Enhanced nitrogen fertilizer technologies support the ‘4R’ concept to optimize crop production and minimize environmental losses

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Abstract

Fertilizer nitrogen (N) has been, and will continue to be, essential in nourishing, clothing, and providing bioenergy for the human family. Yet, emissions of ammonia (NH_3) and nitrous oxide (N_2O), and losses of nitrate-N (NO_3-N) to surface and groundwater resources are risks associated with fertilizer N use that must be better managed to help meet expanding societal expectations. Nitrogen fertilizers with polymer coatings, or with addition of urease and/or nitrification inhibitors, or possessing other characteristics that afford them either improved agronomic response and/or lessened loss of N to the environment - compared to a reference water soluble fertilizer - may be considered enhanced efficiency N fertilizers (EEFs). Agronomic and horticultural research with these technologies has been carried out for many decades, but it has been primarily in the last decade that research has increasingly also measured their efficacy in reducing N losses via volatilization, leaching, drainage, runoff, and denitrification. Expanded use of EEFs, within the concept of 4R N management (right source, right rate, right time, right place) may help increase crop yields while minimizing environmental N losses. Coupling these 4R N management tools with precision technologies, information systems, and crop growth and N utilization and transformation models –especially with weather models, may improve opportunities for refined N management in the future.

Key Words

Nitrogen recovery, crop yield, economics, fertilizer technology, climate smart agriculture, sustainability

Introduction to the Issue

Farmers and the agricultural industry around the world are increasingly being confronted with large challenges and opportunities to improve their management of nutrient inputs in crop production; especially N management. Global food demand is expected to continue to rise – including meat and milk consumption - into the next two decades (Mueller et al. 2012, Sattari et al. 2016). Yet, large gaps persist between typical farmer yields and attainable crop yields (Cassman et al. 2003). Keys to achieving these critical needs of the human family, while minimizing the human environmental footprint, are improving crop recovery and the overall efficiency and effectiveness of fertilizer N use. Freney (1997) emphasized that in addition to using the appropriate fertilizer N rate, there are multiple ways to achieve such improvements: i) use of the correct form and time of application, ii) use of continuous soil cover, iii) correct tillage, drainage, and irrigation, iv) greater knowledge on the effects of biomass burning on grasslands and croplands, v) use of foliar N fertilizer applications, vi) use of slow or controlled release fertilizers, and vii) use of urease and nitrification inhibitors. Yet, “much more needs to be known about the dynamics and nutrient-use efficiency of various types of fertilizers used individually and also for combinations of organic and synthetic fertilizers…” (Tomich et al. 2011).

Existing Understanding

In a review of several options to improve the efficiency of fertilizer N use and to mitigate environmental N losses in Australia, particularly agricultural N_2O emissions, Dalal et al. (2003) suggested that it is important: “ … to match the supply of mineral N (from fertilizer applications, legume-fixed N, organic matter, or manures) to its spatial and temporal needs by crops/pastures/trees. Thus, when appropriate, mineral N supply should be regulated through slow-release, (urease and/or nitrification inhibitors, physical coatings, or high C/N ratio materials) or split fertilizer application. Also, N use could be maximized by balancing other nutrient supplies to plants.”

In good agreement, Robertson and Vitousek (2009) stated: “Mismatched timing of N availability with crop need is probably the single greatest contributor to excess N loss in annual cropping systems.” The Cameron et al. (2011) review also agreed, stating: “Careful management of temperate soil/plant systems using best management practices and newly developed technologies can increase the sustainability of agriculture and reduce its impact on the environment.” Appropriate N management, in the context of good crop and soil system management to help mitigate agricultural cropping system greenhouse gas emissions, has been discussed in reports by Snyder et al. (2009) and Flynn and Smith (2010). Snyder and Fixen (2012) also emphasized the impacts of balancing N fertilization with the input needs of other essential nutrients, to help optimize crop N recovery, reduce the risks for residual inorganic soil N buildup, and to reduce the risks for nitrate-N leaching losses.

The objective of all agricultural nutrient use is to "increase the overall performance of cropping systems" (Fixen et al. 2014). Cropping system performance in many parts of the world may be increasingly threatened by climate change and less predictable weather patterns. In recognition of such weather uncertainties, it is evident that effective water management and nutrient management should be collective priorities. This point was emphasized by Fixen et al. (2014), who reported: "… even though nitrogen use efficiency (NUE) generally decreased as N rates increased, the simultaneous increase in water use efficiency (WUE) and yield until an optimum N rate was attained improved over-all system performance. Efficient and effective use of either water or crop nutrients requires that both be managed at optimum levels for the specific system."

Appropriate fertilizer N use fosters carbon dioxide capture by crops (IFA 2009b) and helps build and sustain soil organic matter (Dourado-Neto et al. 2010, Powlson et al. 2010). Yet, the benefits of soil carbon sequestration should not be over-emphasized to the disadvantage of other measures also important to combating climate change; and should be weighed in the balance of greenhouse gas emissions associated with the production and use of fertilizer N (Powlson et al. 2011). Meta-analyses by scientists in Australia showed that elevated atmospheric carbon dioxide levels impact the N cycle and result in: increased biological N fixation by legumes (38%), increased above- and below-ground biomass production (24 and 33%), increased plant uptake of fertilizer N (17%), no significant effect on soil-plant system total N recovery, and increased N_2O emissions 27% (Lam et al. 2012). These findings exposed the potential for aggravating effects of elevated atmospheric carbon dioxide on N_2O emissions from soils; which is especially concerning in view of N_2O's large radiative forcing (298x compared to carbon dioxide), ozone depleting impacts, and its $\geq$ 100-year life-span in the atmosphere (UNEP 2013).

Renewed and sustained research/education/outreach with crop nutrition emphases are needed to improve site-specific, knowledgeable nutrient management for major cropping systems around the world - relying on all available nutrient management technologies, tools, and science. With these looming complex challenges, we face grand opportunities to: i) lessen crop yield gaps, ii) decrease nutrient management knowledge gaps, and iii) implement actions that lessen environmental N losses.

Aim of this Review

This paper highlights opportunities to improve crop recovery of applied fertilizer N and to reduce losses of N to the environment, by sharing recent (~ last five years) examples of published research results addressing management of different N sources, rates, timing, and place of application [the 4Rs (*right source, right rate, right time, right place*) of fertilizer N stewardship (Bruulsema et al. 2009, IPNI 2012, Johnston and Bruulsema 2014)]; with a focus on enhanced efficiency N fertilizers (EEFs). Examples of recent industry N management actions and outcomes, and emerging opportunities for crop sensor-based N management will also be briefly mentioned.

Results

4R Nitrogen Management - Gaining Global Industry Adoption

Inadequate and imbalanced plant nutrition and soil fertility affect agronomic N use efficiency and constrain food production in many parts of the world, perhaps most notably in sub-Saharan Africa (Chicowo et al. 2009, Sanchez 2002, Vanlauwe et al. 2011). Many partners have aligned through the United Nations Environment Program, "… steering dialogues and actions to promote effective nutrient management" (GPNM 2014), to address both the challenges of global crop production and natural resource protection. Some global industry-led actions were initiated in 2009 around the framework of 4R nutrient stewardship (IFA 2009a and 2009b, Bruulsema et al. 2009), to provide more consistent fertilizer producer/wholesaler/retailer and agricultural crop adviser/farmer/consumer alignment on the principles of science-based nutrient management that underscore production and sustainability. Those industry 4R outreach initiatives also communicate a common vision for the development of fertilizer best management practices (BMPs). These 4R nutrient management principles are also being extended to smallholder farmers in Africa (Zingore et al. 2014), to canola producers in Australia (Norton 2013), and to farmers in China (http://china.ipni.net/topic/4r-publications) and elsewhere.

A prominent example of that voluntary, industry-led, 4R–based education and outreach in the United States, is the "N-Watch" project (Payne and Nafziger 2015) in coordination with the Illinois Fertilizer and Agrichemical Association's "Keep it 4R Crop 2025" agricultural retailer program (http://www.keepit4rcrop.org/).The goal of "N-Watch", and its partnering and networking approaches is to enable farmers and their professional advisers to improve N management for maximized crop utilization of applied N. The program also strives to connect public Land Grant University research-based N recommendations, seasonal and current cropping system N dynamics, and the state of Illinois' Nutrient Loss Reduction Strategy (http://www.nutrientstrategy.iastate.edu/), while complying with the Illinois Environmental Protection Agency's water quality guidance and rules. A recent paper by McIsaac et al. (2016) indicates > 50% declines in flow-weighted nitrate-N concentrations and loads in the Illinois River since 1990, while river flow declined >15%, and may reflect increasing N use efficiency in agriculture and a depletion of legacy N stored in the watershed. However, it is not known how much the industry-led 4R N stewardship actions in Illinois since about 2010 may have contributed to these most recent water quality improvements.

Enhanced efficiency N fertilizer (EEF) benefits

Enhanced efficiency N fertilizers encompass 'right source', 'right time', and 'right place' components of the 4R nutrient stewardship concept. Slow- and controlled-release N fertilizer (coated or encapsulated), nitrification inhibitor-treated, urease inhibitor-treated N fertilizer, or products treated with both nitrification and urease inhibitors are considered EEF products. Inhibitor treated N products are sometimes referred to as "stabilized" N fertilizers (Trenkel 2010; Halvorson et al. 2014). The representative products, manufacturing, characteristics, and impacts of EEFs on nutrient use efficiency were nicely covered in a review by Trenkel (2010), and will not be repeated here. Trenkel (2010) cited Grant (2005) in stating that if the economic benefits of EEFs to society are substantial … "some costs should perhaps be borne by society, possibly through incentives for development and advisory work on slow- and controlled-release and stabilized fertilizers, and for encouraging their wider adoption by farmers".

As reported by Snyder et al. (2014):

> "In the last 5–10 years, there has been increased research into, and farmer adoption of, enhanced efficiency nitrogen fertilizers (EENFs, or EEFs for simplicity here). These EEFs are defined by the Association of American Plant Food Control Officials (AAPFCO) as 'fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment (e.g. gaseous losses, leaching, or runoff) when compared to an appropriate reference product' (Halvorson et al. 2014). Such reference products are 'soluble fertilizer products (before treatment by reaction, coating, encapsulation, addition of inhibitors, compaction, occlusion, or by other means) or the corresponding product used for comparison to substantiate enhanced efficiency claims'."

In a meta analysis and review of studies from the early 1970s to 2001, Wolt (2004) reported that the average effects of the nitrification inhibitor – nitrapyrin, as compared to N fertilization without nitrapyrin, increased crop yield 7%, increased soil N retention 28%, decreased nitrate-N leaching 16%, decreased greenhouse gas emissions by 51%; but had no effect on agronomic or environmental N performance about 25% of the time. A recent global literature synthesis by Pan et al. (2016) showed that use of nitrification inhibitors may increase the risks of ammonia volatilization from some fertilizer N sources. Although nitrification inhibitor use may not increase grain yield, better cropping system performance may be reflected in indicators of increased N use efficiency (Burzaco et al. 2014): plant N uptake, apparent crop N recovery (differential ratio of plant N uptake to N applied), or internal crop N efficiency (the differential ratio of grain yield to plant N uptake).

Citing Singh et al. (2008), Saggar et al. (2013) provided a good overview of urease-inhibiting compounds and their classification according to their structures and binding modes with the urease enzyme. Saggar et al. (2013) also provided additional details on one of the more widely used and effective compounds, N-(n-butyl) thiophosphoric triamide (nBTPT) - tradename Agrotain® - and also summarized multiple studies on reduced ammonia emissions with nBTPT in grazed pastures (primarily in New Zealand) that were fertilized with urea, or with animal urine.

Newer production processes and the increased scale of farmer demand have helped make it possible for the industry to provide polymer coated urea (PCU) fertilizers more economically. Generally, PCU sources are water soluble, and have urea release rates that are affected by the polymer chemistry, the coating process, the coating thickness, and temperature of the environment where they are applied. The timing of urea N release is important and can be an issue, especially if the PCU source does not release the N synchronous with crop demand and the prevailing environmental conditions (Golden et al. 2011, Maharjan et al. 2016, Suter et al. 2013). Hatfield and Venterea (2014) provided a synopsis of the special section on EEFs that was published in the Agronomy Journal (https://dl.sciencesocieties.org/publications/aj/tocs/106/2), noting that the EEFs provided: i) an inconsistent effect on crop production, ii) increased crop N use efficiency, and iii) mixed impacts on N_2O. Those authors observed that reduced N_2O emissions often occurred immediately following fertilizer application compared to the reference non-EEF material, and noted that the rainfall pattern during the remainder of the growing season may determine the overall efficacy of these materials in different cropping systems and soils.

Tables 1, 2, and 3 illustrate the wide ranges in crop yield responses to EEFs in recently published reports, and they expose the challenges of simultaneous measurement of three environmental N losses in the same study. Table 1 illustrates recent data on nitrification and urease inhibitor EEF effects. Table 2 includes results from recent studies involving polymer coating EEF and related technologies. Table 3 contrasts fertilizer N (with or without EEF technologies) with manure N, and also includes examples of some other improved fertilizer N technologies and/or fertilizer management combinations. Sizeable, but variable, environmental N loss reduction opportunities exist with the noted EEF technologies. The list of recent results in Tables 1-3 should not be considered comprehensive, and readers of this report are encouraged to consider the full body of science; to include previously published results of other authors. Research is increasingly revealing that reductions in N losses to the environment, and crop N use efficiency improvements with EEFs employed in a 4R approach, will be site-specific; with benefits varying depending on soil characteristics, cropping system, and climatic/weather conditions (Hatfield and Venterea 2014; Venterea et al. 2016). The purchase and use of EEFs may depend to a great extent on: i) the farmer's cropping system management abilities, ii) the agronomic and environmental knowledge of the agricultural retailer and professional crop adviser, iii) regional crop and fertilizer economics, iv) the soil and water conservation practices also implemented by the farmer on each field, v) nutrient management technology availability and costs, vi) risks and magnitudes of the dominant environmental N losses, and vii) any governmental support or regulatory policies that may affect crop or cropping system choices (Weber and McCann 2015) and/or record-keeping (i.e. tracking) of nutrient performance over time (IPNI Scientists 2014).

Table 1- Examples of recently reported nitrification and urease inhibitor enhanced efficiency nitrogen fertilizer (EEF) impacts on: crop yield, nitrate leaching, ammonia volatilization, and direct nitrous oxide (N_2O) emissions (negative values indicate decreased yield or increased N loss relative to reference conventional sources).

	Range or mean of EEF or technology effect compared to reference conventional source, %				
EEF N technology	**Crop yield increase**	**Nitrate leaching reduction**	**Ammonia volatilization reduction**	**Direct nitrous oxide emission reduction**	**Source of information- review/meta analysis (R) or original study (O)**
nitrification inhibitor	nil to 13				Gagnon et al. (2012)-O
	-6 to 3			24	Burzaco et al. (2013)-O
	7				Linquist et al. (2013)-R
	3	17			Quemada et al. (2013)-R
	<2				Burzaco et al (2014- R & O
				19-100	Snyder et al. (2014)- R
				37 to 44	Lam et al. (2015)-O
	5 to 14	48	-20	44	Qiao et al. (2015)- R
	-3 to -7				Suter et al. (2015)-O
			-3 to -65	8 to 57	Lam et al. (2016)-R
			-38		Pan et al. (2016)-R
	nil			nil to 36	Wang et al. (2016)-O
				-433 to 66	Van der Weerden et al. (2016)-O
urease inhibitor			68		Franzen et al. (2011)-O
	5				Linquist et al. (2013)-R
			25 to 100 (weighted mean 63 with ≥0.02% w/w N-(n-butyl) thiophosphoric triamide)		Saggar et al. (2013)-R
	-17 to -5		23 to 70		Suter et al. (2013)-O
				nil to 5	Snyder et al. (2014)-R
	-4 to 6				Suter et al. (2015)-O
			54		Pan et al. (2016)-R
				-400 to 6	Van der Weerden et al. (2016)-O
urease inhibitor plus nitrification inhibitor	3				Linquist et al. (2013)-R
	-11	-28		18	Maharjan et al. (2014)-O
	nil to 5			25 to 42	Gao et al. (2015)-O

				37 to 46	Snyder et al. (2014)-R
	-2			17	Venterea et al. (2016)-O

Table 2- Examples of recently reported polymer-coated enhanced efficiency nitrogen fertilizer (EEF) impacts on: crop yield, nitrate leaching, ammonia volatilization, and direct nitrous oxide (N_2O) emissions (negative values indicate decreased yield or increased N loss relative to reference conventional sources).

	Range or mean of EEF or technology effect compared to reference conventional source, %				
EEF N technology	**Crop yield increase**	**Nitrate leaching reduction**	**Ammonia volatilization reduction**	**Direct nitrous oxide emission reduction**	**Source of information- review/meta analysis (R) or original study (O)**
polymer coated urea	nil			17 to 39	Hyatt et al. (2010-O)
		-20 to 10		18 to 40	Venterea et al. (2011)-O
	nil to 34				Gagnon et al. (2012)-O
	12 to 30			-28 to 14	Nash et al. (2012)-O
	-1 to 20		38 to 91		Xu et al. (2012)-O
	12 to 22				Yang et al. (2012)-O
	7				Linquist et al. (2013)-R
	7				Nelson and Motavalli (2013)-O
	-15 to 12				Nelson et al. (2013)-O
	-7	34			Quemada et al. (2013)-R
	-3 to 13				Ye et al. (2013)-O
	-10	-41		20	Maharjan et al. (2014)-O
		nil			Nash et al. (2014)-O
				14 to 42	Snyder et al. (2014)-R
	-6 to 5			26	Gao et al. (2015)-O
	3 to 6			29 to 45	Fernandez et al. (2015)-O
	-27 to -10				Suter et al. (2015)-O
	10 to 59				Maharjan et al. (2016)-O
			68		Pan et al. (2016)-R
				-50 to 31	Wang et al. (2016)-O
maleic-itaconic acid copolymer	-5 to nil		-10 to nil		Franzen et al. (2011)-O
	0.05; -5 to 10		nil		Chien et al. (2014)-R

Table 3 - Examples of recently reported enhanced efficiency nitrogen fertilizer (EEF) effects compared to manure, or in combination with some other 4R N management practices on: crop yield, nitrate leaching, ammonia volatilization, and direct nitrous oxide (N_2O) emissions (negative values indicate decreased yield or increased N loss relative to reference conventional sources).

	Range or mean of EEF or technology effect compared to reference conventional source, %				
EEF N technology	**Crop yield increase**	**Nitrate leaching reduction**	**Ammonia volatilization reduction**	**Direct nitrous oxide emission reduction**	**Source of information- review/meta analysis (R) or original study (O)**
Fertilizer N (with or without EEFs) instead of manure N				nil to 81	Snyder et al. (2014)-R
				37 to 112	Van der Weerden et al. (2016)-O
Improved fertilizer N technologies and/or fertilizer management					Quemada et al. (2013)-R
recommended rate and/or, reduced rate, and/or optimal timing, and/or fertigation		40			
controlled release and/or nitrification inhibitor	-1	24			
fertigation	-7	7			
split urea N application, with urease and nitrification inhibitor, and/or 15% reduction of recommended N rate	1.6 to 2.1			20 to 53	Venterea et al. (2016)-O

EEF consumption trends

Trenkel (2010) reported that world consumption of slow- and controlled-release fertilizers increased from an estimated 325,00 tons in 1983 to >2.2 million tons in 2006-2007; with tonnage proportions as follows: China 59%, U.S. 26%, Canada 6%, Western Europe 5%, and Japan <5%. The U.S. consumption of sulfur coated and polymer coated urea increased from about 110,000 tons in 1990 to >400,000 tons in 2009 (Landels 2010). Relying on data from the U.S. Department of Agriculture Resource Management Survey, Weber and McCann (2015) reported that only 10% of the surveyed corn farmers used “N transformation inhibitor”/controlled-release N fertilizer (sources were not separated) in 2010. According to communications with Apostolopoulou (2016) and Heffer (2016), world consumption of slow- and controlled -release fertilizers in 2014 had risen to about 2.9 million tons, with China consumption alone accounting for >60%: while an additional one million tons of stabilized fertilizers were consumed in China in 2014. Environmental concerns and labor shortages are affecting EEF consumption in several regions (Apostolopoulou 2016). As rural workers leave farms for higher paying employment in cities, less labor may be available on farms to make timely split or multiple applications of N in a manner synchronous with crop uptake demand during the crop growing season. This may be causing some farm managers to consider EEFs as a new tool to help address those N timing challenges.

Because of the growing regional demand for EEFs and the advent of new and improved EEF technologies, the 4th International Conference on Slow-and Controlled-Release and Stabilized Fertilizers was held in Beijing, China on 4-6 April 2016 (https://www.newaginternational.com/index.php/conferences/our-conferences/86-2016-new-ag-international-conferences-beijing-china). There has been increased research with 100% polymer coated urea - or different proportions of blends with regular urea - in several different provinces in China during the last seven years. Crop yield increases and improved N recovery efficiency have been evaluated with rice, maize, potato, banana, cotton and sugarcane. Results of work reported at the 2016 conference in Beijing China (Tu 2016) indicate that optimal combinations of controlled release urea (polymer coated urea) with regular urea may allow current N rates to be reduced by 25% with most of those crops, but not with cotton or sugarcane in the provinces investigated.

Nitrogen sensors and variable rate application

The 2013 precision agriculture survey of agricultural retailers in the U.S. by CropLife and Purdue University (https://www.agecon.purdue.edu/cab/ArticlesDatabase/ articles/2013PrecisionAgSurvey.pdf) showed that use of crop N-sensors is relatively low at <10%, although >45% of those same retailers provide variable rate fertilizer applications for their farmer customers. In western Europe, the Yara N-Sensor™ is being used on >1.2 million hectares of the total 104 million cropland hectares in the EU-27 (Snyder et al. 2014 citing personal communication with J. Jasper, 6 February 2014). Sixteen field-scale corn studies in Missouri USA showed possible N rate reductions of 10 to 50 kg/ha when using N-sensors (Roberts et al. 2011). Research with N sensor-based N applications on wheat in Oklahoma USA indicated that N rates were reduced about 60% of the time, and average rate reductions were about 20 kg/ha, compared to typical farmer practice (Butchee et al. 2011). However, neither of those two USA studies included any measurements of N loss via gaseous emissions, nitrate leaching, or runoff. One earlier study in Missouri USA on six grower fields in three different soil regions, showed that applying N at economic optimum rates (as may be determined using N sensors and addressed with variable rate application) resulted in residual soil nitrogen levels at the 0.9m depth that were at least 12 kg/ha lower than with typical farmer-applied N rates (Hong et al 2007).

Snyder et al. (2014) anticipated a heightened probability that N-sensing capabilities by farmers and their service providers would increase in the near future because of the growth in the production and sales of unmanned aerial vehicles (UAVs). Such UAV platforms, when equipped with N-sensing capabilities, may empower farmers and their crop advisers with a greater ability to regularly monitor their crop's N nutritional condition (i.e. greenness or chlorophyll levels). That could raise the prospects for more in-season N applications, to possibly supplement pre-plant or side-dress applications; potentially improving the opportunity for greater crop N recovery and less risk of N loss to the environment (Mulla 2016).

Li et al. (2016) performed an environmental Life Cycle Assessment modeling analyses to estimate the potential impact of sensor-based N fertilization, by relying on corn grain yield and N rate data from a sensor-based variable-rate N experiment on corn in Lincoln County, Missouri, USA. The modeling experiment indicated that sensor-based variable-rate N application could reduce fertilizer N use by 11% with no loss in corn grain yield; while soil N_2O emissions were predicted to be reduced by 10%, volatilized ammonia loss reduced by 23%, and leaching losses of nitrate-N reduced by 16%.

Conclusion

Recent research has shed light on additional N management opportunities that may help raise crop productivity while also limiting environmental N losses. The wide range in the effects on crop yields, N recovery, and reduced risks of N loss reflect the importance of regional or site-specific use of EEFs in 4R N management planning and implementation. There is some evidence of N loss trade-offs with some EEFs (e.g. risk of heightened volatilization of ammonia when using some nitrification inhibitors), which underscores the need for studies that simultaneously measure volatilization, leaching, and N_2O emissions. Such studies could better inform and help ensure accurate parameterization of existing and future N loss models. Coupling EEFs and other 4R N management tools with precision technologies, information systems, and crop growth and N utilization and transformation models – especially models with real-time weather sensitivity - may improve opportunities for refined N management in the future. Many of the EEF technologies and new tools briefly described in this report are still beyond the reach and implementing abilities of many farmers and their professional crop advisers. Several of the mentioned technologies are scale-neutral and applicable to small-holder farmers and larger-scale operations. Challenges remain to get the 4R N management and EEF science extended through more intensive education and outreach programs; which must demonstrate not only the agronomic benefits, but also the economic returns to the farmer, social implications, and environmental N impact reductions.

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