 4R. Improving equitable access to participation and benefits can also be considered when implementing 4R programs[96]. Circularity of nutrients is a relatively new metric[e], intended to reflect contribution to a more circular economy through increased reuse and recycling, thus reducing depletion of finite resources. A methodology for calculating circular transition indicators has been published[97]. Precisely how it would be measured, calculated, or related to nutrient use at the farm level requires discussion, but it should reflect a more optimal allocation of livestock manures and other biowaste to soils where the nutrients are most needed, and the safe recycling of nutrients to reduce the rate of depletion of finite natural resources[98].

WHO NEEDS TO DO WHAT?

The following guidelines outline the roles of each stakeholder group in furthering 4R Nutrient Stewardship. They build on the roles outlined by FAO[3] and the Scientific Panel on Responsible Plant Nutrition[2]. Specific recommendations and actions will vary from one country to another depending on regional priorities and level of technical development.

- **Fertilizer industry:** Implement decision support systems and recommendations for source-rate-time-place choices in accord with 4R principles. Deliver or make available the right sources at the right time. Provide information to the buyer, including farmers, on the environmental footprint of fertilizer products. Collaborate with research institutions, governments, and civil society organizations to develop sustainability standards for the agricultural value chain, incorporating 4R practice standards and performance metrics. Train retailers, agronomists and farmers on 4R principles, site-specific 4R practices, and responsible cropping system practices. Drive innovation, as well as provide resources, to develop technologies for reuse and recycling of nutrients for safe use as fertilizers. On a regional basis, provide leveraged support to public research on key issues related to the 4Rs.
- **Fertilizer retailers, agri-service providers, and crop advisers:** Provide farmers with evidence-based information on specific 4R practices and responsible agronomic practices. Collaboratively with farmers, support on-farm adaptive management and research evaluating fertilizer products and additives, and associated rate-time-place practices, for impacts on yield, nutrient use efficiency, and soil health. Ensure that application services meet 4R practice and quality standards. Support and promote the safe and appropriate use of nutrients derived from recycled sources.
- Farmers and other fertilizer users: Optimize nutrient management with available source-rate-time-place combinations, based on crop needs and soil fertility conditions, and using appropriate decision support tools. Participate in on-farm evaluations of specific 4R

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[e] See https://international-animalhealth.com/the-value-of-circularity-in-sustainable-food-systems/

combinations. Seek out recommendations from professionally recognized, certified, agri-service providers. Where feasible share data on 4R and agronomic practices to platforms reporting, recognizing, and rewarding improved sustainability performance. Ensure that locally available nutrient sources—including animal manures, composts, crop residues—are utilized appropriately.

- **Scientists:** Working with crop advisers and farmers, define and describe 4R practice standards relevant to more regenerative farming systems. Develop, validate, and build credibility for methods to predict environmental and social outcomes of such farming system changes, and support their incorporation into platforms for sustainability performance reporting. Investigate socioeconomic and ecological barriers for farmers' adoption of 4R practices, and identify policy and technology opportunities for addressing these barriers. Develop methodologies for multi-level assessments of 4R implementation programs. Develop new more efficient, climate-smart, and circular-economy-friendly nutrient sources.
- **Governments:** Facilitate collection of statistical data at greater level of detail to support reporting of 4R practices. Support scientists and scientific research in developing models to assess the impact of 4R practices on sustainability performance. Adopt policies that incentivize and reward 4R practice adoption, production of more nutritious foods, development and use of climate-smart fertilizers, and innovation in recycling nutrients from wastes. The Joint EPA-USDA Partnership and Competition on Next Gen Fertilizers to Advance Agricultural Sustainability in the United States is an excellent example of government collaboration with industry to incentivize innovation in fertilizer product development[f].
- **Food traders, processors and retailers**: Recognize and reward 4R practices used to products sold. Include 4R practice and performance metrics in sustainable production standards to accelerate farmer adoption of improved 4R practices.
- **Civil Society Organizations:** Advocate recognition and rewarding of 4R Nutrient Stewardship in collaborative platforms advancing sustainable agriculture. Communicate successes in behavior change and the resulting benefits to ecosystems and society.
- **Investors:** Invest in technologies, businesses and organizations that support 4R as a recognized means of advancing nutrient stewardship.

WHAT WILL SUCCESS LOOK LIKE?

Furthering 4R Nutrient Stewardship with a new set of principles can produce the following results within the next ten years.

1. Collaboration within the agri-food industry has led to development of trusted agencies with which farmers are willing to share data on nutrient application practices for purposes of monitoring, evaluation, and reporting of sustainability outcomes.
2. The fertilizer and livestock industries have collaboratively developed 4R practice standards integrating fertilizer and manure management to address nutrient cycling among arable land, grazing land, and livestock.
3. Digital technologies are increasingly used on farms ranging in scale, both for purposes of on-farm research and adaptive management, and for sharing data to report sustainability outcomes.
4. A green label for agricultural products grown with practices protecting biodiversity recognizes and requires 4R practice and performance data.
5. Innovation in technology and management has resulted in registered fertilizer products using nitrogen and phosphorus extracted from manure and other biowaste in transportable forms suitable for use as fertilizer.
6. Regenerative cropping systems that provide extended green cover to soil are supported by 4R practice recommendations.
7. Robust methods and standards have been adopted to better assess nutrient stewardship and guide further investments in research and policies supporting accelerated innovation at farm, landscape, and country levels.
8. Accepted practice standards for source, rate, time and place addressing specific priorities of regional cropping systems are used by farmers and recognized by buyers of agricultural commodities.

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[f] See https://www.epa.gov/innovation/next-gen-fertilizer-challenges

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