

Enhanced Efficiency Fertilizers for Improved Nutrient Management: Potato (*Solanum tuberosum*)

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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. Enhancing fertilizer efficiency in potato is particularly important because relatively high rates of fertilizer and water are necessary to compensate for an inefficient rooting system and extreme sensitivity to deficiencies. Several new fertilizer materials have been designed to enhance fertilizer efficiency. The modes of action of these materials include: (i) slow or controlled release to meet plant need in a more timely fashion; (ii) addition of high charge-density materials that isolate nutrients from interfering elements and compounds; (iii) complexation or chelation of the nutrient to enhance solubility; and (iv) modification of the micro-site pH to enhance nutrient solubility.

The Need for Better Nutrient Management in Potato

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 (16). History demonstrates that ecological and sociological problems occur when soils become exhausted of nutrients through crop removal and poor soil management. For example, agricultural soils in Alabama and other southeastern states became nutrient depleted during the 19th century, largely due to lack of fertilizer resources, contributing to a regional farm crisis during the last half of the century (9). The maintenance of fertile soil through application of fertilizer materials, which became more readily available during the last half of the 20th century, is one of the keys to the agricultural boom resulting in steadily increasing yields and agricultural efficiency in the United States (16).

Crop harvest removes essential plant nutrients from soil. Although fertile soils have a large reserve of some nutrients, many of these are part of the soil structure and, as such, are bound in mineral forms largely unavailable to plants (16). Many other nutrients are only found at very low concentrations in soil solution and others become depleted after repeated harvests. Nutrients do not regenerate following removal — they must be replenished through addition of fertilizer, soil amendments, and, to a lesser degree, through atmospheric

deposition, irrigation and, in the case of N, through fixation of atmospheric N by legumes and some microbes. However, excessive nutrient application often has detrimental consequences (11,27,48).

Nitrogen is the mineral nutrient most commonly deficient in agricultural soils (16). 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) (62,69), a long-lived gas that is a source of nitric oxide (NO), that is thought to contribute to ozone (O_3) depletion in the stratosphere and increases in global temperatures (31). In addition, the NO_3^- form is mobile and is potentially leached below the rooting zone to groundwater (48). Nitrogen can also move laterally to surface waters (59). At high concentration in drinking water, nitrate poses a potential health risk to humans and livestock and is also one of the contributing factors for eutrophication and hypoxia in surface waters (19,49,58).

Phosphorus is another nutrient that crops need in large quantities. Unlike nitrate, phosphate is not very mobile in the soil (4,11,16,44). However, it can be transported to surface water bodies through overland flow, especially if soluble P concentrations are exceptionally high (48,66). 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 (48,66). 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 (48,66).

Although most widespread concerns regarding environmental impacts of poor nutrient management are focused on N and P, other nutrients can also become problematic (11,16). Excessively high levels of many nutrients can cause nutritional imbalances in plants and other organisms deriving their nutrients from the soil (42). Animals feeding off of these plants can also develop nutritional imbalances (26,51). Other toxicities can occur with over-application, especially for copper, boron, and chloride (1,6,26,28,42).

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. Furthermore, enhancing efficiency reduces the amount of resources used to manufacture fertilizer. This paper will examine the unique nature of nutrient management and the role of enhanced efficiency fertilizers in potato production.

Nutrient Management in Potato

Although considered a minor crop, potatoes rank 8th in acreage and 3rd in value according to the most recent US agricultural census (50). Potatoes have a relatively high cost of production and value, with average expenditures of \$1780 to \$2690/acre (55). Nearly 20% of operating cost is fertilizer, and potatoes require more than most crops (47,49,57,91). The combination of high fertilizer rates and acreage makes nutrient management an important priority in potato production.

Potatoes require a steady supply of nutrients (75,83). Deficiencies or fluctuations of soluble nutrients (especially N) cause poor vine health, increased pathogen and insect susceptibility, reduced tuber yields, and diminished tuber quality (52,53,74,75). Potatoes require high amounts of fertilizer not only because of high nutrient demand, but also because they have a shallow, inefficient rooting system (49,54,56,87). Tanner et al. (76) found that potato roots reside in the top two feet of soil, with 90% of root length in the top 10 inches, whereas most other crops root deeper. Consequently, potatoes receive most of their nutrients from the top foot of soil (5). In addition to shallow rooting, many potato cultivars have relatively inefficient nutrient and water

uptake systems (39,64). Nutrient management is made even more challenging due to nutrient leaching from relatively high irrigation rates required due to the combination of potato being grown commonly on sandy soils with low water-holding capacity and extreme sensitivity to moisture stress (68).

Inherent inefficiencies in the soil-plant system lead to less than complete recovery of applied fertilizer. Potato recovery of soil-applied N has been reported at only 16 to 36% under conditions of severe leaching (14). Other researchers have reported slightly higher numbers (22,45), but utilization is nonetheless inefficient.

The consequence of poor efficiency and high water/fertilizer rates in potato is the potential for significant N contamination to surface (23,24,47,49) and groundwater (22,24,41,47,48,49,60,86,91). In addition, nitrous oxide emissions from potato fields are higher than those of most other crops (61,62), which is likely related partially to high fertilizer and water application rates (49). Although not studied as extensively as N in potatoes, high soil P is a potential environmental problem as well (11).

Improving Nitrogen Efficiency

Nitrogen management is a high priority in potato cropping systems (7,14,75,83,84). Typically, N is the most limiting nutrient in crop production and is higher in concentration than all other mineral nutrients in most plants (16). In potatoes, N rivals only K in highest mineral concentration (49,75,83). Potatoes are especially sensitive to N deficiencies and excesses (7,15,75).

Potatoes require a modest amount of N early in the season for adequate canopy development (75,80,83). However, excessive N early on can delay the linear tuber growth period for 7 to 10 days for indeterminate cultivars, potentially reducing tuber yields (33). Once tubers are formed and begin the bulking phase, potatoes require a higher, steady supply of N. Mid-season deficiencies of N reduce canopy growth and often cause premature senescence, which can reduce yields (75,83). Excess mid-season N slows tuber bulking in favor of vegetative growth (43,81). Fluctuating N levels have been shown to cause irregular tuber growth and can increase the susceptibility of internal (brown center and hollow heart) and external (misshapen) tuber deformities (75,83). As plants approach maturity, N concentrations in the plant must subside in order to maximize transport of above-ground carbohydrates into tubers and enhance "skin" formation.

Synchronizing N availability and potato demand is recommended to maximize yield, tuber quality, and N efficiency (14,18,32,49,57,62,63,71,72,75,82,83,84,86). Most irrigated potato growers incrementally supply N throughout the growing season — 25 to 50% of the N is applied sometime between pre-plant and plant emergence and the remainder injected into irrigation water throughout the growing season (fertigation). The amount and timing of N application is based upon weekly petiole nitrate-N analysis. Although applying N incrementally in this fashion increases yields and improves tuber quality, it is labor intensive and liquid N fertigation sources are more costly than the dry forms.

Some irrigation systems and non-irrigated cropping systems are unsuited for N fertigation. In these situations, growers apply the N in one application or split it into two or more applications through various combinations of pre-plant broadcast, starter banding, side-dress, or aerial applications.

Although many studies suggest that incrementally applying N helps maximize yield and tuber quality in irrigated soils; other studies show no benefit with rain-fed soils (89). However, there is little doubt that a primary benefit of applying N near plant uptake time is improved N-use efficiency (NUE) (15,49,62,81,82). Nitrate (NO_3^-) and ammonium (NO_4^+) are forms of N plants absorb, and the risk of losing them from the soil is proportional to the time they reside unused in the soil. Nitrate is subject to loss from the plant root zone through leaching (especially in sandy soils), denitrification (especially in clay soils), and runoff/erosion (especially on steep slopes and compacted/crusted soils). Ammonium-N is also subject to runoff/erosion; as well as volatilization (especially in alkaline soils common in Central and Western US potato-growing

regions). Proper N management techniques reduce N loss and potentially negative impacts to the environment; however, losses may still be prevalent if significant precipitation occurs and the N is in a soluble form in soil solution (65). Thus, new fertilizer technologies are needed to further improve NUE.

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 (3,4,12,30,46,49,54,69,70,91). CRN fertilizers are coated or encapsulated and SRN fertilizers are low-solubility compounds, primarily sulfur-coated urea, urea-formaldehydes, methylene ureas, and triazine compounds (79).

The concept of CRN and SRN fertilizer materials is not new (2,8,40), but previous work has been mostly unsuccessful in potatoes. Fertilizer costs were high and N release was too early, too late, and/or too unpredictable, resulting in delayed tuberization and yield loss (10,30,36,37,38,43,81). In other studies, however, potatoes fertilized with sulfur-coated urea, isobutylidene diurea (IBDU), gypsum-coated urea, or rock phosphate-coated urea were more effective than soluble fertilizers under severe leaching conditions (13,36). Although Liegel and Walsh (36) found sulfur-coated urea to perform better than urea under severe leaching conditions, it was not as effective under normal weather conditions.

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 (17,49,77,90). 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 (79). Zvomuya et al. (91) found that polyolefin-coated urea (POCU) caused 34 to 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 (90) had similar results. Shoji et al. (69) found that a CRN material significantly reduced N₂O 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, 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 in 2006 compared 33%, 67%, 100%, and 133% of recommended N (100% rate = 270 lb of N per acre) applied as (i) ESN at emergence, (ii) urea "at emergence," or (iii) urea "split" applied treatments to *Russet Burbank* potato. A pre-plant ESN treatment at the 67% rate was also included. 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 three equal portions approximately 14 days apart beginning shortly after tuber formation. All N treatments were irrigated using overhead sprinkler systems.

Total yield treatment differences were highly significant (Fig. 1), with only the 33%, 67%, and 100% ESN rates and the 67% split having significant increases over the unfertilized check. The 67% split urea yielded similarly to the three significant ESN treatments. Although total yield is important, fresh market growers are generally paid premiums for tubers without defects (US No. 1 grade). Yields of US No. 1 tubers for this trial showed similar trends as the total yields, but only at the $P = 0.10$ level of significance (Fig. 1). All of the ESN treatments had significantly better US No. 1 yields than the untreated check. Only the 100% and 133% split treatments had better US No. 1 yields than the untreated check. In addition, while the 67% ESN treatment applied at emergence had significantly higher US No. 1 yield than the non-split urea treatments it was only significantly higher than the 33% and 67% split urea treatments.

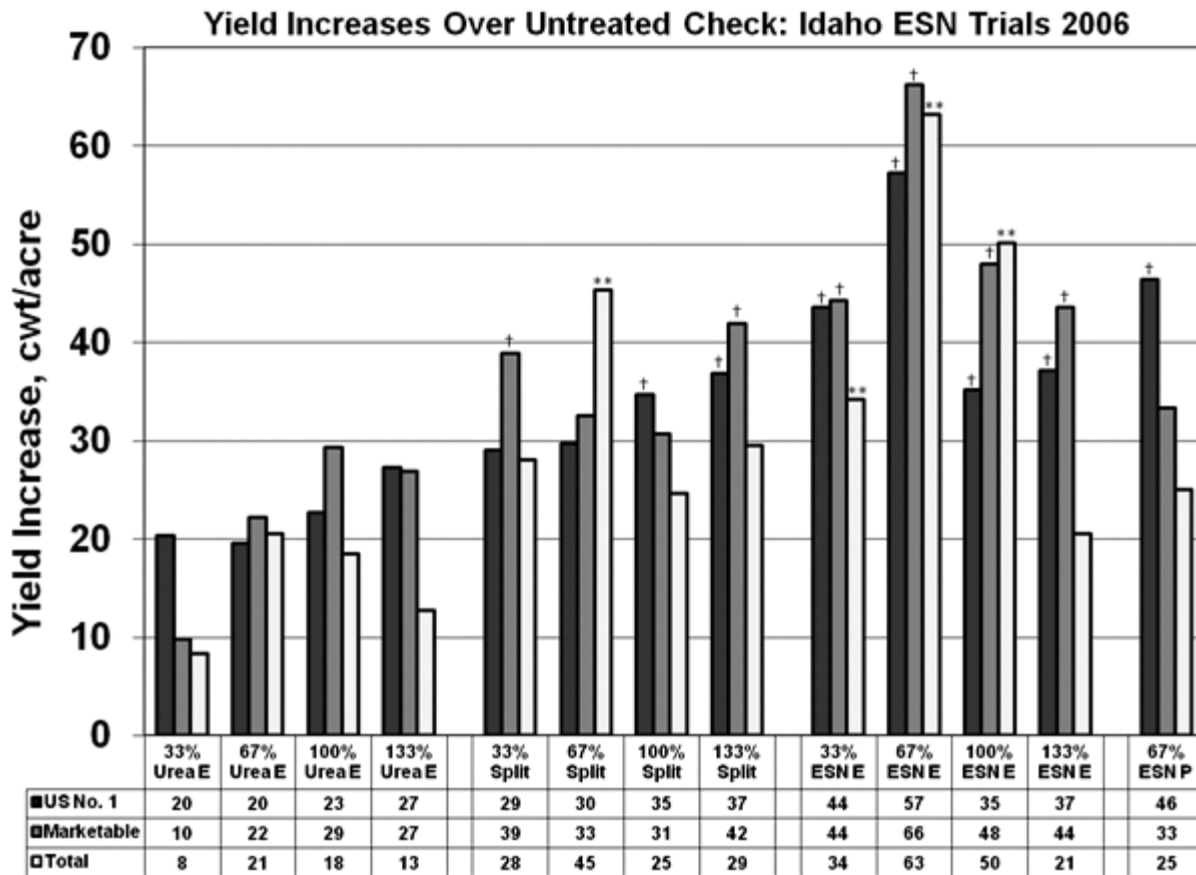


Fig. 1. Potato tuber yield increases (cwt/acre) of 2006 Idaho ESN trials, averaged across three fields. Values shown are treatment yields minus yields of untreated check. Nitrogen applied at four rates — 33, 67, 100, and 133% of recommended — using four methods of application: (i) urea at emergence (E), (ii) urea with 50% applied at emergence and remaining 50% applied in three in-season applications (split), (iii) ESN at emergence, and (iv) ESN at pre-plant (P). ESN P treatment only applied at 67% rate. Differences for total yield (LSD 31 cwt/acre) significant at $P = 0.01$ (denoted by **); differences for US No. 1 (LSD 33 cwt/acre) and marketable yield (LSD 39 cwt/acre) significant at $P = 0.10$ (denoted by †).

Growers with processing contracts—primarily those for the fried potato products industry—are often paid incentives for "marketable" tubers (combination of US No. 1 and 2 tubers). Marketable yields for this trial showed similar trends as the total yields and a nearly identical response to the US No. 1 yields at a significance level of $P = 0.10$ (Fig. 1). All ESN treatments applied at emergence were significantly higher in marketable yields than the untreated check. Only the 33% and 133% urea split treatments were higher than the untreated check and only the 67% ESN treatment applied at emergence had significantly more US No. 1 yield than the 33 and 67% non-split urea treatments. This effect was similar to research in Florida on Atlantic cultivar, in which the reduced rate of 65% of recommended N was optimum for the CRN (30,54).

Overall, the ESN applied at emergence tends to yield better than the urea applications. At the 33% and 67% applications rates the total, US No.1 and marketable yield were generally higher than all rates of urea application regardless of timing. Total yield for 67% urea split applied is the only value that does not fit this trend. Although the differences are not always significant the increased ESN yields demonstrate greater NUE over the urea.

Applying contract pricing and fertilizer costs is highly speculative, but in an estimate using five-year-average grower contracts and average 2006 fertilizer prices (assuming ESN at \$0.42/lb of N and urea at \$0.30/lb of N), both ESN and urea (combined across rates) performed significantly better than the untreated check for US No. 1, marketable, and total yield; as well as for gross crop value and incentive adjusted value. However, only ESN was significantly

better than the untreated check (\$148 net difference) in net value when factoring in all crop value parameters and fertilizer cost estimates, while urea was not.

Another ESN trial in Idaho the previous year had similar results. The ESN applied immediately prior to hilling performed significantly better than urea concurrently applied for US No. 1, marketable, and total yield, with increases of 50, 47, and 39 cwt/acre, respectively. Notably, similar to the 2006 data, the reduced rate of N applied as ESN (80% in 2005 vs 67% in 2006) had significantly better US No. 1 tuber yields than the 100% ESN treatment with a 30 cwt/acre difference.

The target timing of ESN application at emergence in the Idaho studies was based on research conducted in Minnesota with 'Russet Burbank' during 2004-2005. In 2004, ESN was applied at 40, 120, 200, and 280 lb of N per acre compared with equivalent rates of urea. An additional 40 lb of N per acre was applied as diammonium phosphate to all treatments except the control. ESN was applied as a band at planting, except one additional 200 lb of N per acre treatment in which the application was split between planting and emergence. All urea was split-applied between emergence and hilling. In addition, two post-hilling urea-ammonium nitrate treatments were included to simulate fertigation at 200 lb of N per acre. As with the Idaho trials, all N treatments were irrigated using overhead sprinkler systems.

Total, marketable, and US No.1 tuber yields increased with increasing N rates for both sources (Fig. 2). All yield categories were higher with ESN than with urea at the lower N rates and were similar to urea at the higher N rates when applied in two or more splits. Splitting ESN application between planting and emergence resulted in significantly higher yields than applying urea in multiple splits. In 2005, similar treatments, plus an ESN treatment applied all at emergence, were compared. The latter resulted in significantly higher total and marketable yields than most all of the other ESN and urea treatments applied entirely or partially at planting (Fig. 3). However, US No. 1 yields with ESN and multiple split soluble N sources were significantly lower than those with urea applied early in the season. Reasons for the lower yields of US No. 1 tubers in 2005 but not in 2004 with extended N applications are unclear. Poor irrigation practices can lead to misshaped tubers causing a higher proportion of US No. 2 yields (74). Less rainfall in 2005 than in 2004 and improper irrigation may have led to the higher incidence of US No. 2 tubers in 2005. These results suggest that water stress is more detrimental to tuber shape when extended-season N is used compared with early-season N application.

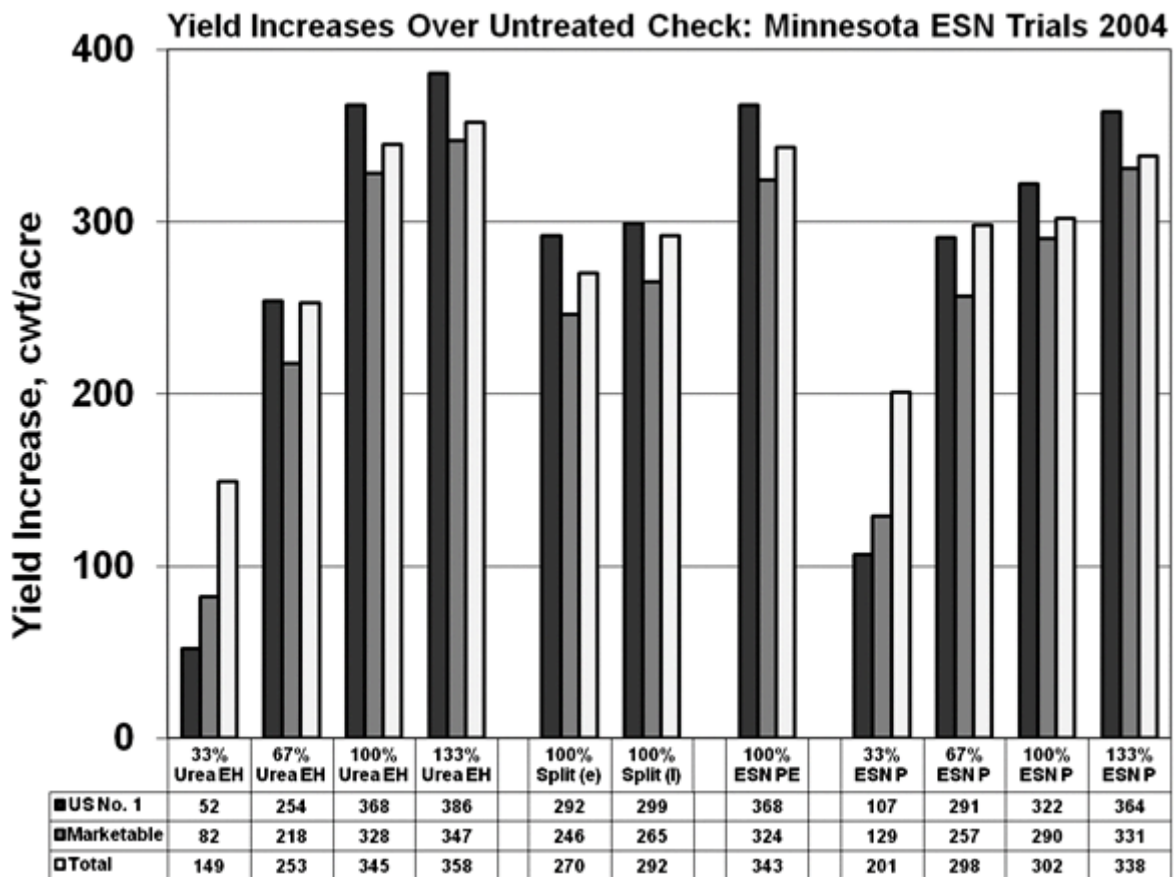


Fig. 2. Potato tuber yield increases (cwt/acre) of 2004 Minnesota ESN field trials. Values shown are treatment yields minus yields of untreated check. Nitrogen applied at four rates — 33, 67, 100, and 133% of recommended — using five methods of application: (i) urea with 50% at emergence and 50% at hilling (EH), (ii) split urea with 60% applied early season (e), (iii) split urea with 80% applied late season (l), (iv) ESN with 60% pre-plant and 40% at emergence (PE), and (v) ESN pre-plant (P). The urea early split treatment applied at 40 (P), 60 (E), 60 (H), and four applications of 20 lb of N per acre each post-hilling. The urea late split treatment applied at 40 (P), 20 (E), 40 (H), and four applications of 40 lb of N per acre each post-hilling. The split urea and ESN PE treatments applied at 100% rate. All treatments have significant increases over untreated check. Differences for total (LSD 43 cwt/acre), marketable (LSD 39 cwt/acre), and US No. 1 yield (LSD 38 cwt/acre) significant at $P = 0.10$.

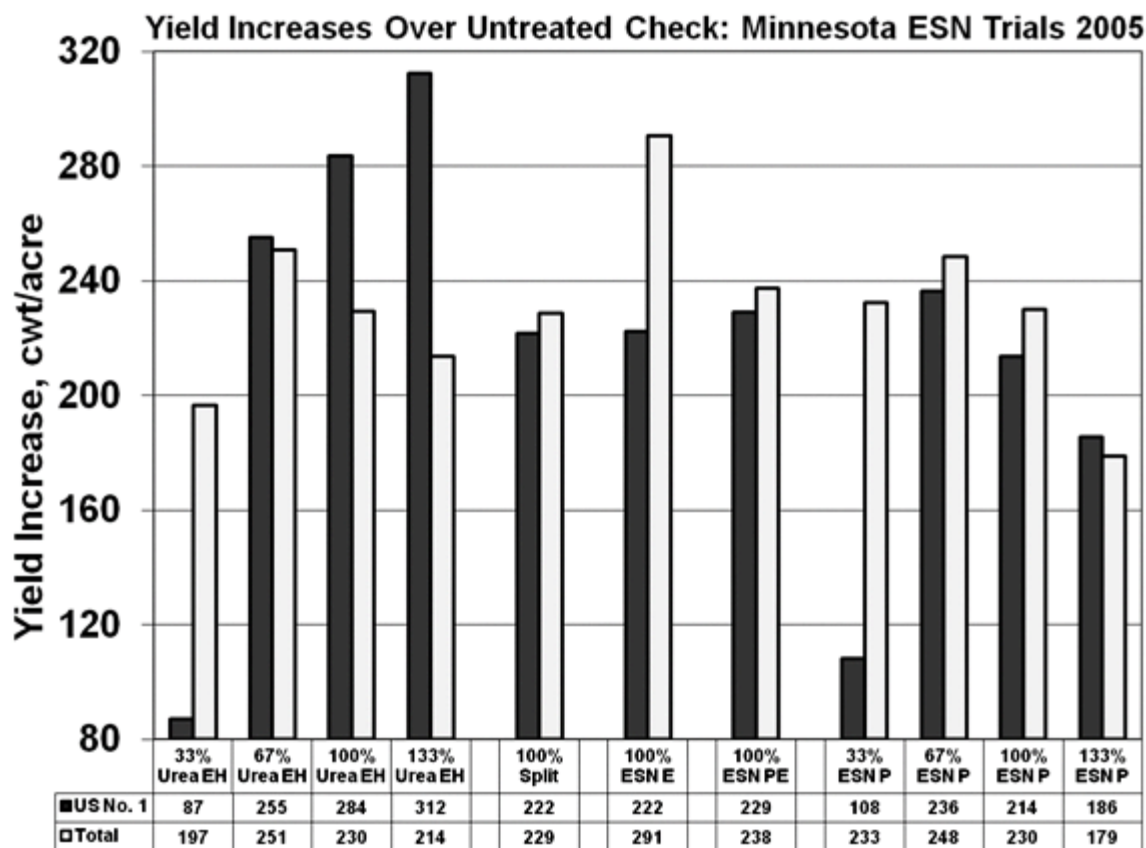


Fig. 3. Potato tuber yield increases (cwt/acre) of 2005 Minnesota ESN field trials. Values shown are treatment yields minus yields of untreated check. Nitrogen applied at four rates — 33, 67, 100, and 133% of recommended — using five methods of application: (i) urea with 50% at emergence and 50% at hilling (EH), (ii) split urea, (iii) ESN applied at emergence (E), (iv) ESN applied with 60% pre-plant and 40% at emergence (PE), and (v) ESN pre-plant (P). The urea split treatment applied at 40 (P), 100 (E), 20 (H), and four applications of 20 lb of N per acre each post-hilling. The split urea and ESN E and PE treatments applied at 100% rate. All treatments have significant increases over untreated check. Differences for total (LSD 47 cwt/acre), marketable (LSD 48 cwt/acre), and US No. 1 yield (LSD 49 cwt/acre) significant at $P = 0.10$.

Results from the Idaho trials support the recommendation that ESN be applied and incorporated into the soil near the time of plant emergence (Fig. 1) rather than at or prior to planting. Based on the Idaho trials data, optimum economic rates of recommended N may be below normal rates when using ESN, thus improving NUE. In summary, the polymer-coated urea ESN is a new fertilizer product with the potential to improve N use efficiency and allow growers to reduce or eliminate time-intensive in-season applications of N to potatoes when using overhead sprinkler irrigation systems.

Although many SRN and CRN fertilizers are available to growers, ESN is of particular focus because the amount of data available on potatoes and because it only costs about 30% more than uncoated urea. There is little or no data on most SRN and CRN fertilizers in potatoes and cost can be 150 to 500% more than urea. Researchers are continuing to evaluate various N products for enhanced efficiency on potatoes.

Research in Wisconsin from 2004-2006 on a urea-based polymer SRN fertilizer (Nitamin, Georgia-Pacific, Atlanta, GA) shows promise (73). Nitamin was applied 1/3 at emergence and 2/3 after tuberization and compared with the grower's standard practice of the same rate and split percentages, but with ammonium sulfate applied at emergence and ammonium nitrate at tuberization (200 to 230 lb of N per acre). Four of five fields showed equivalent yields for both the Nitamin and the standard. The fifth field had a significant increase of 53 cwt/acre. However, there was not a significant increase at any location for Grade-A yields. A half-rate Nitamin treatment was also included, but often had significantly lower yields and tuber quality than the full-rate treatments.

Further work with Nitamin, coupled with an experimental dry SRN fertilizer (GP-43G, Georgia-Pacific) was performed at two Idaho locations in 2006 (full recommended rate was 270 lb of N per acre). One treatment with a reduced (67%) N rate had half applied as the 43G at emergence and the other half as Nitamin shortly after tuber initiation. This treatment had the highest US No. 1, marketable, and total yields at both locations with significant differences over the untreated check in all cases. In contrast, the grower's standard practice of multiple applications had relatively lower yields and did not have a significant increase over the check for US No. 1 yield at one location nor total yield at the other. There was also a significant increase in yield of the greater-than-10-oz tubers at both locations for the reduced rate 43G/Nitamin combination, but at only one location for the grower's standard practice. Notably, other application timings of SRN materials and the all full-rate application timings did not generally perform better than the grower's standard.

Another new concept in N fertilization is an elemental sulfur-coated urea with an outer polymer coating (TriKote, Agrium Inc., Calgary, Alberta). Results of a potato trial conducted in Idaho in 2006 showed no significant differences over the grower's standard N fertilization practice; however, additional research is needed properly evaluate this product. Another product tested in the same study (Nutrisphere-N or NSN at 0.5 gal/ton of urea, Specialty Fertilizer Products, Belton, MO) did show significant crop improvement. Although research is currently underway to verify the mode of action of NSN, the manufacturer claims it is based on an ultra high-charge density, which attracts the positively charged nickel ion co-factors found in the urease enzyme. The intended effect is to slow the enzymatic reaction of urea conversion to ammonium, similar to urease inhibitors, such as NBPT (N-butyl thiophosphoric triamide; Agrotain, Agrotain International LLC, St. Louis, MO). Urease inhibitors effectively prevent N loss under high precipitation conditions (79). Although no work with Agrotain has been published on potatoes, it is reasonable to assume that any mode of action that slows the conversion of urea to ammonium reduces the amount of time when the N is at risk for loss due to volatilization and leaching. A single trial of NSN in Idaho in 2006 showed promising results: NSN performed significantly better in total and marketable yield than urea when applied in a single application at emergence. Furthermore, when NSN was applied at a reduced rate (85%), it performed significantly better for US No. 1 yield (39 cwt/acre) and at both the full (42 cwt/acre) and reduced (38 cwt/acre) rates for marketable yield than the grower's standard practice (LSD 38 and 30 cwt/a, respectively; $P < 0.10$). Unlike many other SRN and CRN materials, the price differential between NSN and urea is relatively low (\$0.08 per lb urea), which is similar to ESN.

All of the research reported above was conducted on 'Russet Burbank' potato. Research in Florida on another cultivar (Atlantic) showed that a variety of SRN and CRN fertilizers could be used effectively (13,30,54). Similarly, research on a CRF (polymer-coated urea) shows increased yield and quality in the Centennial cultivar in Colorado (69). Other cultivars with similar growth and N-uptake patterns would likely respond similarly. CRN and SRN fertilizer materials need further evaluation on cultivars with a shorter growing season and/or requiring higher percentage of early-applied N to document optimum rates and timing. For example, 'Russet Norkotah' requires N applications earlier in the growing season than 'Russet Burbank' (33). In such cases, CRN or SRN fertilizers probably need to be applied pre-plant and possibly as a mixture with other soluble-N sources. Cultivar differences are generally related to time, maturity, and root density (39,64).

Improving Phosphorus Efficiency

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 (21,67). However, some studies evaluated efficiency of a combination of nutrients in a slow release delivery mechanism (21,44,88). 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 (21,44). Although P can be lost via erosion or surface water flow, only a small portion is generally lost in this manner (66). 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.

As with N, fertilizer P is applied at high rates to potatoes (25,75,83,85), especially in predominately alkaline and calcareous soils common to the potato growing regions in the semi-arid western US. 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 to 7.0) to alkaline (7.6 to 8.3). This problem is exacerbated by free excess lime in calcareous soils (25,75,83). Phosphorus combines with Ca and Mg, which is inherently found at high concentration in alkaline soils, forming poorly soluble compounds. A similar reaction occurs in acidic soils with Al, Fe, and Mn as the cations that combine with P.

A number of rate, timing, and placement options are available to help growers combat P solubility problems. Another approach to enhancing P fertilizer efficiency is to minimize the concentration of potentially reactive cations in the immediate vicinity of the P fertilizer. A new fertilizer product (Avail, Specialty Fertilizer Products, Belton, MO) is engineered for this function. Avail's mode of action is similar to what is claimed for NSN in that it uses a high charge-density compound to sequester interfering compounds and elements. Avail is a long chain dicarboxylic acid copolymer, unique in that it is water soluble but only slightly mobile from point of contact. The distinctive chemistry enables it to remain close to the applied fertilizer P to impact its solubility. Avail has a strongly binding cation exchange capacity (CEC) of approximately 1800 meq/100 g of soil (20) that sequesters Ca, Mg, Al, Fe, Mn, and other multivalent cations in soil solution, thus reducing the interaction with P. Avail is fairly new in the fertilizer market, but it has been studied on several crops, often with favorable responses (78).

Hopkins conducted a study on grower fields in 2004 in which fertilizer spreader-width strips of monoammonium phosphate (11-52-0) was applied with or without the Avail in a randomized, replicated design. A significant increase in total yield was observed with Avail, although US No. 1 yields were not statistically significant (Fig. 4). Other trials conducted in Idaho in 2005-2006 showed similar results, with significant potential to improve potato yields grown on calcareous soils (Jeff Stark, University of Idaho, *personal communication*).

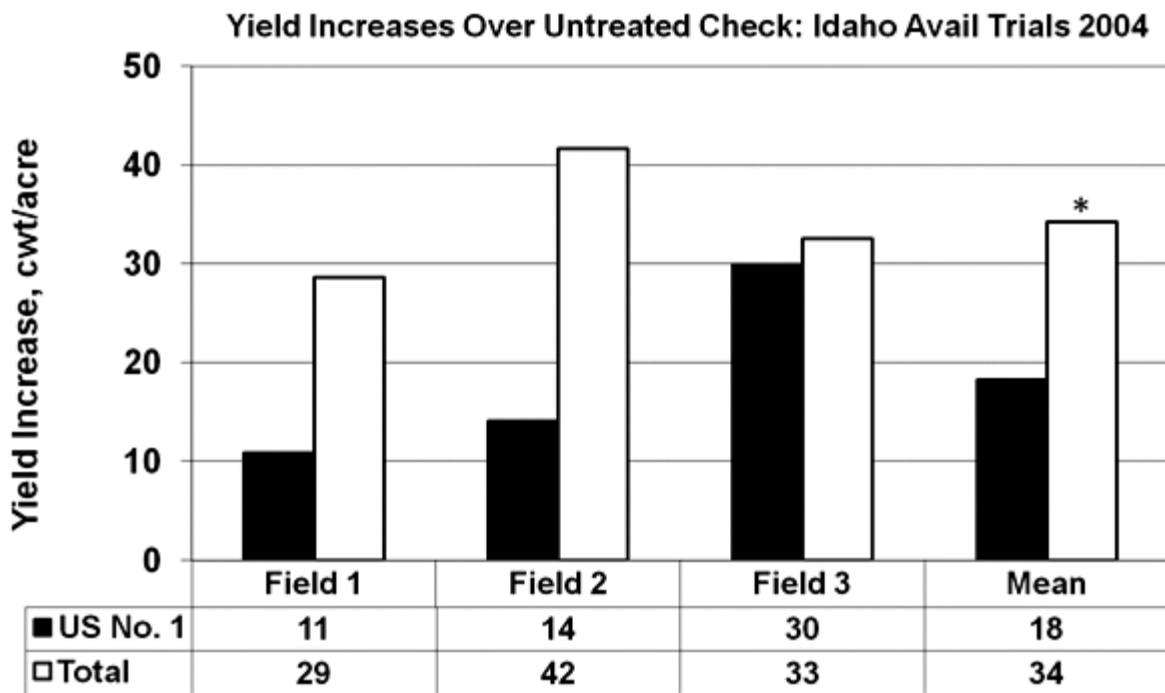


Fig. 4. Potato tuber yield increases (cwt/acre) of 2004 Idaho Avail trials. Values shown are treatment yields minus yields of untreated check. Each of three fields received uniform amount of phosphorus applied as monoammonium phosphate (MAP) ranging from 120 to 210 lb of P_2O_5 per acre. MAP applied to replicated treatment strips had 1% Avail coating sprayed on surface of fertilizer. Differences for total yield (LSD 33 cwt/acre) significant at $P = 0.05$ (denoted by *) when fields averaged. No other differences significant.

A similar study was conducted at six locations in Wisconsin in 2006 (35) comparing monoammonium phosphate (MAP) with Avail and treble super phosphate (TSP) at equivalent rates of N and P. Most locations had high to excessively high soil test P and no significant differences, but the soil test P level was very low at one location and MAP treated with Avail significantly increased total yield by 42 cwt/acre and grade A tubers by 75 cwt/acre.

Many fertilizer and fertilizer additive products other than Avail claim to enhance P efficiency. Another common approach is to combine P with a compound to minimize its precipitation with various cations. This mechanism was studied on highly calcareous Idaho soils from 2000-2002. These soils are representative of those commonly found in much of the Western potato-growing region and have severely limited P solubility. Three rates of P (0, 60, or 120 lb of P_2O_5 per acre) were applied in a liquid fertilizer band during row formation with and without humic acid at a 10:1 v/v ratio (29). Petiole P concentrations during tuber bulking increased an average of 0.03% P with the addition of humic acid. The humic acid treatment significantly increased yields of US No. 1 tubers greater than 10 oz in 2 of 3 years of the study. Averaged across years and P rates, humic acid application increased total yield by 18 cwt/acre, US No. 1 yield by 22 cwt/acre, and gross return by \$152/acre, these differences were significant at $P = 0.10$. As the study was carried out on calcareous soils it is expected that varying soils would yield different results that may not be as significant

Improving the Efficiency of Other Nutrients

Many products intended to improve fertilizer efficiency are available for nutrients other than N and P. Although many products are new, their modes of action are often similar to the humic acid-P research previously described, with chelates or complexes added with fertilizer to enhance solubility and plant uptake. Another common approach is slow-release fertilizers, which have also been previously discussed. These approaches are valid and can enhance fertilizer efficiency by increasing solubility, but research documentation is needed to verify effectiveness.

A new approach to enhancing fertilizer efficiency of certain micronutrients is the impregnation of low-solubility micronutrient metals with elemental S (Tiger Micronutrients, Tiger-Sul Products, Calgary, Alberta). These metals include Zn, Fe, Mn, and Cu. Klikocka et al. (34) cite studies in which potato yields were favorably impacted with elemental S application. In some cases, the effect was related to disease pathogens, but in others it was likely a nutritional effect. Elemental S is commonly used in the semi-arid regions of North America. It is both an efficient form of slow-release S and an amendment to dissolve carbonaceous minerals as the elemental S pastille oxidizes and forms sulfuric acid (16). When impregnated with Zn, Fe, Mn, and/or Cu; elemental S effectively places these nutrients in a microclimate of acid to neutral pH soil. As with P, these micronutrient metals have low solubility in alkaline soil because they form poorly soluble precipitates with sulfate and phosphate anions.

Additionally, micronutrients are much more likely to be spread uniformly and taken up by plants than traditional sources of micronutrients when impregnated with S. For example, the Tiger Micronutrients Potato Mix has 85% S and 1.5% of both Zn and Mn, each pastille weighing approximately 0.000059 lb. Application at a rate of 150 lb of S per acre results in a rate of 2.3 lb/acre for Zn and Mn, with a calculated distribution of 57 pastilles per square foot. In comparison, dry Zn and Mn are commonly applied in the sulfate form with 22 to 36% concentration of the metal in much larger, denser particles. Therefore, application of Zn and Mn sulfate at the same rate results in less than 1 fertilizer granule per square foot, which is poor spreading efficiency.

As impregnated S is relatively new, little field data on potatoes has been collected. Results from a 2006 trial in Idaho do not show significant increases in total yield over the untreated check; however, there was a significant increase in US No. 1 tubers for the elemental S combined with Zn and Mn when compared with the untreated check and the elemental S alone (Fig. 5). Although more data are needed, the preliminary results and the concept behind this new product are promising and are another example of enhanced efficiency fertilizer.

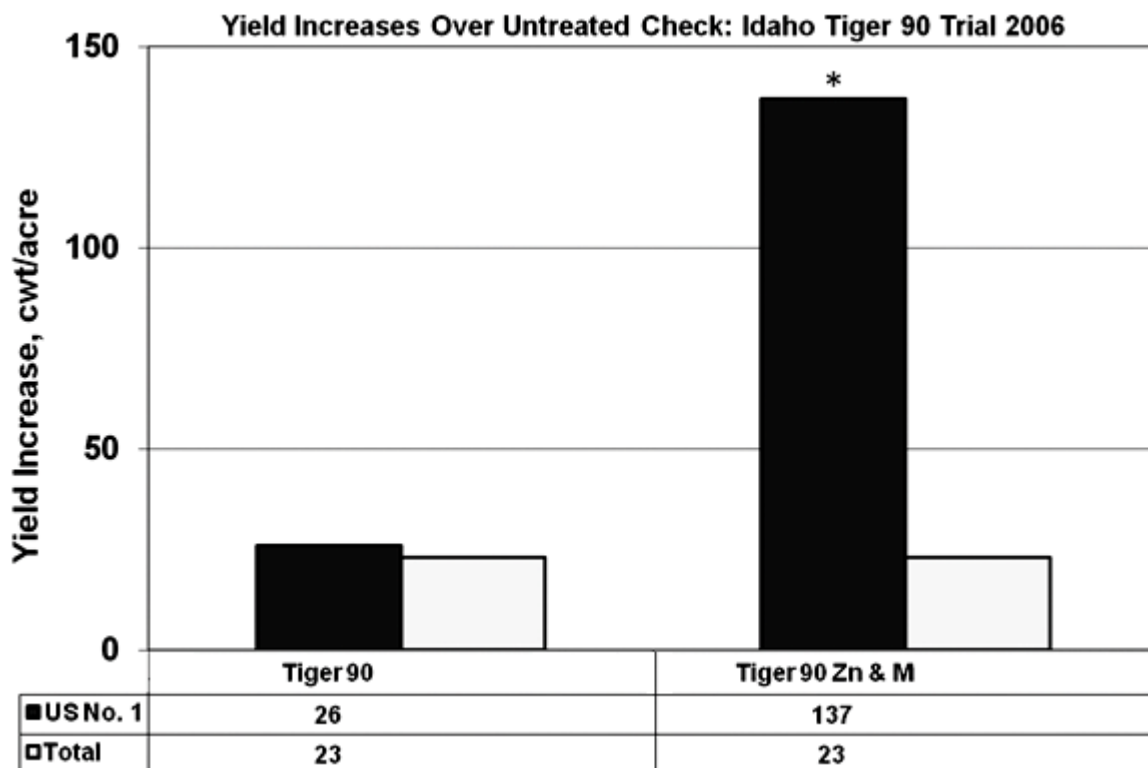


Fig. 5. Potato tuber yield increases (cwt/acre) of 2006 Idaho elemental sulfur-micronutrient field trial. Treated plots received 150 lb of S per acre as Tiger 90 elemental sulfur. Treatment receiving micronutrients had sulfur impregnated with 2.25 lb/acre of both zinc and manganese. Differences for total yield not significant; differences for US No. 1 (LSD 45 cwt/acre) significant at $P = 0.05$ (denoted by *).

Conclusions

Narrow profit margins, environmental concerns, and resource conservation issues are driving forces to improve fertilizer efficiency, especially for potato, which is a high value crop with a shallow, inefficient root system and requires high fertilizer rates. Many fertilizer products claim improved fertilizer efficiency. Several promising products representing cutting-edge technologies that address known problems with nutrient availability have been presented. There is a reasonable theoretical basis for their modes of action and randomized, replicated independent research available to evaluate their effectiveness. However, more data are needed on many of these products before more refined guidelines can be developed. Proper use of fertilizer materials has the potential to not only increase NUE and conserve valuable natural resources, but also to increase potato yields and tuber quality while reducing environmental impacts.

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