ADVANCES IN NUTRIENT USE EFFICIENCY

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ABSTRACT

The improvement of fertilizer efficiency is driven by narrow profit margins, environmental concerns, and resource conservation. Fertile soil is the foundation for food production and successful civilizations; it is developed and maintained through the addition of nutrients lost through harvest. However, nutrient uptake by plants is inherently inefficient and the nutrients remaining in the soil after uptake can cause negative air and water resource impacts. In addition, poor fertilizer efficiency is a waste of natural resources and potentially reduces yields, crop quality, and grower profits. Nutrient use efficiency (NUE) is increased through using optimal source, rate, timing, and placement. Several new fertilizer materials have been developed to enhance fertilizer efficiency. The modes of action of these materials discussed herein include: 1) slow or controlled release to meet plant need in a more timely fashion, 2) addition of high-charge-density materials that isolate nutrients from interfering elements and compounds, and 3) complexation of the nutrient to enhance solubility.

INTRODUCTION

The practice of conventional fertilization is sometimes criticized for purported impacts on the environment and food quality. However, maintaining productive soils through fertilization is an essential component of successful civilizations—those with the ability to feed the masses (Hopkins et al., 2008). However, excessive nutrient application often has detrimental consequences (Hopkins et al., 2008).

Nitrogen is the mineral nutrient most commonly deficient in agricultural soils. As a result, farmers apply relatively high rates of N fertilizers. Soil-plant system inefficiencies prevent complete utilization of the N, leaving residual N in the soil, which is a waste of natural resources and cause for environmental concern. Plants absorb N in the inorganic forms of nitrate (NO_3^-) and ammonium (NH_4^+). Unfortunately, these forms can be lost through conversion to nitrous oxide (N_2O), a long-lived gas that is a source of nitric oxide (NO), which contributes to ozone (O_3) depletion in the stratosphere and global temperatures. In addition, the NO_3^- form is mobile and is potentially leached below the rooting zone to groundwater. Nitrogen can also move laterally to surface waters. At high concentration in drinking water, nitrate poses a potential health risk to humans and livestock as one of the contributing factors for eutrophication and hypoxia in surface waters.

Phosphorus (P) is another nutrient that crops need in large quantities. Unlike nitrate, phosphate is not very mobile in the soil (Hopkins, 2008). However, it can be transported to surface water bodies through overland flow, especially if soluble P concentrations are exceptionally high. As with N, high concentrations of P in surface water bodies is potentially negative. Although N is usually the limiting factor for plant growth in soil-based systems, P is generally the limiting factor in aqueous systems. As a result, high concentrations of P in surface water bodies often lead to algae blooms that can deplete the oxygen and cause death of other aquatic organisms, which can be unsightly and have a pungent odor.

Although most widespread concerns regarding environmental impacts of poor nutrient management are focused on N and P, other nutrients can also become problematic (Hopkins, 2008). Excessively high levels of many nutrients can cause nutritional imbalances in plants and other organisms deriving their nutrients from the soil. Animals feeding off of these plants can also develop nutritional imbalances. Other toxicities can occur with over-application, especially for copper, boron, and chloride.

Environmental impacts of nutrient management, which dominate research funding priorities and the press, are important; however, it is equally important to enhance Nutrient Use Efficiency (NUE) to improve crops, which benefits both producers and the ever-increasing world population (Hopkins, 2008). Furthermore, enhancing efficiency reduces the amount of resources used to manufacture fertilizer.

Improving NUE is facilitated by optimizing fertilizer source, rate, placement, and timing. Optimum timing can be achieved by applying close to the time of need or using technology to delay the release of the nutrient to better match plant need. Placement in the path of roots often enhances uptake and incorporation into the soil often minimizes losses. Avoiding excessive or deficient rates by soil, tissue, and irrigation water analysis and applying rates based on accurate yield prediction, especially when using variable rate methods to customize rates for each unique area, is key to improving NUE while maintaining yields and grower profitability. The focus of this paper will be to examine the role of three enhanced efficiency fertilizer sources in crop production.

NITROGEN

Hopkins et al. (2008) reviewed the role of enhanced efficiency N fertilizers. Controlled-release N (CRN) and slow-release N (SRN) sources are fertilizers that release N into the soil over an extended period of time, ideally matching plant need, possibly reducing or eliminating labor-intensive and costly in-season N applications and increasing NUE and environmental quality (Hopkins et al., 2008). CRN fertilizers are coated or encapsulated and SRN fertilizers are low-solubility compounds, primarily sulfur-coated urea, urea-formaldehydes, methylene ureas, and triazine compounds.

Polymer-coated urea (PCU) fertilizers are one type of CRN that can potentially provide improved N-release timing. Soil temperature controls N release rate and simultaneously influences plant growth and nutrient demand (Hopkins et al., 2008). The release process consists of diffusion of water through the coating, dissolution of urea inside the particle, and diffusion of urea solution through the coating into soil solution. Diffusion is driven by the concentration gradient—temperature being the primary regulator under irrigated conditions. Zvomuya et al. (2003) found that polyolefin-coated urea (POCU) caused 34-49% less nitrate leaching and it increased yield and NUE, but as the fertilizer cost was five times as much as urea, the result was not economical. Zvomuya and Rosen (2001) had similar results. Shoji et al. (2001) found that a CRN material significantly reduced N_2O emissions, improved NUE, and improved comparable potato, corn, and barley yields compared with a traditional N source.

A recently developed PCU is Environmentally Smart N (ESN®[1], Agrium Advanced Technologies, Brantford, Ontario), which predictably releases N to the crop with control based on a micro-thin polymer coating. On-farm research conducted in Idaho at three locations over three years compared 70%, 85%, 100%, and 115% of recommended N applied as 1) ESN at emergence, 2) urea at emergence, or 3) urea "split" applied treatments to *Russet Burbank* or *Ranger Russet* potato. The "at emergence" treatments were applied immediately prior to cultivation and hilling, approximately coinciding with plant emergence. In the "split-applied" treatments, intended to mimic standard multiple N applications, half the N was applied at emergence and the remaining applied in four equal portions approximately 7-10 days apart beginning shortly after tuber formation. The 100% rate was based on University of Idaho guidelines as determined by yield goal, previous crop, soil type, and soil and irrigation water analysis of nitrate-N. In general, yields were greater for ESN than split applied urea and both of these were greater than uncoated urea applied all at emergence (Figure 1). Cost analysis (not shown) revealed that the optimum rate was 85% of recommended for this study. Other researchers have shown similar results for ESN in potatoes and other crops. This source of N fertilizer has proven effective in terms of both yield/crop quality increases and increased NUE. Additional findings have shown reduced NO_3^- leaching and gaseous loss of NH_3 and N_2O (data not shown). Two problems are being addressed with ESN. First, in-season tissue tends to be 10-15% lower for ESN in contrast to conventional fertilization—indicating a need for adjustment in calibration of this predictive tool. Secondly, the coating can be shattered with excessive and improper handling—resulting in loss of the controlled release properties.

ESN is but one of many new generation fertilizers available to growers, but this source seems to have the most independent scientific research performed on it with good consistency in terms of results. Limited work performed by this author on other new N fertilizers show some other sources with promise, but more work is needed on these products.

PHOSPHORUS

Research with fertilizer materials designed to improve NUE have been focused almost exclusively on N due to the high cost of production and its propensity to be lost to the atmosphere and to surface/groundwater with associated environmental impacts (Hopkins et al. 2008). However, some studies evaluated efficiency of a combination of nutrients in a slow release delivery mechanism. In these cases, P efficiency is enhanced, but the chemical mode of action is different than for N. Fertilizer P efficiency depends more on soil fixation than on loss. Although P can be lost via erosion or surface water flow, only a small portion is generally lost in this manner. Soil P more frequently precipitates as mineral complexes that decrease in solubility with time. Thus, a slow-release approach may enhance plant accessibility to P through avoidance of mineral precipitation.

Plant availability of P depends largely on the amount dissolved into soil solution, which declines dramatically as soil pH increases from near neutral (6.8-7.0) to alkaline (7.6-8.3). This problem is exacerbated by free excess lime in calcareous soils. Phosphorus combines with calcium (Ca) and magnesium (Mg), which is inherently at high concentration alkaline soils, forming poorly soluble compounds. A similar reaction occurs in acidic soils with aluminum (Al), iron (Fe), and manganese (Mn) as the cations that combine with P.

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[1] Mention of a trade name or commercial company does not imply endorsement by the author or his institution.

However, improving NUE for P is challenging due to inherent inefficiencies in the soil-plant system that lead to precipitation of fertilizer P with interfering cations—resulting in recoveries of near zero to less than 30% of applied P fertilizer (Murphy and Sanders, 2007). A number of rate, timing, and placement options can be used to improve effeciency (Hopkins et al., 2008, 2011). In addition to the cultural practices that may enhance P uptake and utilization, fertilizer manufacturers have sought to engineer materials to enhance efficiency, such as with slow release coatings. Another approach to enhance PUE is to minimize the concentration of potentially reactive cations in the immediate vicinity of the P fertilizer when applied to soil.

A new fertilizer additive (AVAIL®[1], Specialty Fertilizer Products, Leawood, Kansas) purportedly creates a water-soluble shield that surrounds the P in fertilizer when it is applied to soil (Dunn and Stevens, 2008; Gordon and Tindall, 2006; Murphy and Sanders, 2007). Hopkins (2011) reviewed the proposed mode of action for AVAIL, which is reported to be a high-charge density compound that sequesters interfering cations, thus, reducing the interaction with P by reducing crystalline structure and minimizing precipitate formation. Several fertilizer field trials with AVAIL are reviewed by Hopkins (2011).

Chemical studies by multiple researchers suggest that AVAIL does impact P solubility in the soil (Hopkins, 2011). As a result, there are several reported studies showing that AVAIL addition to P fertilizer results in a yield and/or crop quality increase, often with increases in plant tissue P concentration. It is not surprising that most of these studies show that soil test P and P fertilizer rate does have a role in whether or not there is a response to AVAIL—with responses more likely with low soil test P and/or at low fertilizer P rates. There are notable exceptions to this statement, with Ward and Mengel (2009) and Franzen et al. (2008) both showing a lack of response to AVAIL treated P fertilizer in low P test soils. Other factors could be at work in these situations that resulted in some other factor being more limiting that P fertility and/or conditions not being ideal for a P response. Another potential concern for the Franzen et al. (2008) studies is direct seed contact, which may have been a problem for this species (sugarbeet) that is known to be sensitive to salts at the seed and seedling stages.

Another approach to enhancing P efficiency has been developed (Carbond®[1] P; Land View Inc., Rupert, Idaho, USA) that has been complexed with organic acids in a sophisticated manufacturing process. This complexation is thought to keep P more readily plant available after applied to the soil. Several studies have been performed on this product showing increased P solubility over extended periods of time, which has resulted in increases in P uptake and early season growth for corn (Hill et al., 2011). Field trials have also been performed showing increases in P uptake, which have often resulted in increases in yield (Figure 2). Furthermore, this enhanced P solubility has resulted in movement of P into the rooting zone of perennial crops (data not shown).

SUMMARY

Use of enhanced efficiency fertilizer products can benefit both grower profitability and environmental sustainability. A new polymer coated urea (ESN) has shown increases in crop yield and quality, as well as reductions in air and water quality contaminants. Two new phosphorus fertilizer additives (AVAIL and Carbond P) have shown promise of enhancing P uptake and yield at reduced rates of P, thus reducing likelihood of P transport to surface waters.

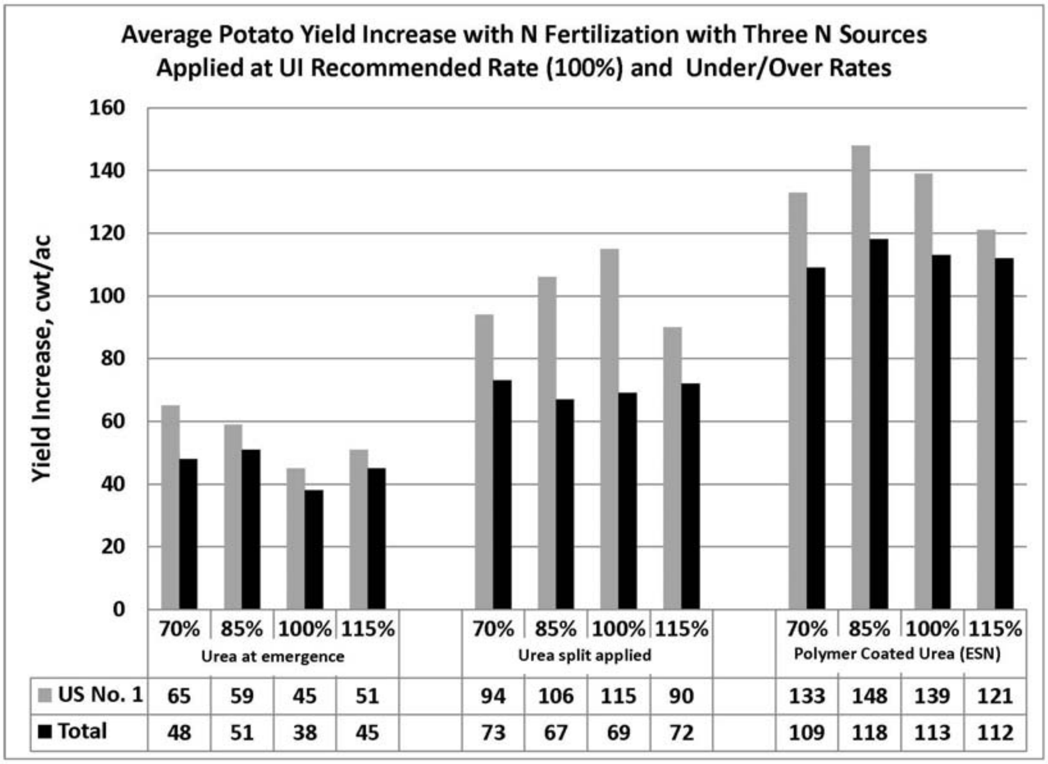

Figure 1. Relative increase in potato yield over an unfertilized control for urea and polymer coated urea applied at emergence and urea split applied (50% at emergence and remaining applied evenly through season) averaged over three years. Fertilizer amounts varied by field, with 70, 85, 100, and 115% applied relative to the amount recommended by University of Idaho guidelines based on yield goal, soil type, previous crop, and soil and irrigation water analysis. Differences greater than 39 and 41 cwt/ac were significantly different for US No. 1 and Total Yields, respectively.

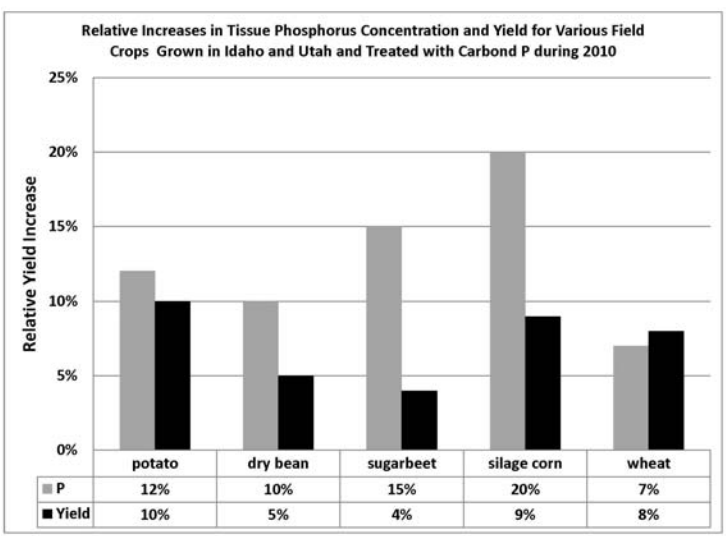

Figure 2. Increase in shoot dry matter with application of Carbond P compared to ammonium polyphosphate (APP) applied to corn in a glasshouse trial at four rates. Increase in biomass signified by “NS” = not significant or “*” = significant at $P < 0.05$.

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