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Review

Enhanced nitrogen fertiliser technologies support the '4R' concept to optimise crop production and minimise environmental losses

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Abstract. Fertiliser 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 fertiliser N use that must be better managed to help meet expanding societal expectations. Nitrogen fertilisers with polymer coatings, or with the addition of urease and/or nitrification inhibitors, or those possessing other characteristics that afford them either improved agronomic response and/or lessened loss of N to the environment (compared with a reference water-soluble fertiliser) may be considered enhanced-efficiency N fertilisers (EEFs). Agronomic and horticultural research with these technologies has been performed for many decades, but it has been primarily in the past decade that research has increasingly also measured their efficacy in reducing N losses via volatilisation, leaching, drainage, run-off and denitrification. Expanded use of EEFs, within the '4R' concept (right source, right rate, right time, right place) of N management may help increase crop yields while minimising environmental N losses. Coupling these 4R N management tools with precision technologies, information systems, crop growth and N utilisation and transformation models, especially weather models, may improve opportunities for refined N management in the future.

Additional keywords: climate smart agriculture, crop yield, economics, nitrogen recovery, sustainability.

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Introduction

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 minimising the human environmental footprint are improving crop recovery and the overall efficiency and effectiveness of fertiliser N use. Freney (1997) emphasised that in addition to using the appropriate fertiliser N rate, there are multiple ways to achieve such improvements, including: (1) using the correct form and time of application of fertilisers; (2) the use of continuous soil cover; (3) correct tillage, drainage and irrigation, (4) greater knowledge of the effects of biomass burning on grasslands and croplands; (5) using foliar N fertiliser applications; (6) the use of slow- or controlled-release fertilisers; and (7) using urease and nitrification inhibitors. Yet, as noted by Tomich *et al.* (2011), '…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'.

In a review of several options to improve the efficiency of fertiliser N use and to mitigate environmental N losses in Australia, particularly agricultural nitrous oxide (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 maximised by balancing other nutrient supplies to plants.

In good agreement, Robertson and Vitousek (2009) stated that '[m]ismatched timing of N availability with crop need is probably the single greatest contributor to excess N loss in annual cropping systems'. The review by Cameron *et al.* (2013) also agreed, stating that '[c]areful 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 greenhouse gas (GHG) emissions from agricultural cropping systems, has been discussed in reports by Snyder *et al.* (2009) and Flynn and Smith (2010). Snyder and Fixen (2012) also emphasised the effects of balancing N fertilisation with the input needs of other essential nutrients to help optimise crop N recovery, reduce the risks for residual inorganic soil N build-up 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*. 2015). 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 emphasised by Fixen *et al*. (2015), 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 fertiliser N use fosters carbon dioxide (CO_2) capture by crops (International Fertilizer Industry Association (IFA) 2009*b*) 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 overemphasised to the disadvantage of other measures also important to combating climate change, and should be weighed in the balance of GHG emissions associated with the production and use of fertiliser N (Powlson *et al*. 2011). Meta-analyses by scientists in Australia have shown that elevated atmospheric CO_2 levels affect the N cycle and result in increased biological N fixation by legumes (38%), increased above- and below-ground biomass production (24% and 33% respectively), increased plant uptake of fertiliser 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 the effects of elevated atmospheric CO_2 on N_2O emissions from soils, which is especially concerning in view of the large radiative forcing of N_2O (298-fold greater than that of CO_2), its ozone-depleting effects and its $\geq$100-year lifespan in the atmosphere (United Nations Environment Programme (UNEP) 2013).

Renewed and sustained research, education and outreach with an emphasis on crop nutrition 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: (1) lessen crop yield gaps; (2) decrease nutrient management knowledge gaps; and (3) implement actions that lessen environmental N losses.

This paper highlights opportunities to improve crop recovery of applied fertiliser N and to reduce losses of N to the environment by sharing recent (over approximately the past 5 years) examples of published research results addressing management of different N sources, rates, timing and place of application (i.e. the 4Rs (right source, right rate, right time, right place) of fertiliser N stewardship; Bruulsema *et al*. 2009; International Plant Nutrition Institute (IPNI) 2012; Johnston and Bruulsema 2014), with a focus on enhanced-efficiency N fertilisers (EEFs). Relevant literature was identified using Google Scholar and ScienceDirect, with searches on various fertiliser technologies and use of terms similar to those used in searches by Abalos *et al*. (2014), as well as through personal communications with leading researchers in the field. Examples of recent industry N management actions and outcomes, as well as emerging opportunities for crop sensor-based N management, are briefly mentioned.

Improving crop nitrogen recovery and reducing losses

4R nitrogen management: gaining global industry adoption

Inadequate and imbalanced plant nutrition and soil fertility affect agronomic NUE and constrain food production in many parts of the world, perhaps most notably in sub-Saharan Africa (Sanchez 2002; Chikowo *et al*. 2010; Vanlauwe *et al*. 2011). Many partners have aligned through the United Nations Environment Program, '. . .steering dialogues and actions to promote effective nutrient management' (Global Partnership on 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 (Bruulsema *et al*. 2009; IFA 2009*a*, 2009*b*) to provide more consistent fertiliser producer, wholesaler or retailer and agricultural crop adviser, farmer or 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 fertiliser 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), to farmers in China (http://china.ipni.net/topic/4r-publications, accessed 14 May 2017) and other regions where IPNI educational programs are active (http://www.ipni.net/regionalprograms, accessed 14 May 2017).

A prominent example of that voluntary, industry-led 4R-based education and outreach in the US 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/, accessed 14 May 2017).The goal of 'N-Watch' and its partnering and networking approaches is to enable farmers and their professional advisers to improve N management for maximised crop utilisation 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.epa.illinois.gov/topics/water-quality/watershed-management/excess-nutrients/nutrient-loss-reduction-strategy/index, accessed 14 May 2017) while complying with the Illinois Environmental Protection Agency's water quality guidance and rules (http://epa.illinois.gov/topics/water-quality/standards/index, accessed 17 May 2017). A recent paper by McIsaac *et al*. (2016) indicates that there has been a >50% decline in flow-weighted nitrate-N concentrations and loads in the Illinois River since 1990, whereas river flow declined >15%, and the former may reflect increasing NUE 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 approximately 2010 may have contributed to these most recent water quality improvements.

Benefits of EEFs

EEFs encompass 'right source', 'right time' and 'right place' components of the 4R nutrient stewardship concept. Slow- and controlled-release N fertiliser (coated or encapsulated), nitrification inhibitor-treated N fertiliser, urease inhibitor-treated N fertiliser or products treated with both nitrification and urease inhibitors are considered EEF products. Inhibitor-treated N products are sometimes referred to as 'stabilised' N fertilisers (Trenkel 2010; Halvorson *et al*. 2014). The representative products, manufacturing, characteristics and effects of EEFs on nutrient use efficiency have been covered in the review by Trenkel (2010) and will not be repeated here. An agribusiness magazine has recently produced a summary article to categorise the technologies, list the country of origin, and the producing company for many different EEFs used around the world (Wu 2016). 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 stabilised fertilisers, 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 with 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'.

Nationwide projects to evaluate the effects of improved cropping system conservation and nutrient management, including the potential benefits of EEFs on GHG emissions, have been established in Australia (e.g. Nitrous Oxide Research Program (NORP; 2009–12) and the National Agricultural Nitrous Oxide Research Program (NANORP; 2013–16)), as well as in the US (USDA Agricultural Research Service; Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet; 2005 to present; Del Grosso *et al*. 2013; Grace 2016).

In a meta-analysis and review of studies from the early 1970s to 2001, Wolt (2004) reported that the nitrification inhibitor nitrapyrin on average increased crop yield 7%, increased soil N retention 28%, decreased nitrate-N leaching by 16% and decreased GHG emissions by 51%, but had no effect on agronomic or environmental N performance approximately 25% of the time, compared with N fertilisation without nitrapyrin. A recent global literature synthesis by Pan *et al*. (2016) showed that use of nitrification inhibitors may increase the risks of ammonia volatilisation from some fertiliser N sources. Although nitrification inhibitor use may not increase grain yield, or modestly (7%) increases grain yield (Thapa *et al*. 2016), better cropping system performance may be reflected in indicators of increased NUE (Burzaco *et al*. 2014), such as 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, namely *N*-(*n*-butyl)thiophosphoric triamide (NBPT; tradename Agrotain; Koch Agronomic Services, Wichita, KS, USA), and summarised multiple studies on reduced ammonia emissions with NBPT in grazed pastures (primarily in New Zealand) that were fertilised 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) fertilisers 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 the 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; Suter *et al*. 2013; Maharjan *et al*. 2016). Hatfield and Venterea (2014) provided a synopsis of the special section on EEFs that was published in the *Agronomy Journal*, noting that the EEFs had an inconsistent effect on crop production, increased crop NUE and had mixed effects on N_2O. Hatfield and Venterea (2014) observed that reduced N_2O emissions often occurred immediately following fertiliser application compared with 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.

Recent field effectiveness and prospects with EEFs and other 4R tools

Tables 1–3 list the wide range in crop yield responses to EEFs in recently published reports and expose the challenges of simultaneous measurement of three environmental N losses in the same study. Table 1 lists recent data on the effects of nitrification and urease inhibitor EEFs, Table 2 includes results from recent studies involving polymer-coated EEFs and related technologies and Table 3 contrasts fertiliser N (with or without EEF technologies) with manure N, and includes examples of some other improved fertiliser N technologies and/or fertiliser management combinations.

Table 1. Examples of recently reported effects of nitrification and urease inhibitor enhanced-efficiency nitrogen fertiliser (EEF) on crop yield, nitrate leaching, ammonia volatilisation and direct nitrous oxide (N_2O) emissions

Negative values indicate decreased yield or increased N loss relative to reference conventional sources. R, review or meta-analysis; O, original study; NBPT, *N*-(*n*-butyl)thiophosphoric triamide

EEF N technology	Range or mean effect of EEF or technology vs reference conventional source (%)				Reference	Type of study
	Crop yield increase	Nitrate leaching reduction	Ammonia volatilisation reduction	Direct N_2O emission reduction		
Nitrification inhibitor	0–13				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
	–5.5 to –1.2			63	De Antoni Migliorati *et al.* (2014)	O
				19–100	Snyder *et al.* (2014)	R
				37–44	Lam *et al.* (2015)	O
	5–14	48	–20	44	Qiao *et al.* (2015)	R
	–3 to –7				Suter *et al.* (2015)	O
	4.5				Abalos *et al.* (2014)	R
	–5 to 1			0–60	Harris *et al.* (2016)	O
	0	0		17–56	Jamali *et al.* (2016)	O
			–3 to –65	8–57	Lam *et al.* (2016)	R
	3				Lester *et al.* (2016)	O
			–38		Pan *et al.* (2016)	R
	–1.6 to 8			32–83	Scheer *et al.* (2016)	O
	7			38	Thapa *et al.* (2016)	R
				–433 to 66	van der Weerden *et al.* (2016)	O
	–5.5 to 7.8			0	Wang *et al.* (2016*a*)	O
	0			0–36	Wang *et al.* (2016*b*)	O
Urease inhibitor			68		Franzen *et al.* (2011)	O
	5				Linquist *et al.* (2013)	R
			25–100 (weighted mean 63 with ≥0.02% w/w NBPT		Saggar *et al.* (2013)	R
	–17 to –5		23–70		Suter *et al.* (2013)	O
				0–5	Snyder *et al.* (2014)	R
	–4 to 6				Suter *et al.* (2015)	O
	10				Abalos *et al.* (2014)	R
			54		Pan *et al.* (2016)	R
	<2		0–36		Thapa *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
	0–5			25–42	Gao *et al.* (2015)	O
				37–46	Snyder *et al.* (2014)	R
	9				Abalos *et al.* (2014)	R
	0			30–34	Thapa *et al.* (2016)	R
	–2			17	Venterea *et al.* (2016)	O

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 are encouraged to consider the full body of science to include previously published results of other authors as well as more recent research results. Research is increasingly revealing that reductions in N losses to the environment, and crop NUE improvements with EEFs used in a 4R approach, will be site specific, with benefits varying depending on soil characteristics, cropping system and climatic or weather conditions (Hatfield and Venterea 2014; Venterea *et al*. 2016). The purchase and use of EEFs may depend to a great extent on: (1) the farmer's cropping system management abilities; (2) the agronomic and environmental knowledge of the agricultural retailer and professional crop adviser; (3) regional crop and fertiliser economics; (4) the soil and water conservation practices also implemented by the farmer on each field; (5) the availability and costs of nutrient management technology; (6) risks and magnitudes of the dominant environmental N losses; and (7) 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; Norton *et al*. 2015).

Table 2. Examples of recently reported effects of polymer-coated or polymer nanocomposite enhanced-efficiency nitrogen fertiliser (EEF) on crop yield, nitrate leaching, ammonia volatilisation and direct nitrous oxide (N_2O) emissions

Negative values indicate decreased yield or increased N loss relative to reference conventional sources. R, review or meta-analysis; O, original study; PCL, polycaprolactone

EEF N technology	Range or mean effect of EEF or technology vs reference conventional source (%)				Reference	Type of study
	Crop yield increase	Nitrate leaching reduction	Ammonia volatilisation reduction	Direct N_2O emission reduction		
Polymer-coated urea	0			17–39	Hyatt *et al.* (2010)	O
		–20 to 10		18–40	Venterea *et al.* (2011)	O
	0–34				Gagnon *et al.* (2012)	O
	12–30			–28 to 14	Nash *et al.* (2012)	O
	–1 to 20		62–91		Xu *et al.* (2013)	O
	12–22				Yang *et al.* (2012)	O
	7				Linquist *et al.* (2013)	R
	7				Nelson and Motavalli (2013)	O
	–15 to 12				Nelson *et al.* (2014)	O
	–7	34			Quemada *et al.* (2013)	R
	–3 to 13				Ye *et al.* (2013)	O
	–10	–41		20	Maharjan *et al.* (2014)	O
		0			Nash *et al.* (2014)	O
				14–42	Snyder *et al.* (2014)	R
	–6 to 5			26	Gao *et al.* (2015)	O
	3–6			29–45	Fernández *et al.* (2015)	O
	–27 to –10				Suter *et al.* (2015)	O
	10–59				Maharjan *et al.* (2016)	O
			68		Pan *et al.* (2016)	R
	0			70	Scheer *et al.* (2016)	O
	0			19	Thapa *et al.* (2016)	R
	–3.5 to 3.9			0	Wang *et al.* (2016*a*)	O
				–50–31	Wang *et al.* (2016*b*)	O
Maleic–itaconic acid copolymer	–5 to 0		–10 to 0		Franzen *et al.* (2011)	O
	0.05; –5 to 10		0		Chien *et al.* (2014)	R
Nanocomposite of polyacrylamide hydrogel or PCL				70–95	Pereira *et al.* (2015)	O

EEF consumption trends

Trenkel (2010) reported that world consumption of slow- and controlled-release fertilisers increased from an estimated 325 000 tons in 1983 to >2.2 million tons in 2006–07, with tonnage proportions as follows: China 59%, US 26%, Canada 6%, Western Europe 5% and Japan <5%. The US consumption of sulfur-coated urea and PCU increased from approximately 110 000 tons in 1990 to >400 000 tons in 2009 (Landels 2010). Relying on data from the USDA Resource Management Survey, Weber and McCann (2015) reported that only 10% of the surveyed corn farmers used ‘N transformation inhibitor’ or controlled-release N fertiliser (sources were not separated) in 2010. According to communications with E. Apostolopoulou (Senior Consultant, IHS Chemical, London, UK) and P. Heffer (IFA, Paris, France), world consumption of slow- and controlled-release fertilisers in 2014 had risen to approximately 2.9 million tons, with consumption in China alone accounting for >60%; an additional 1 million tons of stabilised fertilisers was consumed in China in 2014. Environmental concerns and labour shortages are affecting EEF consumption in several regions (E. Apostolopoulou, pers. comm.). As rural workers leave farms for higher-paying employment in cities, less labour 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 Stabilised 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, accessed 14 May 2017). There has been increased research with 100% PCU, or different proportions of blends with regular urea, in several different provinces in China over the past 7 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 by Tu (2016) indicate that optimal combinations of controlled-release urea (PCU) 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.

Table 3. Examples of recently reported effects of enhanced-efficiency nitrogen fertiliser (EEF) compared with manure, or in combination with some other 4R (right source, right rate, right time, right place) N management practices or cropping system management, on crop yield, nitrate leaching, ammonia volatilisation and direct nitrous oxide (N_2O) emissions

Negative values indicate decreased yield or increased N loss relative to reference conventional sources. R, review or meta-analysis; O, original study

EEF N technology	Range or mean effect of EEF or technology vs reference conventional source (%)				Reference	Type of study
	Crop yield increase	Nitrate leaching reduction	Ammonia volatilisation reduction	Direct N_2O emission reduction		
Fertiliser N (with or without EEFs) instead of manure N				0–81 37–112	Snyder *et al.* (2014) van der Weerden *et al.* (2016)	R O
Improved fertiliser N technologies and/or fertiliser 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				
Urease inhibitor, with irrigation				30	Thapa *et al.* (2016)	R
Urease inhibitor, rain-fed only				0		
Urease inhibitor plus nitrification inhibitor, with irrigation				45		
Urease inhibitor plus nitrification inhibitor, rain-fed only				17		
Urease inhibitor plus nitrification inhibitor, banded subsurface application				45		
Urease inhibitor plus nitrification inhibitor, broadcast application				14		
Nitrification inhibitor, single application	0			26		
Nitrification inhibitor, split application	7.3			53		
Split urea N application, with urease and nitrification inhibitor and/or 15% reduction of recommended N rate	1.6–2.1			20 to 53	Venterea *et al.* (2016)	O

Nitrogen sensors and variable rate application

The use of precision agriculture technologies to better manage the spatial and temporal variations in crop N nutrition has received considerable global attention. For example, summaries of national and regional surveys of the broad-acre grain industry conducted from 2006 to 2009 in Australia showed that the adoption of variable-rate fertiliser technology (which included the use of crop sensor-based technologies) had increased from <5% estimated 6 years earlier to an average of 20%, ranging from 11% to 35% depending on the region (Robertson *et al.* 2012). Issues affecting precision agriculture N technology adoption by the grain industry in Australia include the costs of the technologies, the relatively low rates of N application in some regions, an inability to accurately sense grain protein on the go (which hampers the development of accurate N budgets), equipment and software incompatibilities (Bramley and Trengrove 2013) and much larger variation (i.e. greater uncertainty) in the predictive performance of crop N and biomass sensing technologies in broad-acre paddocks compared with prediction capabilities observed previously in small-plot research (Perry *et al.* 2012). Challenges in accurately assessing the crop and soil moisture status, and large uncertainties in growing season rainfall predictions, pose both limitations to and opportunities for the adoption of precision agriculture N technology. Accurate sensing of the soil and crop water status may be prerequisite to improving the efficiency of N applications with variable-rate N technologies to avoid costly N applications to water-limited crops or under highly variable rainfall conditions (Tilling *et al.* 2007).

The 2013 precision agriculture survey of agricultural retailers in the US by CropLife and Purdue University (http://agribusiness.purdue.edu/search?q=precisionag+survey, accessed 14 May 2017) showed that the use of crop N sensors is relatively low at <10%, although >45% of those same retailers provide variable-rate fertiliser applications for their farmer customers. In Western Europe, the Yara N-Sensor (Yara UK Limited, N E Lincolnshire, UK) is being used on >1.2 million hectares of the total 104 million cropland hectares in the EU-27, which comprises the following European Union member states: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom (Snyder *et al.* 2014). Sixteen field-scale corn studies in Missouri (USA) showed possible N rate reductions of 10–50 kg ha^{-1} when using N sensors (Roberts *et al.* 2010). Research with N sensor-based N applications on wheat in Oklahoma (USA) indicated that N rates were reduced approximately 60% of the time, with average rate reductions of approximately 20 kg ha^{-1}, compared with typical farmer practice (Butchee *et al.* 2011). However, neither of those two US studies included any measurements of N loss via gaseous emissions, nitrate leaching or run-off. One earlier study in Missouri 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 0.9 m depth that were at least 12 kg ha^{-1} 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 the N nutritional condition of their crops (i.e. greenness or chlorophyll levels). That could raise the prospects for more in-season N applications to possibly supplement pre-planting or side-dressing 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 modelling analysis to estimate the potential effect of sensor-based N fertilisation by relying on corn grain yield and N rate data from a sensor-based variable-rate N experiment on corn in Lincoln County (MO, USA). The modelling experiment indicated that sensor-based variable-rate N application could reduce fertiliser N use by 11% with no loss in corn grain yield, whereas soil N_2O emissions were predicted to be reduced by 10%, volatilised ammonia loss was reduced by 23% and leaching losses of nitrate-N were reduced by 16%.

Discussion

Recent research has shed light on additional N management opportunities that may help raise crop productivity while 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 volatilisation of ammonia when using some nitrification inhibitors), which underscores the need for studies that simultaneously measure volatilisation, leaching and N_2O emissions. Such studies could better inform and help ensure accurate parameterisation 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 utilisation 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 herein are still beyond the reach and implementing abilities of many farmers and their professional crop advisers. Several of the technologies mentioned are scale neutral and applicable to both smallholder 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 reductions in environmental N effects.

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