IFA International Workshop on Enhanced-Efficiency Fertilizers
Frankfurt, Germany, 28-30 June 2005

POLICY ASPECTS RELATED TO THE USE OF ENHANCED-EFFICIENCY FERTILIZERS: VIEWPOINT OF THE SCIENTIFIC COMMUNITY

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Introduction

One of the most important challenges facing humanity today is that of increasing food production while avoiding environmental degradation. As the world's population grows, the crop yield on land currently under production must be increased to maintain food security without converting marginal land or natural ecosystems to agriculture. This increase in production will require an adequate supply of plant-available nitrogen (N) to support both crop yield potential and nutritional quality. Therefore, N fertilization will play a critical role in improving crop yields and ensuring food security (Mosier et al., 2004). Inorganic fertilizer is the single largest input into the global N cycle (Smil 1999). Currently, it is estimated that cereal crops recover only about 30 to 50 % of applied fertilizer N (Cassman et al., 2002). Without major improvement in nitrogen use efficiency (NUE), increasing N inputs may lead to negative environmental impacts as the inorganic N moves from the soil-plant system to the air or water (Cassman et al., 2002).

Losses of Nitrogen from Agricultural Systems

Regardless of the form of N supplied to the system, the majority of N is taken up by the plant as inorganic ammonium or nitrate - N. Most chemical N fertilizers are applied directly as ammonium (NH4+) and nitrate (NO3-), or as urea, which converts rapidly to NH4+ through the action of the urease enzyme. Therefore, N fertilizers move rapidly into the pool of plant-available soil solution N (Figure 1).

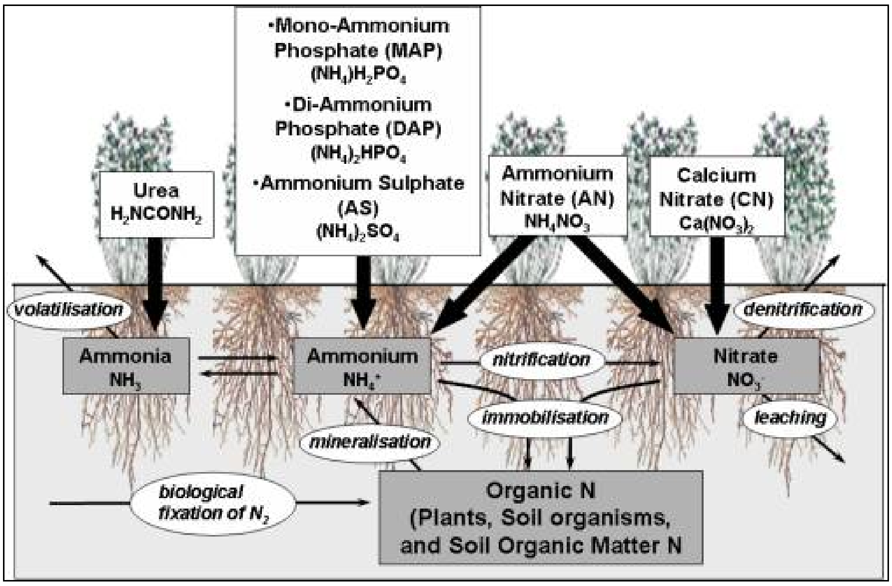

Figure 1: The Nitrogen Cycle
(http://www.grdc.com.au/growers/res_upd/south/04S/baldock.htm)

The longer inorganic N is in the soil solution before plant uptake, the greater the potential for losses, particularly under wet conditions. In the soil, ammonium is rapidly converted to the nitrate form. Nitrate may leach if moisture supply is sufficient to move the nitrate below the rooting zone. Both ammonium and nitrate may be utilized by soil microorganisms and converted to organic forms through immobilization. Nitrogen may be lost as NO and N2O, produced biologically through nitrification and denitrification (Harrison 2001). Also, nitrate sources may be denitrified to N2 under anaerobic conditions (Smil 1999). Anaerobic conditions may occur in the bulk soil or in microsites if soils are wet, flooded or compacted.

Practices for Reducing N losses and Enhancing NUE

One of the simplest and most effect methods of improving NUE is to avoid over-application of N, as N losses tend to be proportional to solution concentration. Yield response to fertilizer generally follows a pattern of diminishing returns, with NUE being greatest at low rates of application, when yield is primarily limited by N supply (Cassman et al., 2002). As the N supply increases relative to the N requirements of the crop, the response to each increment of N applied decreases, and NUE falls. In the developed countries, N application rate is often high relative to the N requirements of the crop and NUE may be relatively low. In contrast, N application rate in some developing countries such as sub-Saharan Africa are often low relative to the N demand and NUE is high. Suboptimal levels of N application will reduce yield potential, profitability, and may lead to long-term nutrient depletion and organic matter decline. Conversely, continued application of N above agronomically necessary rates will reduce economics of production and increase risk of movement of N from the soil to the air and water. Improved prediction of N requirements and N rates matched more closely to crop needs are critical to optimize crop yield and NUE.

In principle, N use by plants will be optimized and N losses minimized if N supply is closely matched with N demand by the plant in timing as well as in rate. Synchrony between plant-available N in the rooting zone and the crop uptake of N, in rate and timing, will minimise N losses prior to plant uptake. Use of split applications, where N is applied in small increments frequently during the growing season rather as than a single large application at the beginning of the season, can be used to more closely match N supply with the period of maximum N demand (Power et al., 2000). In rice production, split applications of N may be used to improve the synchrony between N supply and crop N uptake (Cassman et al., 2002) and to reduce the concentration of ammonia in the water and thus reduce volatilization. Use of in-crop sensors to detect N deficiency of the crop can allow for improved prediction of N requirements and better timing of in-crop applications (Cassman et al., 2002; Power et al., 2000).

With high value crops equipped with drip irrigation systems, N may be added efficiently in the irrigation water to respond to crop requirements (Neilsen et al., 2002), but split applications can also be applied with trickle and centre pivot systems in lower-value irrigated crops. However, multiple applications of fertilizer may be impractical for lower value crops in non-irrigated broad area agriculture, due to the cost associated with the extra applications. In drier regions where rainfall is erratic, in-crop applications may be stranded on the soil surface and not be taken up effectively by the crop. Foliar fertilization may be effective in applying relatively small amounts of N, for example for protein enhancement, but may not be able to supply the bulk of N to support crop yield. Surface applications may also be lost by volatilization or immobilized on surface residues. Volatilization losses from surface applications can be minimized by selecting nitrate-based fertilizers rather than urea or ammonium-based fertilizers.

Table 1: Effect of N fertilizer source, placement and timing on N removal in the grain under reduced- and conventional-tillage (RT and CT) management over four years on a clay loam soil (Grant et al., 2001)

Treatment	1992		1993		1994		1995	
	CT	RT	CT	RT	CT	RT	CT	RT
	----------------kg ha $^{-1}$----------------							
NH_3-Spring Band	53.1	52.5	63.4	50.8	81.7	71.7	70.7	67.6
UAN-Spring Band	63.2	50.8	63.0	54.3	87.1	69.2	65.0	53.1
Urea-Spring Band	60.8	55.3	65.0	54.7	77.2	70.8	56.8	51.1
UAN-Dribble Band	58.9	48.8	64.1	52.9	79.7	52.8	65.0	38.8
Urea-Dribble Band	57.9	52.3	51.8	40.6	82.1	50.4	68.8	40.3
AN-Dribble Band	55.6	60.7	50.2	46.3	78.3	44.4	64.6	37.7
AN-Broadcast	55.1	45.3	57.1	47.1	75.2	48.8	64.0	41.5
Urea-Broadcast	60.9	46.9	63.1	55.2	78.2	45.4	65.5	37.9
Control - No N, P Banded	53.0	37.2	39.3	35.1	60.2	44.3	43.5	30.2
SEM (Fertilizer within column)	5.09	3.42	5.00	4.05	4.06	4.78	2.41	3.00
SEM (Tillage within year)	2.89^{y}		3.47		4.24**		0.89***	
Contrast	Probability values from orthogonal contrasts							
N vs no N	ns	0.0295	0.0001	0.0001	0.0001	0.0062	0.0001	0.0001
Spring NH_3 vs UAN	ns	ns	ns	ns	ns	ns	0.0982	0.0011
Spring NH_3 vs urea	ns	ns	ns	ns	ns	ns	0.0002	0.0003
Spring UAN vs urea	ns	ns	ns	ns	0.0912	ns	0.0207	ns
Band vs surface urea	ns	0.0611	ns	0.0884	ns	0.0001	0.0001	0.0001
Band vs surface UAN	ns	ns	ns	ns	ns	ns	ns	0.0070
Urea vs AN	ns	ns	ns	ns	ns	ns	ns	ns
Surface UAN vs urea	ns	ns	ns	ns	ns	ns	ns	ns
Surface UAN vs AN	ns	ns	0.0935	ns	ns	ns	ns	ns

$^{y.}$ SEM values followed by †, *, ** and *** indicate that tillage systems differ at significance level of $p<0.1$, 0.05, 0.01 and 0.001, respectively

While split applications timed to N demand of the crop may potentially provide improved NUE, in annual cropping N is often applied as a single application prior to or at the time of seeding. The longer the fertilizer is applied prior to crop uptake the greater the potential for losses of N from the cropping system. In-soil banding or rapid incorporation of ammonia or ammonium-producing sources can reduce volatilization losses to low levels, as will irrigation after application to move the fertilizer below the soil surface. Similarly, in rice production, flooding of the fields within two days of fertilizer application can reduce volatilization losses (Carreres et al., 2004).

Leaching and denitrification losses occur once N is in the nitrate form. Gaseous losses of N may occur during both the nitrification and denitrification process (Dalal et al., 2003), with the amount and form of loss dependant on soil moisture. The nitrous oxide (N_2O) loss is usually low below about 40% water filled pore capacity (WFPC) (Dalal et al., 2003). Nitrous oxide emissions increase with increasing soil moisture between 40% and 60-70% WPPC. As moisture increases above this 60-70%, reduced aeration enhances denitrification and both N_2O and N_2 will be emitted, with N_2 emissions dominating above 90% WFPC.

Applying ammonium or ammonium-producing sources as an in-soil band will minimise access of soil microorganisms to the fertilizer and slow nitrification. Thus, banding can improve NUE and reduce gaseous losses to the atmosphere, nitrate leaching to groundwater and N fertilizer required to optimize crop yield (Table 1) (Grant et al., 2001; Grant et al., 2002; Hou et al., 2003; Power et al., 2000). However, in-soil banding may not be possible for established pastures, and may be problematic in some no-till systems and with winter annual crops. In-soil banding requires an additional operation, increasing fuel and labour costs. The disturbance associated with banding may reduce soil moisture and disrupt seed-bed integrity. Pressure injection of liquid fertilizers could avoid this problem. One-pass seeding and fertilising systems are widely used to avoid the extra operation, but the cost of the equipment and the draft required is greater than for traditional seeding equipment.

Role of Enhanced Efficiency Fertilizers

Various types of enhanced efficiency fertilizers are available that provide alternative methods of improving NUE by slowing volatilization, inhibiting nitrification or controlling the rate of release of N fertilizer into the soil solution. Thus, enhanced efficiency fertilizers can reduce losses of N fertilizers by matching N supply with crop demand.

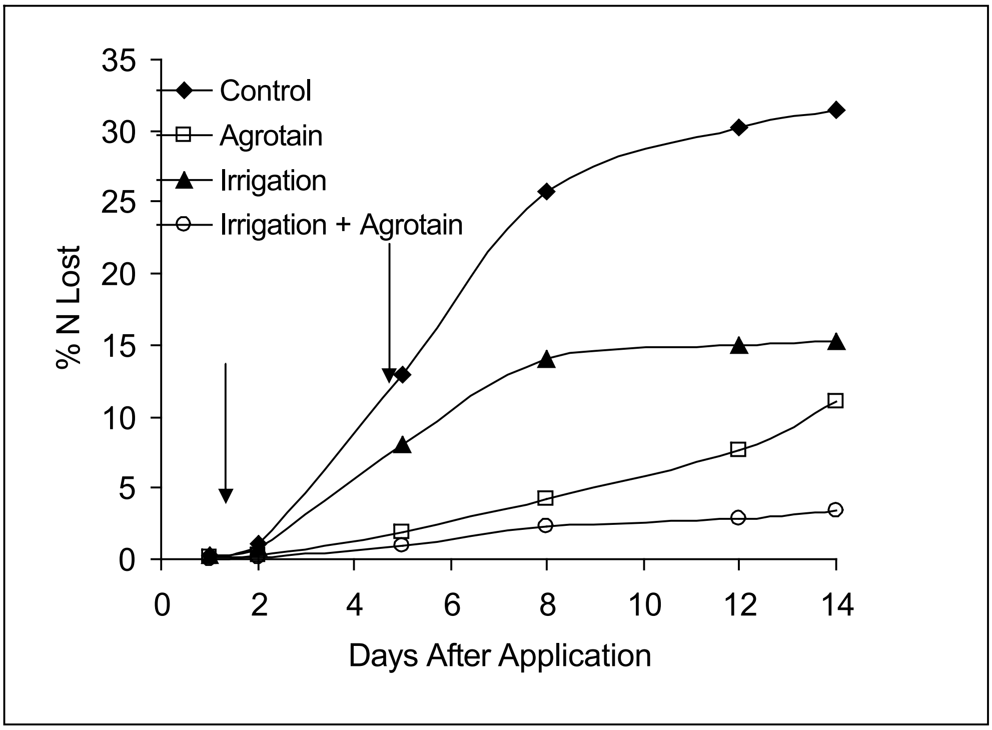

Figure 2: Effect of NBPT and simulated rainfall (2.0 cm on day 4 and day 7) on volatilization losses from surface applied urea fertilizer (Rawluk 2000)

Rate of hydrolysis of urea and the soil pH surrounding the application site are the major factors influencing volatilization of urea (Harrison 2001). Therefore, slowing the rate of urea hydrolysis through the use of urease inhibitors can reduce volatilization losses from surface applications of urea fertilizers (Watson et al., 1994). Urease inhibitors will have the greatest benefit in reducing volatilization in situations where incorporation is difficult, where there is little opportunity for urea to move into the soil with infiltrating water, or where the soil has a high urease activity because of lack of cultivation or the accumulation of organic material (Byrnes et al., 1995).

Delaying urea hydrolysis will provide time for rainfall to move the urea into the soil where the released ammonia will be protected from movement to the atmosphere (Figure 2) (Grant et al., 1996;Rawluk 2000; Rawluk et al., 2001; Watson et al., 1994;).Urease inhibitors can improve the efficiency of split applications of urea by reducing volatilisation losses from surface applications. In lowland rice production, urease inhibitors can reduce ammonia concentration in the water, thus reducing potential volatilization (Buresh et al., 1988). Benefit from urease inhibitors in enhancing rice yield has been erratic, possibly because the inhibition period was too short, the urea hydrolyzed before the N-(n-butyl) thiophosphoric acid triamide (NBPT) was converted to its active oxygen analog (NBPTO), or because denitrification of conserved N reduced the yield response (Byrnes and Freney 1995).

Losses of N_2O from NH_4^+ or NH_4^+ -producing fertilizers may be reduced by use of a nitrification inhibitor such as nitrapyrin, dicyandiamide (DCD), or acetylene (Clayton et al., 1997; Freney et al., 2000;Magalhaes et al., 1984; McTaggart et al., 1997; Shoji et al., 2001). Nitrification inhibitors slow the oxidation of NH_4^+ to NO_3^- and so directly reduce the amount of N_2O released. They also reduce denitrification by reducing the amount of NO_3^- that is present in the soil solution (McTaggart et al., 1997). Benefits of inhibition will be greatest under conditions that promote losses by leaching and denitrification, for example under wet soil conditions. The longer the fertilizer remains in the ground before crop uptake, the greater the potential benefit for use of an inhibitor, so inhibitors have been of more consistent benefit with fall applications (Wolt 2000). Use of a urease inhibitor in combination with a nitrification inhibitor can prolong the process further, by slowing the conversion of urea to ammonium.

Table 2: Effect of fertilizer treatments on partial factor productivity of N applied and agronomic nitrogen-use efficiency (g g^{-1} N) for 1997 and 1998, in Indica rice (adapted from (Fashola et al., 2002)

Water	1997			1998		
Treatment	POCU	Urea	LSD 5%	POCU	Urea	LSD 5%
	PFP[1]					
GWM	66.9	68.5	ns	59.0	54.9	ns
PWM	62.9	52.8	7.3*	57.2	43.4	4.6*
	ANUE[2]					
GWM	49.7	51.3	ns	40.5	36.5	ns
PWM	36.9	26.8	ns	35.0	21.2	12.8*

[1]Partial factor productivity (PFP): Yield=Nx .

[2]Agronomic nitrogen use efficiency (ANUE): Yield at Nx-yield at No=applied N at Nx.

GWM: Good water management. PWM: Poor water management.

**Significant at 5% level, ns not significant.*

Controlled or slow release nitrogen can also be effective in increasing NUE. In flooded rice systems, slow release of urea from the fertilizer granule can reduce the concentration of ammonia in the solution decreasing the volatilization gradient (Wakimota 2004). Under relatively low input systems with poor water management, controlled release urea reduced N losses from leaching and run-off and allowed for greater yield with lower levels of N, even as compared to split applications of urea (Table 2) (Fashola et al., 2002). By allowing effective N utilization with a single basal application in rice, as compared to split applications, controlled or slow release products can be effective management tools where supplies of N or labour are limited.

In upland production systems, use of controlled release fertilizers to slow the release of the nitrogen into the soil solution can also improve NUE and reduce the risk of losses by leaching or denitrification (Guertal 2000; Mikkelsen et al., 1994; Nyborg et al., 1999; Shaviv 2001). The controlled release products can allow producers to increase the crop yield per unit of N applied By controlling the release of the fertilizer over the growing season, controlled release products can substitute for split applications, reducing the requirement for multiple field operations, reducing time, labour and fuel costs (Guertal 2000; Shoji et al., 2001). In addition to the benefits obtain by the producer, controlled release fertilizers also can provide significant environmental benefits, through reduced nitrate leaching (Guertal 2000; Shuman 2003) and reduced emissions of NO_x gases (Delgado et al., 1996; Shoji et al., 2001).

Table 3: Effect of N fertilizer applied as uncoated urea, urea treated with Agrotain, or polymer coated urea (CRU) on stand density and grain yield of durum wheat (adapted from (Malhi et al., 2003)

N Rate	Stand Density			Grain Yield		
kg ha^{-1}	----------------plants m^{-2}----------------			-------------------- kg ha^{-1} -------------------		
	Urea	Agrotain	CRU	Urea	Agrotain	CRU
28	88.2	90.6	93.4	1491	1844	1877
56	47.3	88.9	95.5	1169	2249	2300
81	34.6	79.4	83.5	1075	2571	2519
112	30.2	67.8	78.5	1028	2365	2571
140	28.7	61.5	70.4	891	2309	2414
LSD$_{0.05}$	N rate=4.54***; Urea Source=4.54*** N Rate x Source = 10.17***			N rate=124.1***; Urea Source=124.1*** N Rate x Source = 277.4***		

Another niche for enhanced efficiency fertilizers may be with seed-placed application of N (Table 3). Excess application of N fertilizers can lead to seedling damage, through direct ammonia toxicity or osmotic effects. Use of urease inhibitors or slow release products can reduce seedling damage by reducing the concentration of ammonia/ammonium close to the seed (Wang et al., 1995) In field studies, both urease inhibitors and coated products reduced seedling damage and led to improved crop yield as compared to conventional urea (Malhi et al., 2003).

For crops such as wheat, where high protein content may be an important quality consideration, protein premiums may encourage rates of N application above the agronomic optimum. Use of slow release fertilizers could be used to ensure that N is available late in the season to enhance protein, while avoiding inefficiencies due to excess N in the soil solution during the early stages of growth.

Controlled release phosphorus products are also available that release P slowly into the soil solution (Diez et al., 1992). These products may be effective in improving the P use efficiency on soils where P availability is reduced through fixation into relatively insoluble sources (Pauly et al., 2002). This may be of particular benefit on highly calcareous soils, where P fertilization has proven problematic.

Benefits of Enhanced Efficiency Fertilizers

As discussed previously, enhanced efficiency N fertilizers can be effective tools to chemically or physically influence the movement and transformations of N in order to reduce losses. This requires that the pathways of loss within the system are characterized so that technology can be applied where the benefits will be the greatest. While there are a number of management practices that can be used to increase NUE, enhanced efficiency fertilizers have some specific advantages over alternative methods.

1) Enhanced efficiency fertilizers can allow for presence of minimal concentration of inorganic N in the soil solution, reducing the potential for loss and negative environmental impact.
2) Enhanced efficiency fertilizers can substitute for capital investment in specialised machinery. They can be used with current equipment, or may allow the use of simplified, less expensive equipment or practices (eg. seed-placed as compared to mid-row or side-band systems; surface applications rather than in-soil band).
3) Enhanced efficiency fertilizers can allow for reduction of labour. They may allow for one-pass seeding/fertilizing in direct tilling systems or eliminate the need for repeated passes and extra labour for split applications in a range of production systems.
4) Enhanced efficiency fertilizers increase the flexibility in the timing of application, so fertiliser can be applied efficiently in a single application during a much broader window.
5) Use of enhanced efficiency fertilizers can avoid the potential for "missing" window of application for split applications due to poor weather, physical condition of the field or time constraints
6) Enhanced efficiency fertilizers potentially can be used to selectively supply N to the crop as NH_4^+ or NO_3^-, for crops that have a preference for a specific ratio of N form.
7) Enhanced efficiency fertilizers do not require specialized knowledge, such as assessment of crop N level in season or determination of best physiological timing of applications.

Enhanced efficiency fertilizers can be used in combination with other technologies to optimise efficiency. For example, in-soil banding of inhibited or controlled release products can capture benefits both of the banding action and of the slow release, allowing fertilizers to remain in the soil for a longer period with reduced losses. This allows the producer and the industry to distribute operations when resources are in lower demand, improvising the efficiency of use of capital investments and available labour.

As compared to split applications, use of slow release production or inhibitors with all N applied prior to seeding still requires assessment of yield potential at the time of nutrient application. Therefore, it leaves the system sensitive to changes in yield potential which can result in either excess or inadequate application use of urease inhibitors with split applications of N and methods of in-crop analysis of N deficiency can allow for split applications to reduce the N application prior to seeding or to more closely match N application to crop demand, while reducing the risk of volatilisation losses from surface applications.

Constraints to Use of Enhanced Efficiency Fertilizers

The major constraint associated with the wide-spread use of enhanced efficacy fertilizers is the cost of the products. Currently, in North America and Europe, most controlled release fertilizers are used in non-farm uses such as golf courses, home gardening, landscaping and nurseries, where the perceived benefit relative to the cost of the technology is high (Shaviv 2001). There is also some utilization in high-value cash crops such as vegetable and fruit crops, particularly on light soils or where labour costs are high. Usage of both controlled release fertilizers and inhibitors in rice production is increasing. However, general adoption for lower value crops is still limited by the technology cost.

Analysis of the benefits of the use of enhanced efficiency fertilizers as compared to alternative methods of reducing must consider not just the cost of the material, but also factors such as differences in machinery costs, impact on time, labour, fuel costs and efficiency of operations, differences in impact on seed-bed, soil moisture or other agronomic factors, and management skill required to apply the technologies. It is important that a production system optimises the use of all available resources. The relative value of any resource varies with scarcity. For example, use of labour and time in place of capital is more attractive in environments where labour is plentiful and relatively inexpensive. Adoption of technologies to increase NUE varies substantially form region to region, as the limitations and relative costs associated with various practices changes. As the cost of the factors conserved with the enhanced efficiency fertilizers increases, the relative benefit of the technology will increase. Therefore, the current trends towards increasing energy costs, increased cost of fertilizer N, and scarcity of agricultural labour will make enhanced efficiency fertilizers more attractive.

Currently, the value of the enhanced efficacy fertilizers is primarily based on the increased yields or reduced production costs to the farmer. In many jurisdictions the environmental benefits to society are not ascribed an economic value. Life cycle analysis is needed to more clearly define the costs and benefits throughout the system associated with adoption of enhanced efficiency, including manufacturing, emissions on and off farm, transport, and the total potential off-site impacts. Life-cycle analysis could clarify the value to society and provide guidance for methods of transferring some of the costs of development and use of the products to those that benefit from the technology, possibly through subsidies or incentives for adoption of the technology.

Technical constraints that still exist include premature loss in effectiveness of both nitrification inhibitors and urease inhibitors. Another concern is excess delay or too rapid release of N from coated products, leading to a lack of synchrony with crop uptake (Shaviv 2001). Improved control of the release rate and clearer identification of the pattern of release required for different crops in different environments would allow for closer matching of release to crop demand.

Pathways of loss and the magnitude of loss are both influenced by soil characteristics, weather conditions, and crop management practices, as well as the fertilizer source and management used. Large variations in loss can occur even on a small scale within a field, due to variation in drainage and micro-environment (Goulding 2004). Therefore, advantages to use of enhanced efficiency fertilizers will also vary substantially, indicating a clear benefit from the integration of use of enhanced efficacy fertilizers with site specific management techniques.

In addition, there is still significant need for research to define and value the advantages associated with use of enhanced efficacy fertilizers. Quantification of the reduction in application rate possible with enhanced efficiency fertilizers is needed, so that producers can recover a portion of the extra cost of the products by using a lower application rate. Identification of the benefits possible in terms of reduced lodging, reduced disease incidence, controlled maturity, enhanced protein content, changes in oil content and oil quality, and trace element content of the crop will be important in more clearing defining the benefits of the products.

Consideration of Use within a System

Improved NUE will not simply rely on use of improved fertilizer technologies. For crops to take advantage of improved fertilizer efficiency, the overall cropping system must be optimised. Tillage management, crop genetics, pest control, water management and soil tilth must all be managed effectively so that the crop is able to convert the N supplied into usable yield with the greatest efficiency. Yield variability due to environmental stress must be reduced, as the greatest risk to NUE is crop failure.

If crop yields are increased due to increases in N application, NUE will decline with higher rates of N application as other factors aside from N become limiting to crop yield (Cassman et al., 2002). As the yield potential of the crop increases due to factors other than N input, such as better use of water, balanced fertility, higher yielding cultivars, disease control, timeliness of operations or improvements in soil structure, the incremental N response (yield per kg of N) will be maintained at an acceptable level at ever increasing yield levels. Hence, all resources will be used more effectively if yield potential is increased. It is estimated that good agronomic practices could raise the average N use efficiency by at least 25-30% during the next two generations (Smil 1999). Use of enhanced efficiency fertilizers can play an important role in meeting that goal.

Reference List

1. Buresh R. J., DeDatta S. K., Padilla J. L. and Samson M. I. 1988. Effect of two urease inhibitors on floodwater ammonia following urea application to lowland rice. Soil Sci. Soc. Am. J. 52:856-61.

2. Byrnes B. H. and Freney J. R. 1995. Recent development on the use of urease inhibitors in the tropics. Fert. Res. 42(1/3):251-9.

3. Carreres R., Sendra J., Ballesteros R., Fernandez Valiente E., Quesada A., Carrasco D., Leganes F. and Garcia de la Cuadra J. 2004. Assessment of slow release fertilizers and nitrification inhibitors in flooded rice. Biol. Fertil. Soils 39:80-7.

4. Cassman K. G., Dobermann A. and Walters D. T. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. 31(2):132-40.

5. Clayton H., McTaggart I. P., Parker J., Swan L. and Smith K. A. 1997. Nitrous oxide emissions from fertilised grassland: A 2-year study of the effects of N fertiliser form and environmental conditions, Biology and Fertility of Soils. Biol. Fertil. Soils 25:252-60.

6. Dalal R., Wang W., Robertson G. P. and Prton W. J. 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: A review. Australian Journal of Soil Research 41:165-95.

7. Delgado J. A., Mosier A. R. 1996. Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. J. Environ. Qual. 25(5):1105-11.

8. Diez J. A., Cartagena M. C. and Vallegjo A. 1992. Controlling phosphorus fixation in calcareous soils by using coated diammonium phosphate. Fert. Res. 31:269-74.

9. Fashola O. O., Hayashi K. and Wakatsuki T. 2002. Effect of water management and polyolefin-coated urea on growth and nitrogen uptake of indica rice. J. Plant Nut. 25(10):2173-90.

10. Freney J. R., Randall P. J., Smith J. W. B., Hodgkin J., Harrington K. J. and T.C. Morton T. C. 2000. Slow release sources of acetylene to inhibit nitrification in soil. Nutrient Cycling in Agroecosystems 56:241-51.

11. Goulding, K. 2004. Pathways and losses of fertilizer nitrogen at different scalesMosier AR, Syers JK, Freney JR. Agriculture and the Nitrogen Cycle. Assessing the impacts of fertilizer use on food production and the environment. SCOPE 65. Washington: Island Press. p 209-19.

12. Grant C. A., Brown K. R., Racz G. J. and Bailey L. D. 2001. Influence of source, timing and placement of nitrogen on grain yield and nitrogen removal of Sceptre durum wheat under reduced- and conventional-tillage management. Can. J. Plant Sci. 81:17-27.

13. Grant C. A., Brown K. R., Racz G. J. and Bailey L. D. 2002. Influence of source, timing and placement of nitrogen fertilizer on seed yield and nitrogen accumulation in the seed of canola under reduced- and conventional-tillage management. Can. J. Plant Sci. 82 (629-638).

14. Grant C. A., Jia S., Brown K. R. and Bailey L. D. 1996. Volatile losses of NH_3 from surface applied urea and urea ammonium nitrate with and without the urease inhibitor NBPT. Can. J. Soil Sci. 76:417-9.

15. Guertal E. A. 2000. Preplant slow-release nitrogen fertilizers produces similar bell pepper yields as split applications of soluble fertilizer. Agron. J. 92(2):388-93.

16. Harrison R. W. J. 2001. A review of the effect of N fertilizer type on gaseous emissions. Adv. Agron. 73:65-108.

17. Hou A. X., Tsuruta H. 2003. Nitrous oxide and nitric oxide fluxes from an upland field in Japan: effect of urea type, placement, and crop residues. Nutrient Cycling in Agroecosystems 65(2):191-200.

18. Magalhaes A. M. T., Chalk P. M. and Strong W. M. 1984. Effect of nitrapyrin on nitrous oxide emission from fallow soils fertilized with anhydrous ammonia. Fert. Res. (5):411-21.

19. Malhi S. S., Oliver E., Mayerle G., Kruger G. and Gill K. S. 2003. Improving effectiveness of seedrow-placed urea with urease inhibitor and polymer coating for durum wheat and canola. Commun. Soil Sci. Plant Anal. 34:1709-27.

20. McTaggart I. P., Clayton H., Parker J., Swan L. and Smith K. A. 1997. Nitrous oxide emissions from grassland and spring barley, following N fertiliser application with and without nitrification inhibitors. Biol. Fertil. Soils 25:261-8.

21. Mikkelsen R. L., Williams H. M. and Behel A. D. Jr. 1994. Nitrogen leaching and plant uptake from controlled-release fertilizers. Nutrient Cycling in Agroecosystems 37:43-50.

22. Mosier A. R., Syers J. K. and Freney J. R. 2004. Nitrogen Fertilizer: An essential component of increased food, feed and fibre production. 3-15.

23. Neilsen D., Neilsen G. H. 2002. Efficient use of nitrogen and water in high density apple orchards. HortTechnology 12:19-25.

24. Nyborg M., Malhi S. S., Solberg E. D. and Zhang M. 1999. Influence of polymer-coated urea on mineral nitrogen release, nitrification, and barley yield and nitrogen uptake. Commun. Soil Sci. Plant Anal. 30(13/14):1963-74.

25. Pauly D. G., Nyborg M. and Malhi S. S. 2002. Controlled-release P fertilizer concept evaluation using growth and P uptake of barley from three soils in a greenhouse. Can. J. Soil. Sci. 82(2):201-10.

26. Power J. F., Wiese R. and Flowerday D. 2000. Managing nitrogen for water quality - lessons from management systems evaluation area. J. Environ. Qual. 29(2):355-66.

27. Rawluk CDL. 2000. Effect of soil texture, temperature and irrigation on the performance of urea fertilizers amended with the urease inhibitor N-(n-butyl)thiophosphoric triamide [M. Sc. Thesis]. Winnipeg, Manitoba: University of Manitoba. 127 pp .

28. Rawluk C. D. L. , Grant C. A. and Racz G. J. 2001. Ammonia volatilization from soils fertilized with urea and varying rates of urease inhibitor NBPT. Can. J. Soil Sci. 81:239-46.

29. Shaviv A. 2001. Advances in controlled release fertilizers. Adv. Agron. 71:1-49.

30. Shoji S., Delgado J., Mosier A. and Miura Y. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Commun. Soil Sci. Plant Anal. 32(7/8):1051-70.

31. Shuman L. M. 2003. Fertilizer source effects on phosphate and nitrate leaching through simulated golf greens. Environ. Pollut. 125(3):413-21.

32. Smil V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochemical Cycles 13(2):647-62.

33. Wakimota K. 2004. Utilization advantages of controlled release nitrogen fertilizer on paddy rice cultivation. Japan Agricultural Research Quarterly 38:15-20.

34. Wang X., Xin J., Grant C. A. and Bailey L. D. 1995 . Effects of placement of urea with a urease inhibitor on seedling emergence, N uptake and dry matter yield of wheat. Can. J. Plant Sci. (75):449-52.

35. Watson C. J., Poland P. M. H., Allen M. B. D. G. M. K. and Christianson C. B. 1994. Agronomic assessment and ^{15}N recovery of urea amended with the urease inhibitor nBTPT ([N-(n-butyl) thiophosphoric triamide) for temperate grassland. Plant Soil 161:167-77.

36. Wolt J. D. 2000. Nitrapyrin behavior in soils and environmental considerations. J. Environ. Qual. 29(2):367-79.