Polymer Coated Urea in Russet Burbank Potato Production

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Authorization to Submit Thesis

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Abstract

Potato (*Solanum tuberosum* L.) growth rate increases with increased soil and air temperatures, therefore increasing nitrogen (N) demand. A relatively new PCU may meet this demand in a more timely and efficient manner through temperature-controlled release of N. If so, this PCU may have the potential to increase yield and tuber quality, while minimizing gaseous and leaching N losses and increasing nitrogen use efficiency (NUE). Russet Burbank potato was grown in three locations near Aberdeen and Blackfoot, Idaho, USA in 2006 and near Aberdeen in 2007 with five rates of N (0, 33, 67, 100, and 133%) applied as either split-applied urea (similar to grower standard practices), urea applied all at emergence, or PCU applied all at emergence. The PCU-fertilized treatments produced higher US No. 1, marketable, and total tuber yields than the other fertilizer treatments and the unfertilized control. There was also a trend for increased tuber size, for PCU fertilized treatments. Increased NUE was demonstrated with increased yields per unit of N applied when using PCU.

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Chapter 1

An Introduction to Polymer Coated Urea in Russet Burbank Potato Production

Abstract

Potato (*Solanum tuberosum* L.) response to nitrogen (N) is important for tuber yield, size, specific gravity, and defects. Growers typically apply a portion of the N pre-plant and the remaining fertigated in-season—based on need for a steady, but not excessive supply of N throughout the vegetative and tuber bulking growth periods. Polymer-coated urea (PCU), a controlled release N fertilizer source, is an alternative to this standard practice. Potato growth rate increases with increased soil and air temperatures, therefore increasing N demand. A relatively new PCU may meet this demand in a more timely and efficient manner through temperature-controlled release of N. If so, this PCU may have the potential to increase yield and tuber quality, while minimizing gaseous and leaching N losses and providing a more convenient and less labor-intensive N fertilization system. The objectives of this study were to determine the effects of PCU on potato yield and quality, as well as nitrogen use efficiency (NUE). Russet Burbank potato was grown in three locations near Aberdeen and Blackfoot, Idaho, USA in 2006 and near Aberdeen in 2007 with five rates of N (0, 33, 67, 100, and 133%) applied as either split-applied urea (similar to grower standard practices), urea applied all at emergence, or PCU applied all at emergence. The PCU-fertilized treatments produced higher US No. 1, marketable, and total tuber yields than the other fertilizer treatments and the unfertilized control. There was also a trend for increased tuber size, for PCU fertilized treatments. Increase NUE was demonstrated with increased yields per unit of N applied when using PCU. These results, along with others, suggest that this PCU fertilizer efficiently meets the seasonal N requirement for Russet Burbank potato.

Introduction

Nitrogen Essential for Life

Perhaps the most important mineral nutrient in terrestrial ecosystems, including cropping systems, is nitrogen (N). Nitrogen, phosphorus, and potassium are the primary macronutrients for plants and make the vast majority of global fertilizer production, with N sales slightly greater than the other two macronutrients combined. Nitrogen is generally found in plants at higher concentrations than other minerals (Foth and Ellis, 1996; Ludwick et al., 2002). This high demand, coupled with the fact that soil N is lost relatively easily, results in N being the mineral nutrient most commonly deficient and most yield limiting in agricultural soils (Foth and Ellis, 1996).

Understanding the physical, chemical and biological processes involving N in agricultural ecosystems is important in managing this nutrient. The continuous phase changes of N from atmospheric gas to dissolved N in the soil solution and water bodies to solid phase found in plants and other organisms is the N cycle (Foth and Ellis, 1996). The main source of N is found in the atmosphere with a concentration of ~78% N_2 gas. This form of atmospheric gas is in a mostly biologically and chemically inert form. For plants to be able to utilize this N, it must be combined with hydrogen or oxygen (termed “N fixation”).

Fixation occurs via diazotroph soil microorganisms—both those living in a symbiotic connection with roots of plants (*Rhizobium* and *Frankia*) and those free living in soil or water (cyanobacteria, green sulfur bacteria, and *Azotobacteracea*). Legumes [such as alfalfa (Medicago sativa L.), clover (*Trifolium* spp.), peanut (*Arachis hypogaea* L.), and lupine (*Lupinus* spp. L.)] are commonly known to have this symbiotic association that results in N entering the plant-soil system. This N is used by the organisms responsible for fixation—followed by their eventual death and decomposition resulting in the N becoming available for uptake by other organisms. Another source of natural N fixation is lightning—with the extreme energy provided causing N_2 and H_2O to combine and be deposited on the surface of the Earth. These natural processes generally provide adequate N nutrition for leguminous crop plants and for plants in low N demand, native ecosystems, but is wholly inadequate for modern crop production systems involving non-leguminous plants responsible for providing food, fuel, and fiber for seven billion plus people on the planet. Currently, the only other means to fix N is through mechanical fixation into commercial fertilizers.

These N fertilizer sources are essential for long-term sustainability of human society. The Latin expression "*ex nihilo nihil fit*" is based on a thesis first presented by the Greek philosopher Parmenides, which essentially states that "out of nothing comes nothing"—an idea that is associated with the modern physical laws of conservation of mass and energy. Crop produce contains nutrients that are removed from fields during harvest. Fertile soils need replenishment of these nutrients to maintain high levels of crop production. There are many examples throughout history when this practice was not observed with devastating results. For example, the Middle East was once known as the "fertile crescent", but soil mismanagement anciently resulted in a loss of productivity in many areas of this part of the world even today. History was repeating itself during the late 19th and early 20th century in the southern US. Fortunately, George Washington Carver (1864-1943) and others recognized that these farming practices were not sustainable and were instrumental in getting farmers to correct this situation. Fertilizer use in the US increased dramatically during this time and was a major component of the Green Revolution, which has resulted in unprecedented levels of food production in the US and other developed nations.

The Green Revolution would not have been possible without replenishment of soil nutrients. Most of plant biomass is composed of non-mineral nutrients—carbon, oxygen, and hydrogen, which come from the air and water. However, plants are also composed of at least fourteen essential mineral nutrients. Although some of these mineral nutrients are supplied in part from atmospheric deposition and irrigation/precipitation deposition, the vast majority come from the soil. Fertile soils have a large reserve of many of the nutrients, but many of these are part of the solid phase fabric of the soil and, as such, are bound in solid mineral and organic matter forms largely unavailable to plants (Foth and Ellis, 1996). Plants have to "drink" their nutrients and, as such, only nutrients in the liquid phase are available to plants. Solid minerals containing nutrients have to dissolve and organic materials, such as plant residues, have to decompose before the nutrients are available for plant uptake. This latter process is especially important for N nutrition.

The normal release rate of nutrients from the fabric of the soil is usually inadequate to match the rate of loss from agrarian systems with high production efficiency. Therefore, application of fertilizer or other soil amendments are necessary for the intensive, highly productive crop production systems required to feed a rapidly growing human population. The products provided by the fertilizer industry are, therefore, essential to maintaining high rates of productivity and fertile soils. Opponents of conventional fertilizers often claim the contrary, but the incontrovertible truth from the law of conservation of mass tells us that crop removal eventually depletes the soil of at least some of the essential plant nutrients. Selecting a field with high fertility can greatly aide in producing a crop with relatively lower fertilizer inputs (Thornton et al., 2007), but eventually all soils can be depleted of essential nutrients and, thus, fertilization is essential. Non-conventional fertilizer sources such as animal manures, composts and industrial by-products can also be used effectively for those wishing to avoid conventional fertilizers, although these sources can be problematic in terms of crop production, economics, and/or environmental quality (Hopkins et al., 2007).

Nitrogen fertilizer and soil N exists in a variety of organic and inorganic chemical forms, but non-leguminous plants and soil microbes take it up exclusively as inorganic forms of nitrate (NO_3^-) and ammonium (NH_4^+). The dominant plant-available form of N in soil is typically NO_3^-, as NH_4^+ is converted quickly to NO_3^- under normal soil conditions and, thus, NO_3^- is the N form primarily taken up by plants and soil microbes (Foth and Ellis, 1996). Once in the plant, NO_3^- is reduced to NH_4^+ before it can be utilized in plant processes. The NH_4^+ ions are the foundation of amino ($C_xH_yO_z$-NH_2) groups, which are incorporated into a variety of organic chemicals, including production of amino acids and nucleotides, which are the building blocks for proteins and nucleic acids. Proteins provide the basic framework for chloroplasts, mitochondria, and other compounds found within plant cells, as well as enzymes that are important in essential plant processes. The nucleic acids formed are important for DNA and RNA formation and function, which are essential in cell division and overall growth of the plant. These N containing compounds are also an important part of chlorophyll, which is needed to absorb energy for photosynthesis, the foundational process in supplying energy for all living organisms.

Nitrogen deficiency can have catastrophic consequences for any plant. Deficiency in plants is generally visible as a yellowing (chlorosis) of leaves due to a reduction in chlorophyll concentration, which gives a plant its green color as this molecule is highly reflective of light in the green spectrum. As N is a nutrient that is easily mobilized in plants, chlorosis tends to appear first on older leaves as the N is transported to higher priority, new growth areas. Eventually, necrosis of tips and margins of N deficient leaves begins to occur, again, starting with more mature leaves and progressing to newer leaves with time, with the end result being early senescence of the entire plant. Plants that are N deficient are also often stunted due to reduced photosynthesis and production of amino acids and nucleic acids.

Nitrogen in the Environment

Although the fertilization methods described above replenish the soil of lost nutrients, excessive or inefficient nutrient application can have detrimental effects to the environment (Davenport et al., 2005; Hopkins et al., 2008; Mueller and Dennis, 1996). The N cycle is “leaky” with some N being “lost” back to the atmosphere and the hydrosphere. There are environmental concerns associated with gaseous losses of ammonia (NH_3) and nitrous oxide (N_2O), as well as with elevated concentrations of NO_3 in groundwater, and N in surface waters.

One form of gaseous loss is volatilization of NH_3, which is an intermediate product formed during the conversion from organic N or urea fertilizer to NH_4^+. This is a particular problem if this transformation occurs at the soil surface where the NH_3 is less likely to pick up a proton from the soil and is more likely to escape into the atmosphere. Ammonium can also be lost through volatilization if equilibrium chemistry reverses the reaction to the gaseous NH_3 state, which reaction is favored and, thus more common, in alkaline soils. This reaction also occurs with fertilizers that have alkaline dissolution reactions, especially when they are reacted on the soil surface where it is less likely for the N to be captured by soil. Reactive NH_3 is of great concern for the environment. The gaseous NH_3 is deposited back on land or bodies of water through either wet or dry deposition. If this deposition occurs in sensitive ecosystems it can lead to soil acidification (Sutton et al., 2008) and surface water eutrophication (Boyd 2000). As a result, this deposition can also lead to reduced plant population and biodiversity (Sutton et al., 2008). Documented cases of the effects of NH_3 deposition show increased aluminum mobility, resulting in forest decline (Fenn et al., 1998).

Increased levels of atmospheric NH_3 affect air quality by contributing to smog (Rochette et al., 2009).

Another common gas loss mechanism is denitrification, which is the microbial facilitated reduction of NO_3^- to N gas (N_2O, N_2; Jacinthe et al., 2000; Mosier et al., 1996, 1998; Ruser et al., 1998; Shoji et al., 2001; Smith et al., 1998). Nitrous oxide is a potent greenhouse gas with a global warming potential 310 times greater than carbon dioxide (CO_2, USEPA 2007). As with plants, microorganisms require oxygen for life processes and some have the ability to utilize the oxygen found in NO_3^- when it becomes depleted in the soil—releasing N_2O gas as a waste byproduct. This occurs in all soils, especially in water saturated soils where oxygen levels are depleted. However, loss of N_2O occurs at background levels even in non-saturated soil conditions. This persistent gas has greenhouse effects (Isermann, 1994; Yung et al., 1976) and is a source of nitric oxide (NO), which has been known to contribute to ozone (O_3) depletion in the stratosphere (Isermann, 1994). The net effects are increased atmospheric warming potential and more UV radiation exposure to living organisms. Emissions of N_2O to the atmosphere via denitrification and nitrification are controlled by many interacting factors, including soil aeration, temperature, texture, NH_4^+ and NO_3^- concentrations, and microbial communities (Snyder et al., 2007). Emission of nitrous oxide from potato (*Solanum tuberosum* L.) fields is typically higher than most other crops (Ruser et al., 1998, 2001), likely due to the relatively high N fertilizer and water application rates (Munoz et al., 2005). Hirsch et al., (2006) estimated anthropogenic emissions of N_2O have increased by approximately 50% over pre-industrial levels. Fertilization accounts for 78% of that total, with automobile and industrial pollution making up most of the remainder (USEPA 2007).

Another loss mechanism for N is leaching into groundwater. The NO_3^- form of N is prone to leaching loss below the plant root zone because it is highly soluble and is negatively charged and, thus, repelled by negatively charged soil particles. Mobility is especially problematic in course textured soils and in soils with large macropores (root channels and soil cracking). The N lost via leaching can eventually contaminate groundwater (Mueller and Dennis, 1996). High applications of fertilizer and poor N Use Efficiency (NUE) in potato can contribute to N contamination to groundwater (Hill, 1986; Honisch et al., 2002; Madramootoo et al., 1992; Milburn et al., 1990; Mueller and Dennis, 1996; Munoz et al., 2005; Porter and Sisson, 1991, 1993; Richards et al., 1990; Westermann et al., 1988; Zvomuya et al., 2003).

Nitrate also poses a potential health risk to humans and livestock at high concentrations in drinking water. The primary concern is methemoglobinemia or "blue baby syndrome", which is a concern with infant's drinking water high in NO_3^-, which effectively blocks the blood from carrying oxygen through the body (Olson et al., 2009). There are a variety of other potential health risks as well, although most are poorly documented and only theoretical.

Nitrate-N can also move laterally to surface waters through runoff or the erosion of soil into surface water bodies, especially on compacted /crusted soils or steep slopes (Randall and Mulla, 2001). In addition to problems related to using this water for drinking purposes, NO_3^- in surface water is one of the primary contributing factors for eutrophication and hypoxia (Goolsby et al., 2001; Munoz et al., 2005; Rabalais et al., 2002). Eutrophication is the enrichment of waters by inorganic plant nutrients (especially N and phosphorus) causing excess growth of algae, growth of aquatic macrophytes, and oxygen depletion—with subsequent death of fish and other aquatic life. Nitrogen deposition can therefore lead to plant community loss and reduction of biodiversity (Sutton et al., 2008). As with groundwater contamination, poor NUE and high water and fertilizer applications in potato can also contribute to significant N contamination in surface water bodies (Hill and McCague, 1974; Honisch et al., 2002; Milburn et al., 1990; Munoz et al., 2005).

In addition, commercial fertilizer manufacturers combine N_2 gas with methane (CH_4) from natural gas in the Haber-Bosch process to form the NH_3 used in artificial fertilizers. Although N_2 gas is in abundance in the atmosphere and, thus, is renewable; CH_4 is a non-renewable resource found in subterranean fossil deposits and, as such, the supply will be exhausted at some point in the future. It has been reported that as much as 3-5% of the world's natural gas production is consumed by the Haber-Bosch process (Smil, V. 2004). In order to conserve these natural resources, it is essential that efficiencies are found to reduce the amount of N lost in the plant-soil system. Finally, all sources of waste, including N fertilizer lost to the environment, cause financial losses to growers.

Potato Nutrient Management

Potato is the most commonly grown root crop, providing the primary source of calories from starch in many developing countries, and is one of six major crops providing 80% of human caloric intake worldwide (Leff et al., 2004; Nabors, 2004). Although considered a minor crop in the United States, ranking 14th in acreage, potato is 6th in crop value according to the most recent US agricultural census (USDA-NASS, 2014).

Potato has a relatively high cost of production. For example, Idaho farmers grow over 30% of US potato production (USDA-NASS, 2014) and have average production expenditures of \$6041 to \$8888 ha^{-1} (including both operating and ownership costs) (Patterson, 2013). Costs in other potato growing regions likely have similar or higher production costs due to longer growing seasons (requiring more nutrients and pesticides to sustain growth) and/or less than optimal conditions (such as regions with high humidity requiring relatively more fungicide). Operating costs are part of the total cost of production and are relatively high for potato as compared to other crops, ranging from \$4003 to \$6091 ha^{-1} in Idaho, with approximately 11-15% of this being fertilizer (Patterson, 2013). Operating costs are rising rapidly with dramatic increases in cost of fertilizer materials, with average prices increasing as two to three-fold+ from 2005 to 2013. However, cost can vary widely depending on the source.

Potato requires more fertilizer than most crops, primarily due to relatively high nutrient demand and a shallow, inefficient rooting system (Hopkins et al., 2008; Izadi et al., 1996; Munoz et al., 2005; Pack et al., 2006; Peralta and Stockle 2002; Westermann, 2005; Yamaguchi and Tanaka, 1990). Potato roots generally reside in the top 60 cm of soil and with 90% of root length in the top 25 cm, compared to most other crops that root much deeper (Tanner et al., 1982). There are also inefficiencies within the soil that prevent plants from utilizing the entire nutrient applied and/or residing in the soil. Another reason for high rates of fertilizer application to potato is that production of tubers desirable by consumers (large and uniform with minimal surface imperfections) is very sensitive to having an adequate, steady supply of nutrients, especially N (Stark et al., 2004; Westermann 2005).

The net result is that nutrient recovery from fertilizer is relatively low due to inherent inefficiencies in the soil-plant-atmosphere system (Hopkins et al., 2008). Potato recovery of soil applied N has been reported at a level of only 16-36% under conditions of severe leaching (Errebhi et al., 1998). Other researchers have reported slightly higher N recovery percentages (Hill, 1986; Meyer and Marcum, 1998), but N utilization is inherently inefficient in all systems. These inefficiencies in N utilization become a waste of the natural resources used to manufacture the fertilizer and, if N is left unused in the soil, may become an environmental pollutant.

As a result, recommended rates of major nutrients needed for economically optimum yields (Hopkins et al., 2007, 2008) are substantially higher for potato compared to other crops (Joern and Vistosh, 1995a; Milburn et al., 1990; Munzo et al., 2005; Prunty and Greenland 1997; Tyler et al., 1983; Zvomuya et al., 2003). This is especially true for N (Stark et al., 2004; Westermann, 2005). For instance, the University of Idaho recommendations for N fertilizer are substantially higher for potato (Stark et al., 2004) compared to spring wheat (*Triticum aestivum* L.; Brown et al., 2001). Not only is potato relatively more sensitive to N deficiencies, but also excesses as compared to many other crops—requiring careful N management prior to and during the growing season (Biemond and Vos, 1992; Errebhi et al., 1999; Geary et al., 2015; Miller and Hopkins, 2007; Stark et al., 2004).

Deficiencies or fluctuations of N often result in the following effects on potato growth and tuber quality: diminished leaf/vine canopy, reduced tuber number, reduced tuber size, malformed shape, excessively high specific gravity (solids), poor skin integrity, increased susceptibility to bruise, dark fry color, increased incidence of brown center and hollow heart, and increased susceptibility to certain pathogens and insects (Geary et al., 2015; Ojala et al., 1990; Olsen et al., 2003; Stark and Love, 2003; Stark et al., 2004).

Adequate or excessive N results in a more succulent plant and, therefore, facilitates attack from pathogens and insects that are thwarted by a non-succulent tissue (Geary et al., 2015). However, other pathogens and insects are favored by a weakened plant and/or the presences of necrotic tissue. In addition to making the plant more susceptible to certain pests, excessive N can also be detrimental in other ways. Most crops will tolerate a modest excess of N without major problems, but potato is relatively sensitive to excess N. In general, potato requires a large portion of its required N early in the season for adequate canopy growth (Stark et al., 2004; Vos, 1999; Westermann, 2005). However, excessive N early in the season can delay the formation of tubers 7-10 days due to excessive vine/leaf growth in many cultivars, possibly resulting in reduced tuber yields (Kleinkopf et al., 1981). This is especially true for indeterminate cultivars, such as *Russet Burbank*, but is not as large of a problem for determinate types, such as Russet Norkotah, which needs to have most of the required N on by the end of flowering (Bohl and Love, 2003).

Following tuber initiation, potato requires an adequate, steady supply of N during the tuber bulking growth phase. If N is deficient during this stage, the result is reduced canopy growth along with premature senescence of potato vines, which also results in reduced tuber yields (Geary et al., 2015; Stark et al., 2004; Westermann, 2005). However, excessive N during tuber bulking and late season development promotes prolonged vegetative growth, resulting in slowed tuber bulking and reduced tuber yields (Maynard and Lorenz, 1979; Waddell et al., 1999). If N levels throughout the season are widely fluctuating instead of steady, the result may be irregular tuber growth and can increase the formation of internal (brown center and hollow heart) and external (misshapen) tuber symptoms (Stark et al., 2004; Westermann, 2005). Ideally, when harvest approaches, N levels must subside in order to maximize transport of above ground carbohydrates to the tubers to provide maximum yield potential and to enhanced formation of an adequate outer layer of “skin” on the tubers, indicating full maturity.

Because potato needs a steady supply of N throughout the growing season, it is recommended that N availability be synchronized with plant demand to maximize NUE and yield and tuber quality (Errebhi et al., 1998; Gayler et al., 2002; Hopkins et al., 2008; Hopkins and Hirnyck, 2007; Joern and Vitosh, 1995b; Munoz et al., 2005; Prunty and Greenland, 1997; Ruser et al., 1998; Saffigna et al., 1977; Singh and Sekhon, 1976a & b; Stark et al., 2004; Waddell et al., 2000; Westermann, 2005; Westermann et al., 1988; Westermann and Kleinkopf, 1985). Researchers and potato growers have learned that overall yield and, often more importantly, tuber quality is greatly impacted by having a steady supply of adequate but not excessive N. For this reason growers generally split-apply N at intervals throughout the growing season to best meet crop growth and demand. This process is sometimes referred to as “spoon feeding” the potato crop. Many studies suggest that “spoon feeding” N is a good practice to maximize yield and to ensure tuber quality (Hopkins et al., 2008); however, others show no benefit or even a detriment to the potato crop (Zebarth and Rosen, 2003). Though, there is little doubt that one of the primary benefits of applying N as close to the time of need as possible is reduced risk of N loss to the environment (Errebhi et al., 1999; Munoz et al., 2005; Ruser et al., 1998; Waddell et al., 1999, 2000).

In general, growers will apply 25-50% of the predicted total N requirement for the crop before or at plant emergence. This can be in one application or a combination of pre-plant, at planting, and side dress applications. The remainder of the required N is applied to the crop in increments throughout the remainder of the growing season. This is typically done as injections into the irrigation system (fertigation) or as broadcast application via air or ground based spreader. The amount applied is somewhat predictable based on pre-plant soil tests and fertilizer recommendations based on research (Stark et al., 2004), but in-season adjustments are based on weekly samples of petiole tissue (Zhang, et al., 1996) and, in some cases, soil samples. In general, petiole NO_3^--N concentrations for Russet Burbank in Idaho should be between 15,000-20,000 mg kg^{-1} to be sufficient for vine and tuber growth during the growing season and then gradually dropping below 10,000 mg kg^{-1} by the end of tuber bulking late in the season (Stark et al., 2004; Westerman, 1993).

A possible option to enhance/replace petiole guided fertilization is the use of optical sensing equipment. This technology has become available and is used to determine plant N needs in conjunction with variable rate fertilizer technology in small grains (Lukina et al., 2001; Moges et al., 2004; Mullen et al., 2003; Raun et al., 2001, 2002, 2005; Tremblay et al., 2008) as well as other crops such as maize (Zea mays L.; Bausch and Duke, 1996; Tremblay et al., 2008), grasses (Solie et al., 1999), and cotton (Tarpley et al., 2000). This instrumentation shows promise to help growers more precisely manage N and other inputs and is being used for some crops (Heege et al., 2008; Lukina et al., 2001; Mullen et al., 2003; Raun et al., 2002, 2005; Scharf et al., 2002; Solie et al., 1999; Tarpley et al., 2000; Tremblay et al., 2008), although utilization for potato is not yet in practice because of a lack of data correlating N need to this technology (Bowen et al., 2005). Research using optical sensing tools for detecting N needs of potato are showing promise (Bowen et al., 2005; Herrmann et al., 2010; Jain, et al., 2007; Wu et al., 2007). The primary optical tool being used is Normalized Difference Vegetation Index (NDVI). An optical sensing device (GreenSeeker, N-Tech Industries, Ukiah, Cal, USA) measures NDVI using wavelengths of 774 nm for the near infrared (NIR) and 656 nm for the visible red spectrum (VIS). NDVI is calculated by taking the difference of intensity at the NIR and VIS wavelengths and then dividing this difference by the sum of the two intensities: NDVI = (NIR - VIS) / (NIR + VIS) (Kriegler et al., 1969). It is hoped that this data will give a general potato plant health assessment of the crop similar to petiole analysis.

It is important to note that the N requirements discussed above generally apply to *Russet Burbank* potato, which represents about 37% of the fall potato acreage in the U.S., (NASS, 2014), and similar medium to long-season indeterminate cultivars that are perhaps more sensitive to N deficiencies and excesses than other cultivars. For example, the determinate Russet Norkotah cultivar and many red and white cultivars require relatively higher amounts of N early in the growing season to promote early vine growth and harvest (Bohl and Love, 2003). Ranger Russet is not as sensitive to N management, as it can have N applied all preplant or during the season depending on soil type, grower preference, or growing area (Love et al., 1998). Another cultivar, Alturas, requires approximately 40% less N than required by *Russet Burbank* (Novy et al., 2003) and is, therefore, more efficient in uptake of N due to an efficient rooting system. These cultivar differences are generally related to time to maturity and/or root density (Love et al., 2003; Sattlemacher et al., 1990). Therefore, it is important for growers to know the cultivar they are producing and how it responds to N application.

Although the practice of “spoon feeding” with the associated NDVI and/or soil/petiole tests can help increase tuber yield and quality, it is labor and equipment intensive and, as a result, more costly. In fact, there are some irrigation systems that cannot be used to inject fertilizer because of the lack of the proper equipment (i.e. backflow valves). In many potato producing regions, there is ample precipitation and growers do not rely a great deal or at all on irrigation, making fertigation for in-season applications a poor or non-existent option. These constraints limit growers to applying the required N in one pre-emergent application or in combination with costly aerial/ground based broadcast applications. However, aerial application is not permissible or safe in some cases and ground application results in field damage as a spreader drives through a fully developed canopy. In all cases, the cost of spoon feeding application N is high. In addition, liquid forms of N that are injected into the irrigation system are typically more costly than the dry forms commonly used for non-fertigated applications.

Improvements in Nitrogen Use Efficiency

It is desirable to eliminate or reduce costly in-season N applications, but it is vital to maintain or improve farm sustainability and profitability (Hopkins et al., 2007, 2008). As mentioned previously, it is also desirable to improve NUE in order to: conserve natural resources, reduce enrichment of NO_3^- in surface and groundwater, and reduce loss of NH_3 and N_2O to the atmosphere. “Spoon feeding” N is commonly used to meet the crops needs throughout the growing season. However, losses still occur even with proper N management under a conventional fertilization system. Therefore, it is important to find efficient ways of supplying N with new fertilizer technologies.

Controlled release N (CRN) and slow release N (SRN) sources are classes of fertilizers that release N into the soil over an extended time—rather than a flush of a large amount of immediately soluble N into the soil solution. This potentially provides an improvement in matching the plant’s needs throughout the growing season. Application of these fertilizers may even eliminate or reduce labor intensive and costly in-season N applications, as well as increase NUE and improve environmental quality (Allen, 1984; Alva, 1992; Amans and Slagen, 1994; Delgado and Mosier, 1996; Hopkins et al., 2008; Hutchinson et al., 2003; Mikkelsen et al., 1994; Munoz et al., 2005; Pack et al., 2006; Shoji and Kanno, 1994; Shoji et al., 2001; Wang and Alva, 1996; Zvomuya et al., 2003). The CRN fertilizers are coated or encapsulated and gradually or time delay release N through the coating. An example of a CRN is Osmocote (Scotts-Sierra Horicultural Products Company, Marysville, OH), which is used commonly in the potting soil industry. The SRN fertilizers are compounds of low solubility that gradually release N and other nutrients as the compound slowly dissolves into soil solution. These products are in contrast to “quick release” N fertilizers that almost instantaneously release N into soil solution and, in the case of urea, convert to NH_4^+ and then NO_3^-. These SRN products include, but are not limited to: sulfur coated urea, urea-formaldehydes, methylene ureas, and triazine compounds (Blaylock et al., 2005; Smith and Harrison, 1991; Trenkel, 1997).

These fertilizer materials and the concepts behind them are not new (Ahmed et al., 1963; Blouin et al., 1971; Lunt and Orteli, 1962; Orteli and Lunt, 1962), but previous work has been mostly unsuccessful and/or often proved too costly for use in potato and many other crops. These fertilizer materials tended to release N too early, too late, and/or in an unpredictable manner—resulting in delays in tuberization and yield losses (Cox and Addiscot, 1976; Hutchinson et al., 2003; Liegel and Walsh, 1976; Lorenz et al., 1972, 1974; Maynard and Lorenz, 1979; Waddell et al., 1999). However, some studies have shown that potato fertilized with sulfur coated urea, isobutylideen diurea (IBDU), or gypsum- or rock phosphate-coated urea were more effective than soluble fertilizers under severe leaching conditions (Elkahif and Locascio, 1983; Liegel and Walch, 1976). In contrast, Liegel and Walsh (1976) also found that sulfur coated urea did not perform as well under more normal weather conditions. Zvomuya et al. (2003) found that a polyolefin coated urea resulted in 34-49% less leaching of NO_3^- and increased yield, as well as improved NUE. However, because of the cost of the fertilizer was five times that of urea, it was not economically feasible. Research performed by Zvomuya and Rosen (2001) had similar economic results. Shoji et al. (2001) found that a CRN material compared to a traditional N source reduced N_2O emissions, improved NUE, and resulted in comparable potato, maize, and barley (*Hordeum vulgare* L.) yields.

Polymer-Coated Urea (PCU) fertilizers are CRN's that release N into the soil solution with the rate of release controlled by soil temperature. Plant growth and, thus, nutrient demand are also temperature driven. The idea behind temperature release PCU fertilizers is to attempt to synchronize N release with N demand, thus minimizing the time the N is exposed to potential loss to the environment (Gandeza et al., 1991; Munoz et al., 2005; Zvomuya and Rosen, 2001). The process of release begins by the diffusion of water thru the coating. The urea is then dissolved into the internal solution—remaining suspended within the capsule. The relatively small water molecules can freely move across the coating membrane, but urea is a larger molecule that cannot move across the membrane until, we hypothesize, the pores of the membrane expand due to increased temperature and/or until the membrane decomposes due to physical, chemical, or microbial action. Once this occurs, the urea diffuses through the coating into the soil solution where it then enters the N cycle and becomes plant available. This diffusion of urea out of the fertilizer shell is driven by the concentration gradient, with temperature being the primary regulator (Agrium Advanced Technologies, 2011). Several studies have looked at the effects of PCU fertilizers on tuber yield and quality and have shown positive results (Belanger et al., 2001; Bero et al., 2014; Cambouris et al., 2014; Hyatt et al., 2010; Hopkins et al., 2008; Hutchinson et al., 2003; Shoji et al., 2001; Wilson et al., 2009; Worthington et al., 2007; Zebarth et. al., 2012; Ziadi et al., 2011; Zvomuya and Rosen, 2001; Zyomuya et al., 2003). Other studies focusing on N loss via leaching and N_2O emissions have also shown promise with PCU fertilizers, as well as increased NUE (Bero et al., 2014; Gagnon and Ziadi, 2010; Venterea et al., 2011; Wilson et al., 2010; Zebarth et. al., 2012; Ziadi et al., 2011; Zvomuya et al., 2003).

One such PCU is Environmentally Smart N (ESN®, 44-0-0; Agrium Advanced Technologies, Brantford, Ontario, Canada). The claim behind ESN is that it is engineered to release N to the crop with control and predictability due to micro-thin polymer coatings, with date of release impacted by thickness of the coatings. A preliminary ESN trial in Idaho in 2005 showed promising results (Hopkins et al., 2008). The ESN applied immediately prior to hilling performed significantly better than urea applied at the same time for US No. 1, marketable, and total yield, with increases of 5.6, 5.3, and 4.4 Mg ha^{-1}, respectively. The grower's standard practice of multiple N applications was significantly better for US No. 1 yield (3.5 Mg ha^{-1}), but not for total or marketable yield. It is also noteworthy that the reduced rate of N applied as ESN (80% of recommended) was significantly better than the 100% ESN treatment for US No. 1 tuber yield with a 3.4 Mg ha^{-1} difference. This effect was similar to research results from Florida with the Atlantic cultivar, in which a 65% of the recommended N fertilizer rate was optimum for the controlled release fertilizers (not ESN) evaluated (Hutchinson et al., 2003; Pack et al., 2006). The N release from ESN closely matches the N uptake needs of *Russet Burbank* potato under field conditions (Wilson et al., 2009). This effectively reduces the time that NO_3^- is exposed to environmental loss from the soil, thus improving NUE and, potentially potato yield and/or quality. Unlike most other CRN (as well as SRN) fertilizers, costs for ESN are typically 25-50% higher than standard urea. Although costs are higher, they are not 2-10 times higher, which has been typical for SRN and CRN materials in the past.

This PCU technology, therefore, has the potential to meet the needs of increased NUE by increasing yields, maximizing net returns to the grower, and decreasing loss of N to the environment, and in addition improve sustainability of potato production, as well as other crops. Utilization of ESN in potato cropping systems may prove to be economical if total

NUE is improved and rate of N applied can be reduced and/or yields and/or tuber quality are improved.

Objectives

The objectives of this study were to develop more efficient N management practices for potato through the use of improved PCU technology (ESN) and crop N monitoring technology. In order to do this a comparison of ESN and uncoated urea to an untreated control was performed on *Russet Burbank* potato production under semi-arid, volcanic sand soil conditions in Idaho for: US No. 1, marketable (US No. 1 and 2), and total tuber yields; tuber size, solids, and internal and external defects; petiole NO_3-N, NDVI, yield per unit of N applied (ΔY/N), and seasonal change in residual NO_3-N (ΔNO_3-N).

Materials and Methods

Three trials were conducted in commercial potato fields evaluating the effectiveness of ESN on *Russet Burbank* potato. The fields were located in southern Idaho, USA near Blackfoot (Bannock loam) and Aberdeen (Declo loam) in 2006 and in Aberdeen (Declo loam) in 2007. In general, the soils were low in organic N and highly calcareous with medium to high concentrations of most nutrients (Table 1). All fields were irrigated with 0.56-0.66 m water that contained 5-6 mg kg^{-1} of NO_3^--N. The previous crop was spring wheat or barley with approximately 2 Mg ha^{-1} of residual grain stubble.

Site selection was based on principles discussed by Thornton et al. (2007). Cooperating growers typically achieve above average potato yields and tuber quality and followed Best Management Practices (Hopkins et al., 2007, 2008; Miller and Hopkins, 2007). Standard grower practices were followed to ensure N was the only potential limiting factor. However, the 2006 Blackfoot location had problems due to a severe early die (*Verticillium dahlia*) infection that resulted in canopy senescence 2-3 weeks earlier than desired. It should be noted that two additional trials were performed on growers’ fields near Rupert, Idaho in 2006 and 2007 with the same treatments and methods. However, the data from these locations were omitted from data analysis because of problems with irrigation and N contamination from irrigation source (Appendix A).

Individual plots were 3.6 m wide (four 0.91 m rows) by 12.2 m in length with treatments established in a randomized complete block design (RCBD) with 4 replications/blocks. Thirteen treatments were evaluated, including: an untreated check and four rates of N (33%, 67%, 100%, and 133% of recommended N) applied as: 1) ESN applied pre-emergence, 2) uncoated urea (46-0-0) applied pre-emergence, or 3) uncoated urea split applied. The four rates of N were 33%, 67%, 100%, and 133% of recommended N rate based on University of Idaho fertilizer recommendations for *Russet Burbank* potato using soil test values, yield potential, and previous crop information for each location (Stark et al., 2004). The recommended N rate for both 2006 locations was within 10 kg N ha^{-1} and, therefore, the rates were rounded up/down to be equivalent. The recommended N rate in 2006 was 303 kg ha^{-1} N. Therefore, the four rates applied were 101, 202, 303, and 404 kg ha^{-1} for the 33%, 67%, 100%, and 133% N rates, respectively. The recommended N rate in 2007 was 269 kg ha^{-1} N. Therefore, the four rates applied were 90, 179, 269, and 359 kg ha^{-1} for the 33%, 67%, 100%, and 133% N rates, respectively.

The pre-emergence applications occurred just prior to cultivation and plant emergence. The timing of the single application of ESN or urea was determined based upon research conducted at the University of Idaho (Hopkins et al., 2008) and the University of Minnesota (Wilson et al., 2009) showing that ESN applied before planting may release N too early for Russet Burbank potato needs and result in a substantial delay in tuber initiation and, thus, yield losses. The University of Minnesota data shows that the N release curve from ESN closely followed that for plant N need when it was applied at plant emergence (Wilson et al., 2009). From these data it was determined that ESN should be applied at or just prior to plant emergence and just prior to cultivation/hilling to ensure fertilizer was incorporated into the soil. This is a common application timing used to supply at least part of the N needs for potato in Southern Idaho. The treatments applied pre-emergence were incorporated into the soil 1-2 days after application. Cultivation occurred on June 3 for both Aberdeen and Blackfoot in 2006, which was 28 and 16 days after planting (DAP) respectively. In 2007, cultivation occurred on May 21 for Aberdeen, which was 23 DAP.

The split-applied treatment at the 100% recommended rate represented the grower standard practice. The split-applied treatments had 50% of the N applied pre-emergence (as described previously); with the remainder applied in three equal applications throughout the growing season. Timing of the first in-season application was based on University of Idaho in-season N recommendations (Stark et al., 2004) based upon petiole NO_3^--N analysis of composite samples from the grower standard practice plots. The composite petiole and Normalized Difference Vegetative Index (red NDVI; GreenSeeker, N-Tech Industries, Ukiah, Cal, USA) results were used to guide petiole sampling from all plots in an effort to identify the optimum date to document maximum petiole NO_3^- -N differences by treatment. In 2006, the first in-season application took place on July 15 for Aberdeen and Blackfoot. In 2007, the first in-season application took place on July 10 in Aberdeen. The subsequent two in-season applications were applied every two weeks thereafter. All N applications were made using a rotary hand spreader to apply pre-weighed fertilizer uniformly across the plot area.

The NDVI measurements were taken in the center of each plot and integrated over ~5 s. Petiole tissue samples were taken from each plot in 2006 on August 16 for Aberdeen and Blackfoot. Plant tissue samples were taken in 2007 on August 15 for Aberdeen. Samples were taken from the fourth fully emerged petiole from the top of each plant (Stark et al., 2004). Thirty-five petioles were sampled from each plot, dried and ground to pass through a 1 mm screen and were analyzed for NO_3-N using the chromotropic acid analysis (Sims and Jackson, 1971). The analysis for nitrate is done using an automated colorimetric produce using flow injection analysis (FIA; Quick Chem 8500, Lachat Instruments, Hach Company, Loveland, Col., USA).

Vines were killed by mechanical defoliation on September 11, 2006 for Aberdeen. Vines were not killed at Blackfoot in 2006 because they were 90% senesced on the date of scheduled vine kill. In 2007 vines were killed by mechanical defoliation on September 8 at Aberdeen. After sufficient time for skins to thicken, the 2006 harvest occurred on October 6 and October 13 for Aberdeen and Blackfoot, respectively. Harvest in 2007 occurred on September 28. Approximately 6.1 m of row were harvested from each of the center two rows of each plot. Tubers were stored in a controlled environment potato cellar in burlap bags for 21 to 31 d until they could be graded for size, shape, internal/external defects, and solids content (specific gravity) based on USDA potato grading standards (USDA, 1998). After grading and weighing, a random subsample of two tubers was taken from each of the four US No. 1 size categories (114-170, 170-284, 284-397, and >397 g). These eight tubers were used to evaluate solids (Kleinschmidt et al., 1984) and internal quality. For the internal analysis the tubers were assessed for the presence of hollow heart and brown center on a percent incidence basis—with a known bias due the fact that an even number of tubers were assessed from each size category when the distribution of as harvested from each plot US No. 1 tubers across size categories was not equally distributed.

Soil samples were taken just prior to initial fertilization (composited for each of the four blocks) and again after harvest (from each of the 52 plots) at each location from within (0-0.46 m) and below (0.46-0.76 m) the primary rooting zone on November 1 and October 20, 2006 for Aberdeen and Blackfoot, respectively; and on November 1, 2007 for Aberdeen. These samples were taken with an eight cm diameter soil auger. Two samples were taken randomly from the center of each plot and composited and were analyzed for post-harvest NO_3-N. Results were then used to calculate ΔNO_3-N by subtracting the pre-plant soil NO_3-N from the post-harvest NO_3-N.

Approximate rainfall in 2006 from the first of May to the 13th of September was 48 and 26 mm for Aberdeen and Blackfoot, respectively, and in 2007 from May first to the end of October was 73 mm for Aberdeen; with no single precipitation or irrigation event so great in magnitude that it resulted in significant leaching or denitrification losses of NO_3-N during the growing season. However, in 2007 there was more rainfall in the months of September and October previous to pulling post-harvest soil samples than in other months, with Aberdeen receiving 37 mm of rainfall.

Because of missing data points due to some plots being washed out from irrigation problems, the data was analyzed with analysis of variance using GLM (General Linear Model) with a P=0.05 criteria using SAS (Version 9.1, SAS Institute, 2003, North Carolina, USA). Means were separated by LSD (Least Significant Difference) test with an alpha of 0.05.

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Chapter 2

Polymer Coated Urea in Russet Burbank Potato: Yield and Tuber Quality

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Abstract

Potato (*Solanum tuberosum* L.) response to nitrogen (N) is important for tuber yield, size, specific gravity, and defects. Growers typically apply a portion of the N pre-plant with the remaining N fertigated in-season—based on the need for a steady, but not excessive supply of N throughout the vegetative and tuber bulking growth periods. Polymer-coated urea (PCU), a controlled release N fertilizer source, is an alternative to this standard practice. Potato growth rate increases with increased soil and air temperatures, therefore increasing N demand. A relatively new PCU may meet this demand in a more timely and efficient manner through temperature-controlled release of N. If so, this PCU may have the potential to increase yield and tuber quality, while minimizing gaseous and leaching N losses and providing a more convenient and less labor-intensive N fertilization system. The objectives of this study were to determine the effects of PCU on potato yield and quality. Russet Burbank potato was grown at three locations near Aberdeen and Blackfoot, Idaho, USA in 2006 and near Aberdeen in 2007 with five rates of N (0, 33, 67, 100, and 133%) applied as either split-applied urea (similar to grower standard practices), urea applied all at emergence, or PCU applied all at

emergence. The PCU-fertilized treatments produced higher US No. 1, marketable, and total tuber yields than the other fertilizer treatments and the unfertilized control. There was also a trend for increased tuber size, for PCU fertilized treatments. These results, along with others, suggest that this PCU fertilizer efficiently meets the seasonal N requirement for Russet Burbank potato.

Introduction

Potato requires more fertilizer than most crops, primarily due to relatively high nutrient demand and a shallow, inefficient rooting system (Hopkins et al., 2008; Izadi et al., 1996; Munoz et al., 2005; Pack et al., 2006; Peralta and Stockle 2002; Westermann, 2005; Yamaguchi and Tanaka, 1990). As a result, recommended rates of major nutrients needed for economically optimum yields (Hopkins et al., 2007, 2008) are substantially higher for potato compared to many other crops (Joern and Vistosh, 1995a; Milburn et al., 1990; Munzo et al., 2005; Prunty and Greenland 1997; Tyler et al., 1983; Zvomuya et al., 2003). This is especially true for N (Stark et al., 2004; Westermann, 2005). Not only is potato relatively more sensitive to N deficiencies, but also excesses as compared to many other crops—requiring careful N management prior to and during the growing season (Biemond and Vos, 1992; Errebhi et al., 1999; Geary et al., 2015; Miller and Hopkins, 2007; Stark et al., 2004).

Because potato needs a steady supply of N throughout the growing season, it is recommended that N availability be synchronized with plant demand to maximize NUE and yield and tuber quality (Errebhi et al., 1998; Gayler et al., 2002; Hopkins et al., 2008; Hopkins and Hirnyck, 2007; Joern and Vitosh, 1995b; Munoz et al., 2005; Prunty and Greenland, 1997; Ruser et al., 1998; Saffigna et al., 1977; Singh and Sekhon, 1976a & b; Stark et al., 2004; Waddell et al., 2000; Westermann, 2005; Westermann et al., 1988; Westermann and Kleinkopf, 1985). In general, growers will apply 25-50% of the predicted total N requirement for the crop before or at plant emergence. This N can be applied in one application or a combination of pre-plant, at-planting, and side dress applications. The remainder of the required N is applied to the crop in increments throughout the remainder of the growing season. These applications are typically made as injections into the irrigation system (fertigation) or as broadcast applications via air or ground based fertilizer spreaders. The amount applied is somewhat predictable based on pre-plant soil tests and fertilizer recommendations based on research (Stark et al., 2004), but in-season adjustments are based on weekly samples of petiole tissue and, in some cases, soil samples.

Although the practice of “spoon feeding” can help increase tuber yield and quality, it is labor and equipment intensive and, as a result, more costly. In fact, there are some irrigation systems that cannot be used to inject fertilizer because of the lack of the proper equipment (i.e. backflow valves). In many potato producing regions, there is ample precipitation and growers do not rely a great deal or at all on irrigation, making fertigation for in-season applications a poor or non-existent option. These constraints limit growers to applying the required N in one pre-emergent application or in combination with costly aerial/ground based broadcast applications. However, aerial application is not permissible or safe in some cases and ground application results in field damage as a fertilizer spreader drives through a fully developed canopy. In all cases, the cost of spoon feeding application N is high. In addition, liquid forms of N that are injected into the irrigation system are typically more costly than the dry forms that are commonly applied.

Controlled release N (CRN) and slow release N (SRN) sources are classes of fertilizers that release N into the soil gradually over an extended time rather than as a rapid flush of a large amount of soluble N into the soil solution. This potentially provides an improvement in matching the N release to the plant’s needs throughout the growing season. Application of these fertilizers may even eliminate or reduce labor intensive and costly in-season N applications, as well as increase NUE and improve environmental quality (Allen, 1984; Alva, 1992; Amans and Slagen, 1994; Delgado and Mosier, 1996; Hopkins et al., 2008; Hutchinson et al., 2003; Mikkelsen et al., 1994; Munoz et al., 2005; Pack et al., 2006; Shoji and Kanno, 1994; Shoji et al., 2001; Wang and Alva, 1996; Zvomuya et al., 2003).

Polymer-Coated Urea (PCU) fertilizers are CRN’s that release N into the soil solution with the rate of release controlled by soil temperature. Plant growth and, thus, nutrient demand are also temperature driven. The idea behind temperature release PCU fertilizers is to attempt to synchronize N release with N demand, thereby minimizing the time the N is exposed to potential loss to the environment (Gandeza et al., 1991; Munoz et al., 2005; Zvomuya and Rosen, 2001).

One such PCU is Environmentally Smart N (ESN®, 44-0-0; Agrium Advanced Technologies, Brantford, Ontario, Canada). The claim behind ESN is that it is engineered to release N to the crop in a controlled and predictable manner due to micro-thin polymer coatings, with date of release impacted by thickness of the coatings. A preliminary ESN trial in Idaho in 2005 showed promising results (Hopkins et al., 2008). The ESN applied immediately prior to hilling performed significantly better than urea applied at the same time for US No. 1, marketable, and total yield, with increases of 5.6, 5.3, and 4.4 Mg ha^{-1}, respectively. The grower's standard practice of multiple N applications was significantly better for US No. 1 yield (3.5 Mg ha^{-1}), but not for total or marketable yield. It is also noteworthy that the reduced rate of N applied as ESN (80% of recommended) was significantly better than the 100% ESN treatment for US No. 1 tuber yield with a 3.4 Mg ha^{-1} difference. The N release from ESN closely matches the N uptake needs of *Russet Burbank* potato under field conditions (Wilson et al., 2009). This effectively reduces the time that NO_3-N is exposed to environmental loss from the soil, thus improving NUE and, potentially increasing potato yield and/or quality. Unlike most other CRN (as well as SRN) fertilizers, costs for ESN over uncoated urea is 25-50% more expensive. Although costs are higher, they are not 2-10 times higher, which has been common for SRN and CRN materials in the past. ESN may prove to be economical if total NUE is improved and rate of N applied can be reduced and/or yields and/or tuber quality are improved.

The objectives of this study were to compare the effects of ESN and uncoated urea on *Russet Burbank* potato production under semi-arid, volcanic sand soil conditions in Idaho for, with respect to US No. 1, marketable (US No. 1 and 2), and total tuber yields; tuber size, solids, and internal and external defects; petiole NO_3-N, NDVI, yield per unit of N applied (ΔY/N), and seasonal change in residual soil NO_3-N (ΔNO_3-N). Results for petiole, NDVI, ΔY/N, and soil ΔNO_3-N are discussed in a companion paper (Taysom et al., 201x). This paper focuses on overall yield and tuber quality.

Materials and Methods

Three trials were conducted in commercial potato fields evaluating the effectiveness of ESN on *Russet Burbank* potatoes. The fields were located in southern Idaho, USA near Blackfoot

(Bannock loam) and Aberdeen (Declo loam) in 2006 and in Aberdeen (Declo loam) in 2007. In general, the soils were low in organic N and highly calcareous with medium to high concentrations of most nutrients (Table 2.1). All fields were irrigated with 0.56-0.66 m water that contained 5-6 mg kg^{-1} of NO_3^--N. The previous crop was spring wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) with approximately 2 Mg ha^{-1} of residual grain stubble.

Site selection was based on principles discussed by Thornton et al. (2007). Cooperating growers typically achieve above average potato yields and tuber quality and followed Best Management Practices (Hopkins et al., 2007, 2008; Miller and Hopkins, 2007). Standard grower practices were followed to ensure N was the only potential limiting factor. However, the 2006 Blackfoot location had problems due to a severe early die (*Verticillium dahliae*) infection that resulted in canopy senescence 2-3 weeks earlier than desired. It should be noted that two additional trials were performed on growers' fields near Rupert, Idaho in 2006 and 2007 with the same treatments and methods. However, the data from these locations were omitted from data analysis because of problems with irrigation and N contamination from irrigation source (Appendix A).

Individual plots were 3.6 m wide (four 0.91 m rows) by 12.2 m in length with treatments established in a randomized complete block design (RCBD) with 4 replications/blocks. Thirteen treatments were evaluated, including: an untreated check and four rates of N (33%, 67%, 100%, and 133% of recommended N) applied as: 1) ESN applied pre-emergence, 2) uncoated urea (46-0-0) applied pre-emergence, or 3) uncoated urea split-applied. The four rates of N were 33%, 67%, 100%, and 133% of recommended N rate based on University of Idaho fertilizer recommendations for *Russet Burbank* potatoes using soil test values, yield potential, and previous crop information for each location (Stark et al., 2004). The recommended N rate for both 2006 locations was within 10 kg N ha^{-1} and, therefore, the rates were rounded up/down to be equivalent. The recommended N rate in 2006 was 303 kg ha^{-1} N. Therefore, the four rates applied were 101, 202, 303, and 404 kg ha^{-1} for the 33%, 67%, 100%, and 133% N rates, respectively. The recommended N rate in 2007 was 269 kg ha^{-1} N. Therefore, the four rates applied were 90, 179, 269, and 359 kg ha^{-1} for the 33%, 67%, 100%, and 133% N rates, respectively.

The pre-emergence applications occurred just prior to cultivation and plant emergence. The timing of the single application of ESN or urea was determined based upon research conducted at the University of Idaho (Hopkins et al., 2008) and the University of Minnesota (Wilson et al., 2009) showing that ESN applied before planting may release N too early for Russet Burbank potato needs and result in a substantial delay in tuber initiation and, thus, yield losses. The University of Minnesota data shows that the N release curve from ESN closely followed that for plant N need when it was applied at plant emergence (Wilson et al., 2009). From these data it was determined that ESN should be applied at or just prior to plant emergence and just prior to cultivation/hilling to ensure fertilizer was incorporated into the soil. This is a common application timing used to supply at least part of the N needs for potatoes in Southern Idaho. The treatments applied pre-emergence were incorporated into the soil 1-2 days after application. Cultivation occurred on June 3 for both Aberdeen and Blackfoot in 2006, which was 28 and 16 days after planting (DAP) respectively. In 2007, cultivation occurred on May 21 for Aberdeen, which was 23 DAP.

The split-applied treatment at the 100% recommended rate represented the grower standard practice. The split-applied treatments had 50% of the N applied pre-emergence (as described previously), with the remainder applied in three equal applications throughout the growing season. Timing of the first in-season application was based on University of Idaho in-season N recommendations (Stark et al., 2004) based upon petiole NO_3^--N analysis of composite samples from the grower standard practice plots.

Vines were killed by mechanical defoliation on September 11, 2006 for Aberdeen. Vines were not killed at Blackfoot in 2006 because they were 90% senesced on the date of scheduled vine kill. In 2007 vines were killed by mechanical defoliation on September 8 at Aberdeen. After sufficient time for skins to thicken, the 2006 harvest occurred on October 6 and October 13 for Aberdeen and Blackfoot, respectively. Harvest in 2007 occurred on September 28. Approximately 6.1 m of row were harvested from each of the center two rows of each plot. Tubers were stored in a controlled environment potato cellar in burlap bags for 21 to 31 d until they could be graded for size, shape, internal/external defects, and solids content (specific gravity) based on USDA potato grading standards (USDA, 1998). After grading and weighing, a random subsample of two tubers was taken from each of the four US No. 1 size categories (114-170, 170-284, 284-397, and >397 g). These eight tubers were used to evaluate solids (Kleinschmidt et al., 1984) and internal quality. For the internal analysis the tubers were assessed for the presence of hollow heart and brown center on a percent incidence basis—with a known bias due the fact that an even number of tubers were assessed from each size category when the distribution of as harvested from each plot US No. 1 tubers across size categories was not equally distributed.

Because of missing data points due to some plots being damaged from irrigation problems, the data was analyzed with analysis of variance using GLM (General Linear Model) with a P=0.05 criteria using SAS (Version 9.1, SAS Institute, 2003, North Carolina, USA). Means were separated by LSD (Least Significant Difference) test with an alpha of 0.05.

Results

General Response

Tuber yields across locations were significantly different for all measured parameters (Table 2.2), which are not surprising, given the differences in soil composition, climate, and the difference from 2006-2007 for the Aberdeen location. Field averages for yield parameters are shown at the bottom of Tables 2.3-2.5 and for specific gravity and internal defects in Table 2.6.

The N rate effect was also significant for nearly all measured parameters, with response similar across locations as indicated by a lack of a location by N rate interaction for most measured parameters (Table 2.2). The only exceptions were significant differences with location by N rate interactions for the smallest and largest size categories of US No. 1 tubers. There was an apparent size shift at both Aberdeen locations—with increasing N rate resulting in significantly reduced small tuber (114-170 g) yield and significantly increased large tuber (>397 g) yield (Table 2.3 and 2.5). This size shift did not occur at the Blackfoot location (Table 2.4). There was also a three-way interaction with source for US No. 2 tubers. This three-way interaction was due to high rates of urea applied at emergence resulting in higher US No. 2 yield at the AB2 location, but with no clear differences at the other two sites (Table 2.3-2.5).

As the interactions were generally not significant for most parameters, results were combined across locations to show the general N response (Table 2.7). The N rate response was significant for nearly all measured parameters (Table 2.7). Most notably, highly significant increases in marketable and total yield as a function of N fertilization was observed (Table 2.2)—with maximum yields first being reached at the 67% N level (Fig. 2.1). Nitrogen rate effects on US No. 1 yields were significant as well, following a trend similar to that for marketable and total yield. However, differences for US No. 1 yield were not as pronounced and maximum US No. 1 yield was first reached at 33% of the full recommended N rate (Fig. 2.1). Additionally, N rate impacted all tuber size categories (Table 2.2) with a general trend towards larger tubers as N rate increased (Tables 2.3-2.5). Specific gravity was also impacted by N rate (Table 2.2), with increasing N rate generally decreasing specific gravity (Table 2.6).

Fertilizer Source

The impact of fertilizer source was significant for many yield and quality factors, with the response generally similar across locations (Table 2.2). Exceptions for the location interaction include US No. 2 (discussed above as the three-way interaction with N rate) and total yield (Table 2.2). The PCU resulted in significant increases in total yield over the untreated control at the Aberdeen 2006 and Aberdeen 2007 fields and was greater than both urea treatments at Aberdeen (Fig. 2.2). The Blackfoot 2006 field followed a similar trend for a general N response, although treatment effects were not significant. The N rate by fertilizer source interaction was not significant for any parameter (Table 2.2) and, thus, results were combined across N rates for the discussion below.

Fertilizer source impacted total yield and several tuber quality parameters—mostly independent of N rate and location (Table 2.2). The PCU treated tubers had significantly greater US No. 1, marketable, and total yield than all other treatments and all fertilized treatments were significantly greater than the unfertilized control (Fig. 2.3). It is interesting to note that there was no difference in yield response between the split-applied urea and urea applied all at emergence. This is not typically observed by growers, and has been documented by researchers (Hopkins et al., 2008; Stark et al., 2004; Westermann, 1993; Westermann and Kleinkopf, 1985; Westermann et al., 1988). In fact, this trend was not observed at all locations

(Tables 2.3-2.5). However, other researchers have shown no benefit to split applications of N in certain conditions (Zebarth and Rosen, 2003).

Tuber size is another important quality factor also impacted by fertilizer source (Table 2.2). All fertilized treatments resulted in significantly lower yields of the smallest tuber size (114-170 g) category (Fig. 2.4). In addition, the PCU fertilized treatment had significantly higher yield of the small tubers than the urea applied at pre-emergence. Further evidence of the size shift is shown with a highly significant increase in the yield of the largest sized tubers (>397 g), with the PCU fertilized tubers having higher yield than both urea treatments. Furthermore, all fertilized treatments produced higher yields of large tubers than the unfertilized control. A similar trend was observed with the next highest size category (284-397 g). Although not significant, the 170-284 g size category trended to have greater yield when plots were fertilizer with the PCU treatment tending to have higher tuber yield as with the upper two size categories (Fig. 2.4).

Other quality parameters were also impacted by fertilizer source. The model was not significant for hollow heart incidence, but it was highly significant for brown center (Table 2.2). The incidence of brown center was higher for the PCU fertilized treatment than other fertilizer sources, which were not statistically different than the unfertilized control (Fig 2.5). Specific gravity and yields of US No. 2 and Cull tubers were not impacted by fertilizer source.

Discussion

These data show that N delivered to potato as this form of PCU applied at emergence is an effective method and source for potato fertilization. As stated above, this study originally included two additional field locations that were likely compromised by excess in-season N fertilizer and improper irrigation due to grower error, which is why they were not included in this paper. There was no N response at these locations and yields generally decreased with the increasing N rate (Appendix A). This is evidence of the over fertilization of the plots. However, ESN fertilized plots tended to have higher yields than the unfertilized check at the 33% and 67% rates, whereas yields for the urea fertilized plots were equal to or lower than the unfertilized check. It appears that the over fertilization of the ESN treated plots may not have been as severe and certainly didn't make it worse.

Previously, controlled release N fertilizers have not performed as well as standard N products or soluble forms of N and were unpredictable in their release (Leigel and Walsh, 1976; Waddell et al., 1999). In addition, their cost made them a poor choice for most crops. Improvements in the polymer coating of new generation PCUs results in N release rates similar to the uptake patterns of plants (Trenkel, 1997) and in particular potato (Wilson et al., 2009). Researchers have now found that certain PCUs can produce similar or greater yields than other soluble N sources at similar rates (Bero et al., 2014; Hyatt et al., 2010; Hopkins et al., 2008; Hutchinson et al., 2003; Shoji et al., 2001; Wilson et al., 2009; Worthington et al., 2007; Zebarth et. al., 2012; Ziadi et al., 2011; Zvomuya and Rosen, 2001; Zyomuya et al., 2003). The yield results in Fig. 2.3 would concur with these observations.

The Agrium product (ESN) used in this trial has been engineered with a sophisticated coating of uniform thickness, which provides more consistent results. We have observed that not all PCUs are as effective as the ESN used in this trial and these data should not be extrapolated to other products.

Also, in the past PCU fertilizers were too expensive to be economically feasible (Trenkel, 1997; Zvomuya and Rosen, 2001). In addition to being a consistent product, ESN is relatively low in cost compared to early generation PCUs. We conducted an informal survey and found that farmers were paying 20-30% more for this PCU than uncoated urea (it is not uncommon to see costs more than double in the past). Results in this trial suggest that this additional cost could be covered by increases in tuber yield and quality—depending on current market rates.

Tuber size can be important to growers because of incentives and disincentives for tubers greater than 170 g. Our results showed a size shift between the US No. 1 tuber categories, with a trend for larger tubers when using PCU as the fertilizer source (Fig. 2.4). Other studies have shown similar results (Worthington et al., 2007; Ziadi et al., 2011; Zvomuya and Rosen, 2001; Zvomuya et al., 2003). However, Wilson et al. (2009) showed increased tuber size as a function of fertilization but no significant differences among source.

As discussed above for total tuber yield, yields among size categories were similar or greater for PCU fertilized treatments than urea treatments.

PCU impacts on internal quality have not been widely investigated and results are mixed. Hollow heart in particular can be dependent on year, weather patterns and tuber size. In general, hollow heart affects larger tubers (Beattie, 1989), which are a result of N fertilization. Wilson et al. (2009) showed a similar trend, and also showed that the split-applied soluble N had the highest incidence of hollow heart, but was only statistically different from the lowest soluble N level and the unfertilized check. In addition, the split-applied soluble N was statistically similar to most PCU applied treatments. Our results for hollow heart were not significant (Fig. 2.5), but there was an opposite trend with the N free check having higher hollow heart incidence than the fertilized treatments. However, we did find a significant increase in brown center with the use of PCU fertilizer (Fig. 2.5), which typically precedes hollow heart. As with our results, Zvomuya and Rosen (2001) did not see an effect of N rate on hollow heart incidence. Brown center was not reported in these studies.

Belanger et al. (2002) found that specific gravity was affected by N fertilization, with low specific gravity being tied to excessive N or over fertilization. Specific gravity results in our study were similar but were not affected by N source (Table 2.2). Zvomuya and Rosen (2001) showed an opposite affect with a significant increase of specific gravity when N rate was doubled from 140 to 280 kg N ha^{-1}. Wilson et al. (2009) and Ziadi et al. (2011) did not see an effect of N fertilization on specific gravity. Worthington et al. (2007) showed a significant decrease in specific gravity using a reduced rate of PCU compared to the ammonium nitrate standard in one of two years, although the difference was slight. Zebarth et al. (2012) showed only minor difference in specific gravity regarding source.

Another objective of our work was to determine if less fertilizer can be used when using PCU in place of urea. As shown previously, N rate effects were highly significant for most measured yield parameters (Table 2.2), but these general N response effects are widely known and not the focus of this paper. However, the response was similar by fertilizer source, as evidenced by a lack of a significant rate x source interaction.

It is interesting to note that each N source curve peaks at nearly the same N rate (data not shown); regression analysis of each of the PCU, urea split, and urea pre-emerge curves shows R^2 values of 0.9884, 0.9572, and 0.8866, respectively with peaks at 87, 85, and 90% of the recommended N rate, respectively, and these differences were not significant (*Pr > F 0.8754*). These results suggest that the fields may have been slightly over-fertilized. More importantly, it is apparent that the N rate does not need to be adjusted when using PCU even though it appears that we see higher yields as indicated in the results above. Fertilizer sources (urea applied pre-emergence or split applied and PCU) produced similar N responses, but the magnitude of the response may be slightly greater for PCU. This is in agreement with the idea of "spoon feeding" the potato crop by supplying a steady supply of N throughout the growing season in order to maximize yield and tuber quality (Errebhi et al., 1998; Gayler et al., 2002; Joern and Vitosh, 1995b; Munoz et al., 2005; Prunty and Greenland, 1997; Ruser et al., 1998; Saffigna et al., 1977; Singh and Sekhon, 1976a & b; Stark et al., 2004; Waddell et al., 2000; Westermann, 05; Westermann et al., 1988; Westermann and Kleinkopf, 1985).

Conclusions

The polymer coated urea fertilizer used in this Idaho study (ESN) appears to have the ability to supply potato with a steady supply of N throughout the vegetative portion of the growing season as evidenced by significant increases in tuber yield and quality. These results have been reported elsewhere under different conditions for ESN, as well as other PCU fertilizers—with yield and quality increases. Our data suggests that, at similar fertilizer rates, PCU fertilizer was more efficient than immediately soluble urea-N in supplying N to Russet Burbank potato. The ESN fertilizer has a higher cost than uncoated urea. Whether or not it is economically viable depends on current market prices for urea, ESN, and potato. One factor that needs to be considered in the economic analysis is the fact that ESN is applied in a single application, whereas grower standard practices include multiple labor intensive fertilizer applications. Using ESN in situations where in-season applications are not possible is especially appealing to growers.

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Tables

Table 2.1. Pre-plant soil test data and nutrient levels for three Idaho locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) for N fertilizer response trials on Russet Burbank potato.

	-------------Location-------------		
Soil Test Data‡	AB1	BF1	AB2
Soil pH	8.4	8.0	8.3
Excess Lime, %	5.7	1.0	7.2
Organic Matter, %	1.7	1.8	1.4
Nitrate-N, mg kg^{-1}	1	5	7
Phosphorus, mg kg^{-1}	13	16	24
Potassium, mg kg^{-1}	170	160	215
Calcium, mg kg^{-1}	4168	2906	2365
Magnesium, mg kg^{-1}	267	401	352
Sodium, mg kg^{-1}	23	23	69
Sulfate-S, mg kg^{-1}	14	8	11
Zinc, mg kg^{-1}	1.2	1.8	1.4
Iron, mg kg^{-1}	5.0	9.6	2.5
Manganese, mg kg^{-1}	6.0	8.4	4.5
Copper, mg kg^{-1}	0.4	0.6	0.9
Boron, mg kg^{-1}	0.4	0.5	0.9

†Soil test methods include: 2:1 (pH), titration (Lime), Walkley-Black (OM), KCl (nitrate), bicarbonate Olsen (P), ammonium acetate (K, Ca, Mg, S, and Na), DTPA (Zn, Fe, Mn, Cu), and hot water (B) (Gavlak et al., 2003)

Table 2.2. Significance (*Pr* > *F*) of overall model and model components, including: block, location (L), N rate (R), fertilizer source (S), with all possible interactions on tuber yield parameters, specific gravity, and internal defects for three locations of a N fertilizer response trial on Russet Burbank potato in 2006-2007. Values in bold face type are significant at *Pr* < 0.05.

Yield Parameters	Model	Block	L	R	S	L*R	L*S	R*S	L*R*S
US No. 1 - 114-170 g	**<0.0001**	**0.0283**	**<0.0001**	**<0.0001**	**0.0089**	**0.0072**	0.9347	0.6528	0.1538
US No. 1 - 170-284 g	**<0.0001**	**0.0116**	**<0.0001**	**0.0196**	0.1307	0.5110	0.7853	0.6085	0.4572
US No. 1 - 284-397 g	**<0.0001**	0.3993	**<0.0001**	**<0.0001**	**0.0505**	0.2564	0.8481	0.0870	0.3480
US No. 1 - > 397 g	**<0.0001**	0.1222	**<0.0001**	**<0.0001**	**0.0019**	**0.0012**	0.7181	0.2660	0.6081
Total US No. 1	**<0.0001**	**0.0049**	**<0.0001**	**0.0022**	**0.0009**	0.2404	0.5961	0.7477	0.4869
US No. 2	**<0.0001**	0.9688	**<0.0001**	**<0.0001**	0.2196	0.7072	**0.0309**	0.5425	**0.0363**
Marketable (US No. 1 & 2)	**<0.0001**	**0.0027**	**<0.0001**	**<0.0001**	**0.0018**	0.4374	0.4430	0.9864	0.6579
< 114 g	**<0.0001**	0.2841	**<0.0001**	**<0.0001**	0.2249	0.2471	0.2144	0.6627	0.9893
Malformed	**<0.0001**	**0.0051**	**<0.0001**	0.5684	0.0595	0.2151	0.6853	0.2725	0.7287
Culls (<114 g + Malformed)	**<0.0001**	**0.0214**	**<0.0001**	**0.0415**	0.0863	0.4596	0.4399	0.2098	0.6162
Total Yield	**<0.0001**	**0.0483**	**<0.0001**	**<0.0001**	**0.0003**	0.7841	**0.0077**	0.8039	0.7266
Solids (Specific Gravity) and Internal Defects									
Specific Gravity	**<0.0001**	0.1058	**<0.0001**	**0.0003**	0.0975	**0.0024**	0.6312	0.1679	0.1014
Hollow Heart	0.1321	0.9078	**0.0054**	0.1935	0.0585	0.4135	0.2187	0.4453	0.6590
Brown Center	**<0.0001**	0.2331	**<0.0001**	0.1766	**0.0130**	0.2694	0.0668	0.7698	0.8442

Table 2.3. Russet Burbank potato yields (Mg ha^{-1}) for a fertilizer trial near Aberdeen, ID in 2006 with five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	----------------- US No. 1 -----------------					US No. 2	Marketable§	------------ Culls -----------			Total
Rate, %†	114-170 g	170-284 g	284-397 g	>397 g	Total			<114 g	Malformed	Total	Tuber Yield
					unfertilized check						
0	7.3	9.4	2.1	0.9	19.7	5.5	25.1	6.2	4.6	10.8	35.9
					PCU at emergence						
33	6.3	12.8	5.3	3.3	27.7	6.5	34.1	4.0	4.5	8.5	42.6
67	4.6	12.9	8.8	6.1	32.4	8.8	41.2	4.1	4.6	8.7	49.9
100	3.8	9.7	5.8	8.0	27.4	12.1	39.4	4.2	5.4	9.6	49.1
133	4.6	11.0	6.3	7.0	29.0	9.7	38.7	3.5	3.2	6.6	45.3
					Urea at emergence						
33	4.7	10.5	4.0	3.1	22.3	6.5	28.8	4.4	5.2	9.6	38.4
67	3.1	9.0	6.6	6.1	24.9	10.4	35.3	2.4	3.9	6.3	41.6
100	4.2	11.5	6.0	4.3	26.0	7.1	33.1	3.1	2.7	5.8	38.9
133	3.9	10.0	5.9	5.8	25.6	8.8	34.3	2.4	4.3	6.7	41.0
					Split-applied urea ‡						
33	5.4	11.3	4.7	2.0	23.4	6.7	30.1	3.8	7.2	11.0	41.1
67	3.6	10.5	5.2	5.1	24.4	8.5	32.9	3.3	5.3	8.6	41.5
100	5.2	11.8	7.7	6.0	30.7	6.3	36.9	2.9	2.3	5.2	42.2
133	4.1	9.8	6.6	7.2	27.7	7.8	35.5	2.8	4.3	7.1	42.6
					Average across all treatments						
	4.7	10.8	5.8	5.0	26.2	8.0	34.3	3.6	4.4	8.0	42.3

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for this field.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

§Marketable = Total US No. 1 + US No. 2 tuber yields

Table 2.4. Russet Burbank potato yields (Mg ha^{-1}) for a fertilizer trial near Blackfoot, ID in 2006 with five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	US No. 1					US No. 2	Marketable§	Culls			Total Tuber Yield
Rate, %†	114-170 g	170-284 g	284-397 g	>397 g	Total			<114 g	Malformed	Total	
						unfertilized check					
0	3.8	3.8	0.7	0.3	8.7	10.3	19.0	6.1	7.7	13.8	32.8
						PCU at emergence					
33	3.2	6.9	2.3	1.6	13.9	10.6	24.5	4.1	8.0	12.2	36.6
67	3.5	5.5	4.2	2.0	15.3	11.9	27.2	3.8	8.5	12.3	39.5
100	3.7	5.6	3.1	2.1	14.5	13.0	27.5	3.9	8.3	12.1	39.6
133	2.3	5.1	3.6	2.8	13.8	12.7	26.5	3.7	7.4	11.2	37.6
						Urea at emergence					
33	2.8	5.6	3.2	2.2	13.8	11.9	25.8	4.8	7.2	12.0	37.7
67	2.2	5.7	2.4	2.0	12.3	13.1	25.4	4.3	8.3	12.6	38.0
100	2.2	5.5	2.2	0.7	10.7	12.5	23.1	4.0	8.4	12.4	35.5
133	3.1	5.4	4.0	1.4	13.9	11.9	25.8	3.8	8.6	12.4	38.2
						Split-applied urea ‡					
33	2.7	6.0	2.2	1.1	12.0	9.8	21.7	4.7	11.3	16.0	37.8
67	3.4	6.5	3.0	2.0	14.9	11.8	26.8	3.7	9.8	13.6	40.3
100	2.9	5.3	1.8	1.2	11.2	11.4	22.6	4.4	12.4	16.7	39.3
133	3.1	6.3	3.2	1.9	14.4	13.2	27.6	4.0	6.8	10.9	38.5
						Average across all treatments					
	3.0	5.6	2.8	1.6	13.0	11.8	24.9	4.3	8.7	12.9	37.8

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for this field.
‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.
§Marketable = Total US No. 1 + US No. 2 tuber yields

Table 2.5. Russet Burbank potato yields (Mg ha^{-1}) for a fertilizer trial near Aberdeen, ID in 2007 with five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	----------------- US No. 1 -----------------					US No. 2	Marketable§	------------ Culls -----------			Total
Rate, %†	114-170 g	170-284 g	284-397 g	>397 g	Total			<114 g	Malformed	Total	Tuber Yield
unfertilized check											
0	7.6	12.1	3.0	0.9	23.6	7.4	31.0	7.7	3.3	11.1	42.1
PCU at emergence											
33	7.5	16.3	6.4	3.8	34.1	7.8	41.8	6.1	3.5	9.6	51.4
67	5.7	12.9	8.0	5.7	32.3	10.0	42.3	4.5	5.5	10.0	52.4
100	5.3	11.8	5.6	6.7	29.4	9.8	39.2	5.1	6.4	11.4	50.7
133	5.0	11.7	6.1	7.0	29.9	10.0	39.9	4.4	7.0	11.4	51.3
Urea at emergence											
33	6.8	12.5	5.5	1.8	26.6	8.6	35.2	6.1	7.4	13.5	48.7
67	5.3	14.9	5.5	6.1	31.8	9.2	41.0	4.3	5.3	9.6	50.5
100	5.2	10.1	7.2	5.5	28.0	13.7	41.8	4.3	5.6	9.9	51.6
133	3.0	8.7	4.6	3.7	20.0	17.0	36.9	2.9	8.4	11.3	48.3
Split-applied urea ‡											
33	5.9	13.7	4.5	2.8	26.8	10.2	37.0	6.2	7.1	13.3	50.3
67	5.7	11.2	5.9	5.7	28.5	11.8	40.2	4.5	6.1	10.6	50.8
100	4.4	11.9	5.7	4.2	26.3	11.8	38.1	4.3	9.2	13.5	51.6
133	5.2	11.2	6.1	4.0	26.4	10.7	37.1	3.6	6.8	10.3	47.5
Average across all treatments											
	5.6	12.2	5.7	4.5	28.0	10.6	38.6	4.9	6.3	11.2	49.8

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 269 kg ha^{-1} for this field.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

§Marketable = Total US No. 1 + US No. 2 tuber yields

Table 2.6. Specific gravity, % hollow heart, and % brown center for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	-------- Specific Gravity --------			-------- % Hollow Heart --------			-------- % Brown Center --------		
Rate, %†	AB1	BF1	AB2	AB1	BF1	AB2	AB1	BF1	AB2
unfertilized check									
0	1.086	1.082	1.083	10.9	14.1	3.1	0.0	1.6	3.1
PCU at emergence									
33	1.083	1.081	1.083	6.3	6.3	4.7	0.0	0.0	17.2
67	1.080	1.084	1.082	7.8	9.4	0.0	3.1	1.6	21.9
100	1.080	1.086	1.082	9.4	6.3	4.7	6.3	3.1	18.8
133	1.077	1.082	1.081	6.3	0.0	4.7	0.0	1.6	21.9
Urea at emergence									
33	1.082	1.086	1.084	14.1	1.6	9.4	1.6	1.6	12.5
67	1.082	1.086	1.083	9.4	4.7	9.4	0.0	1.6	10.9
100	1.078	1.083	1.080	6.3	3.1	0.0	0.0	0.0	9.4
133	1.081	1.083	1.079	17.2	4.7	3.1	1.6	0.0	12.5
Split-applied urea ‡									
33	1.080	1.083	1.083	6.3	4.7	4.7	3.1	0.0	7.8
67	1.079	1.082	1.082	3.1	3.1	1.6	1.6	0.0	18.8
100	1.081	1.085	1.079	4.7	3.1	1.6	1.6	0.0	15.6
133	1.075	1.083	1.081	3.1	1.6	3.1	1.6	1.6	9.4
Average across all treatments									
	1.080	1.083	1.082	8.1	4.8	3.8	1.6	1.0	13.8

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for AB1, and BF1 and 269 kg ha^{-1} for AB2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table 2.7. Russet Burbank potato yields (Mg ha^{-1}) combined across rate and three locations in 2006-2007 with five rates of N applied.

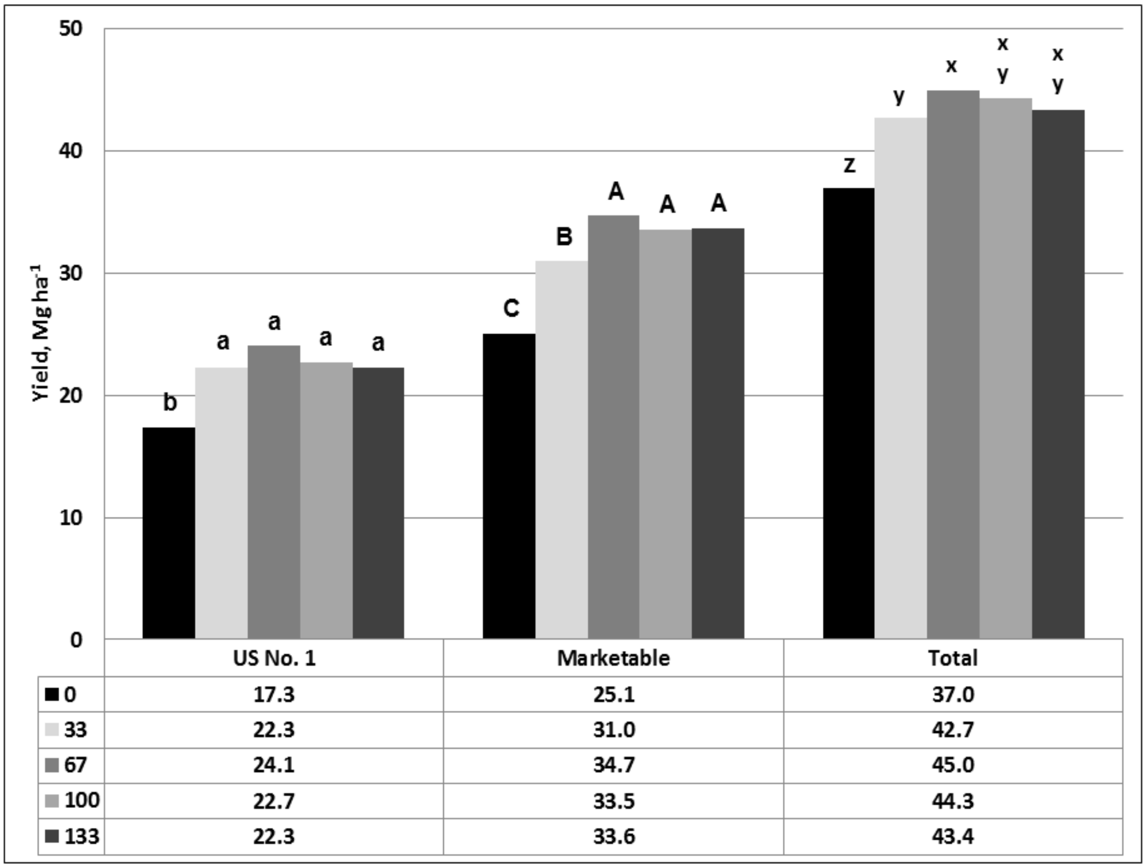
	US No. 1									
Rate, %	114-170 g†		170-284 g		284-397 g		>397 g†		Total	
0	6.2	A	8.4	B	1.9	C	0.7	C	17.3	B
33	5.0	B	10.6	A	4.2	B	2.4	B	22.3	A
67	4.1	C	9.9	AB	5.5	A	4.5	A	24.1	A
100	4.1	C	9.3	B	5.0	A	4.3	A	22.7	A
133	3.8	C	8.8	B	5.2	A	4.5	A	22.3	A

					Culls							
Rate, %	US No. 2†		Marketable‡		<114 g		Malformed		Total		Total Tuber Yield	
0	7.7	B	25.1	C	6.7	A	5.2	A	11.9	A	37.0	C
33	8.7	B	31.0	B	4.9	B	6.8	A	11.7	A	42.7	B
67	10.6	A	34.7	A	3.9	CD	6.4	A	10.3	AB	45.0	A
100	10.8	A	33.5	A	4.0	C	6.7	A	10.7	AB	44.3	AB
133	11.3	A	33.6	A	3.4	D	6.3	A	9.8	B	43.4	AB

†Note that there was a location by N rate interaction for the smallest and largest US No. 1 size categories and a location by N rate by N source interaction for US No. 2 tuber yield.

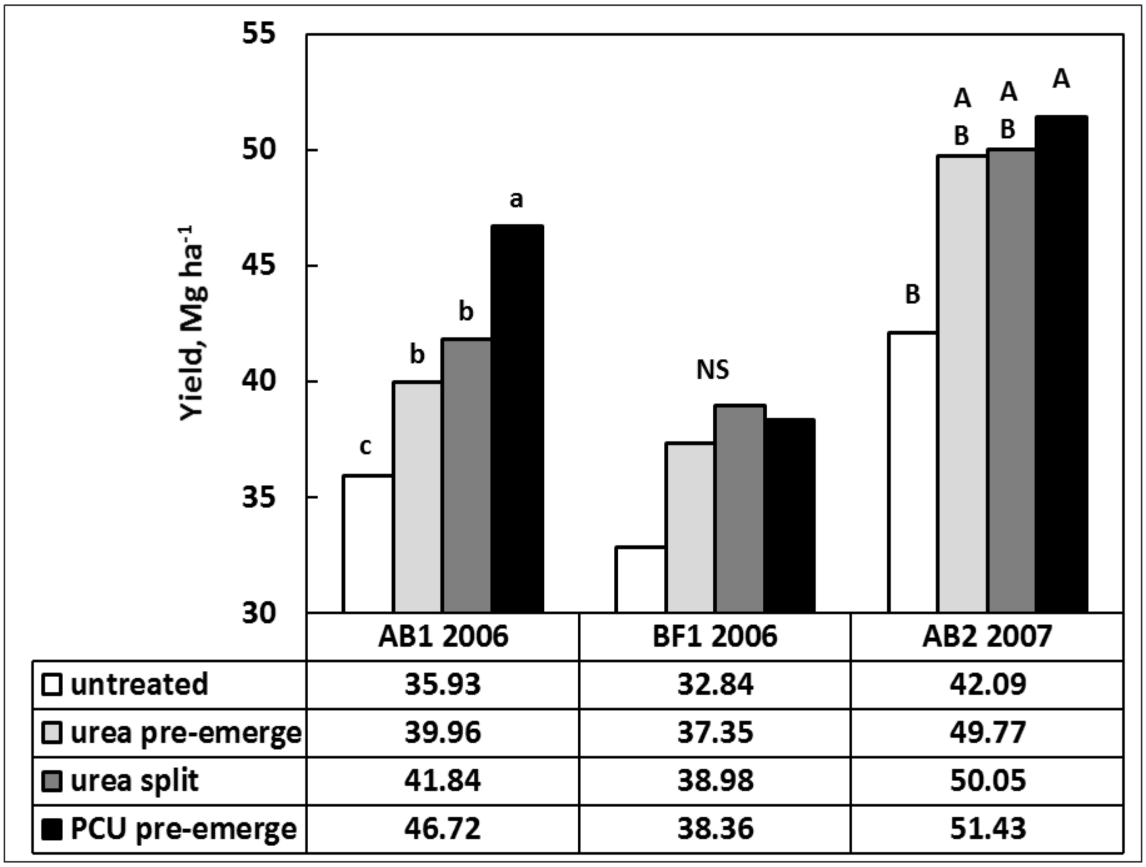
‡Marketable = Total US No. 1 + US No. 2 tuber yields

Figures and Figure Descriptions



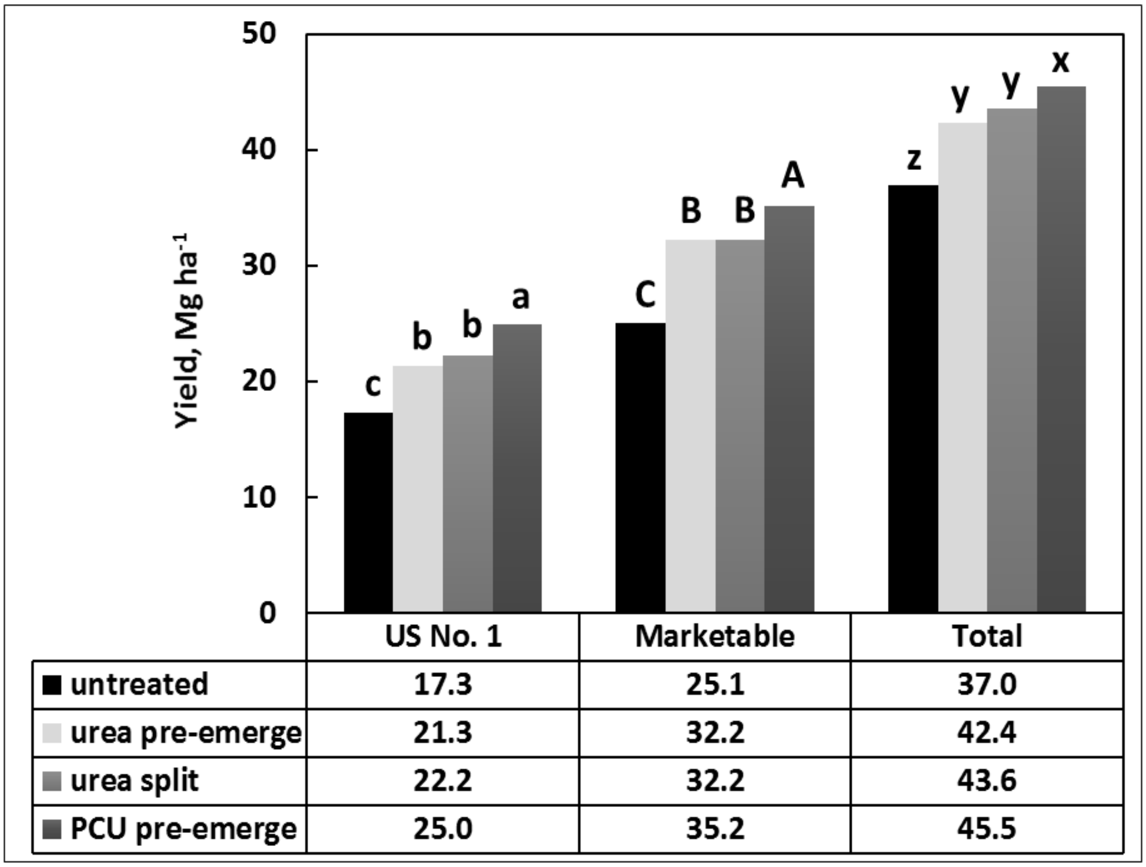
	US No. 1	Marketable	Total
■ 0	17.3	25.1	37.0
■ 33	22.3	31.0	42.7
■ 67	24.1	34.7	45.0
■ 100	22.7	33.5	44.3
■ 133	22.3	33.6	43.4

Figure 2.1. Russet Burbank potato yield response for US No. 1, Marketable, and Total tuber yield for three locations in 2006-2007 in southern Idaho with five rates of fertilizer N applied (averaged across N sources and timings). Bars with the same letters are not significantly different from each other. ($P < 0.05$)



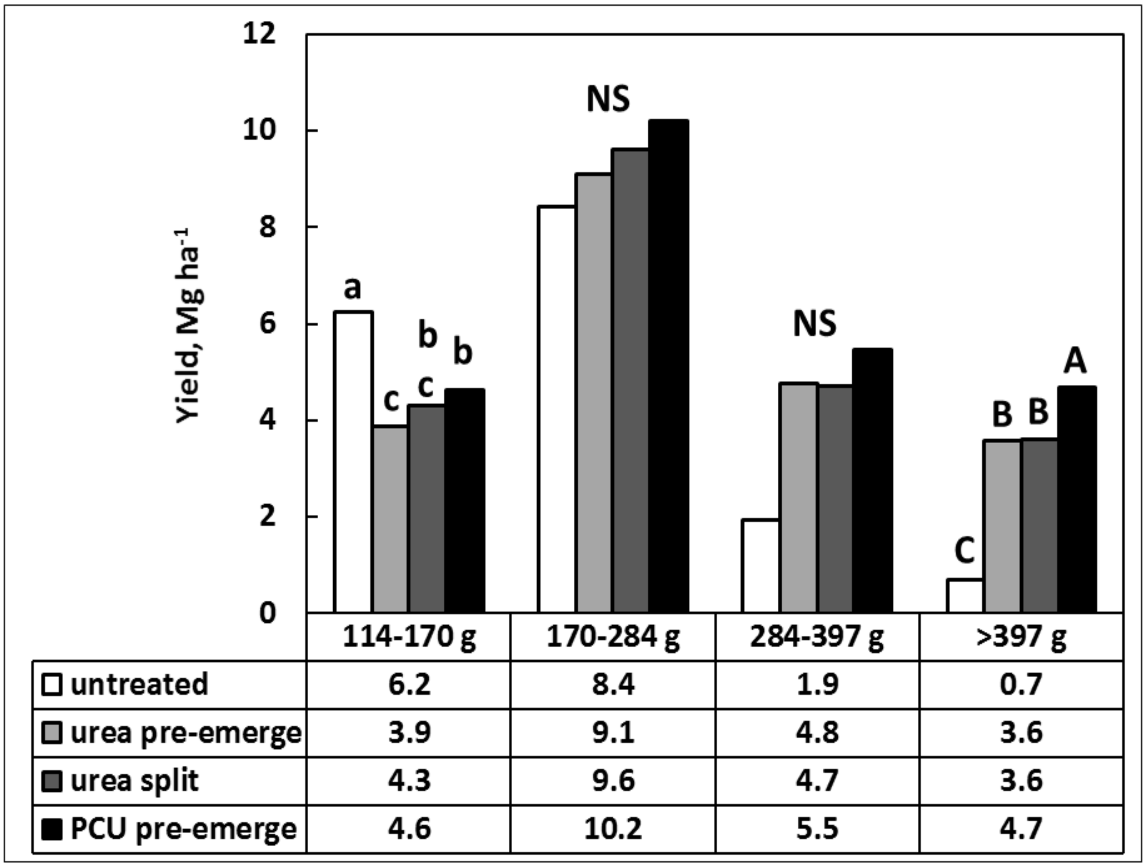
	AB1 2006	BF1 2006	AB2 2007
□ untreated	35.93	32.84	42.09
░ urea pre-emerge	39.96	37.35	49.77
▒ urea split	41.84	38.98	50.05
■ PCU pre-emerge	46.72	38.36	51.43

Figure 2.2. Russet Burbank potato yield response of nitrogen (N) source for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of an N fertilizer response trial on Russet Burbank potato in 2006-2007. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as Split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars with the same letters are not significantly different from each other. NS = Not Significant ($P < 0.05$)



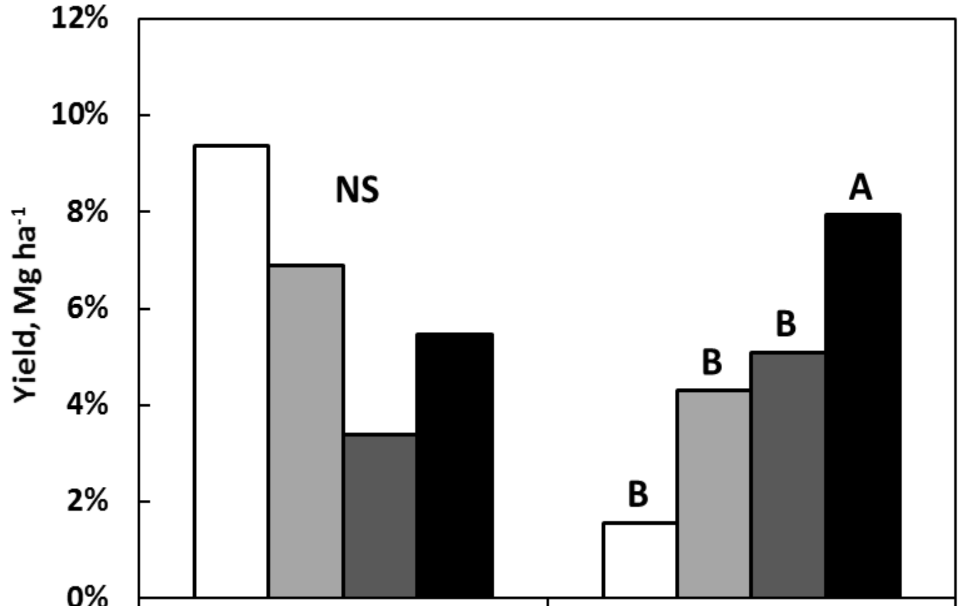
	US No. 1	Marketable	Total
■ untreated	17.3	25.1	37.0
■ urea pre-emerge	21.3	32.2	42.4
■ urea split	22.2	32.2	43.6
■ PCU pre-emerge	25.0	35.2	45.5

Figure 2.3. Russet Burbank potato yield response of nitrogen (N) source for US No. 1, Marketable, and Total tuber yield across three locations of an N fertilizer response trial on Russet Burbank potato in 2006-2007. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as Split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars with the same letters are not significantly different from each other. ($P <$ 0.05)



	114-170 g	170-284 g	284-397 g	>397 g
☐ untreated	6.2	8.4	1.9	0.7
▨ urea pre-emerge	3.9	9.1	4.8	3.6
▨ urea split	4.3	9.6	4.7	3.6
■ PCU pre-emerge	4.6	10.2	5.5	4.7

Figure 2.4. Russet Burbank potato yield response of nitrogen (N) source for standard US No. 1 size categories across three locations of an N fertilizer response trial on Russet Burbank potato in 2006-2007. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as Split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars with the same letters are not significantly different from each other. NS = Not Significant ($P < 0.05$)



	Hollow Heart	Brown Center
□ untreated	9.4%	1.6%
▒ urea pre-emerge	6.9%	4.3%
▓ urea split	3.4%	5.1%
■ PCU pre-emerge	5.5%	7.9%

Figure 2.5. Effect of nitrogen (N) source on hollow heart and brown center incidence across three locations of an N fertilizer response trial on Russet Burbank potato in 2006-2007. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as Split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars with the same letters are not significantly different from each other. NS = Not Significant ($P < 0.05$)

Chapter 3

Polymer Coated Urea in Russet Burbank Potato: NDVI, Petiole, and Residual Post-Harvest Soil Nitrate

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Abstract

A controlled release nitrogen (CRN) fertilizer in the form of polymer-coated urea (PCU) has the potential to reduce excess N loss due to leaching and denitrification, thereby improving nitrogen use efficiency (NUE). In addition, this PCU can potentially increase yield and tuber quality. The objectives of this study were to determine the effects of PCU on Normalized Difference Vegetation Index (NDVI) reflectance as a measurement of canopy health, petiole N concentration, yield response per unit of N applied, and post-harvest soil residual nitrates. Russet Burbank potato was grown in three locations near Aberdeen and Blackfoot, Idaho, USA in 2006 and near Aberdeen in 2007. Five rates of N (0, 33, 67, 100, and 133% of the recommended rate) were applied as urea split-applied (similar to grower standard practices), urea applied all at emergence, or PCU applied all at emergence. In general, PCU fertilized potatoes resulted in the highest yield per unit of N applied for US No. 1, marketable, and total tuber yields. Average petiole NO_3-N values were lower for PCU treated plots when compared to split-applied urea. Soil residual N concentrations following PCU applications were similar

to those for split-applied urea. These results show that PCU not only met potato fertilizer N needs, but also showed greater NUE with respect to yield per unit of N applied.

Introduction

Researchers and growers have learned that a steady supply of adequate but not excessive nitrogen (N) is essential for optimum potato yield and quality. For this reason, N is generally split-applied at intervals throughout the growing season to best meet crop N requirements. Many studies suggest that "spoon feeding" N is an effective practice to maximize yield and to ensure tuber quality (Hopkins et al., 2008); however, others found no benefit or even a detriment to the potato crop with split-applied N crop (Zebarth and Rosen, 2003). However, there is little doubt that one of the primary benefits of applying N as close to the time of need as possible is reduced risk of N loss to the environment (Errebhi et al., 1999; Munoz et al., 2005; Ruser et al., 1998; Waddell et al., 1999, 2000). The amount of N required for potato is somewhat predictable based on pre-plant soil tests and fertilizer recommendations based on research (Stark et al., 2004) and in-season adjustments can be made based on weekly samples of petiole tissue (Zhang, et al., 1996) and in some cases, soil samples. In general, petiole NO_3-N concentrations in Idaho should be between 15,000-20,000 mg kg^{-1} to be sufficient for vine and tuber growth during the growing season and then gradually dropping below 10,000 mg kg^{-1} by the end of tuber bulking late in the season (Stark et al., 2004; Westerman, 1993).

A possible option to enhance/replace petiole guided fertilization is the use of optical sensing equipment This instrumentation shows promise to help growers more precisely manage N and other inputs and is currently being used for some crops (Heege et al., 2008; Lukina et al., 2001; Mullen et al., 2003; Raun et al., 2002, 2005; Scharf et al., 2002; Solie et al., 1999; Tarpley et al., 2000; Tremblay et al., 2008). However, optical sensing is not currently being used for potato because of a lack of data correlating sensor data with crop N need (Bowen et al., 2005).

Recent research using optical sensing tools to detect N levels in potato plants is showing promise (Bowen et al., 2005; Herrmann et al., 2010; Jain, et al., 2007; Wu et al., 2007). The primary optical tool being used is Normalized Difference Vegetation Index (NDVI). An optical sensing device (GreenSeeker, N-Tech Industries, Ukiah, Cal, USA) measures NDVI using wavelengths of 774 nm for the near infrared (NIR) and 656 nm for the visible red spectrum (VIS). NDVI is calculated by taking the difference of intensity at the NIR and VIS wavelengths and then dividing this difference by the sum of the two intensities: NDVI = (NIR - VIS) / (NIR + VIS) (Kriegler et al., 1969). It is hoped that this data will give a general potato plant health assessment of the crop similar to petiole analysis.

Although the practice of “spoon feeding” with the associated NDVI and/or soil/petiole tests can help increase tuber yield and quality, it is labor and equipment intensive and, as a result, more costly. It is desirable to eliminate or reduce costly in-season N applications, but it is vital to maintain or improve farm sustainability and profitability (Hopkins et al., 2007, 2008). However, losses still occur even with proper N management under a conventional fertilization system. Therefore, it is important to find efficient ways of supplying N with new fertilizer technologies.

Polymer-Coated Urea (PCU) fertilizers are CRN’s that release N into the soil solution with the rate of release controlled by soil temperature. Plant growth and, thus, nutrient demand are also temperature driven. The idea behind temperature-release PCU fertilizers is to attempt to synchronize N release with N demand, thus minimizing the time the N is exposed to potential loss to the environment (Gandeza et al., 1991; Munoz et al., 2005; Zvomuya and Rosen, 2001).

One such PCU is Environmentally Smart N (ESN®, 44-0-0; Agrium Advanced Technologies, Brantford, Ontario, Canada). This product is designed to release N to the crop with control and predictability due to micro-thin polymer coatings, with date of release impacted by thickness of the coatings. A preliminary ESN trial in Idaho in 2005 showed promising results (Hopkins et al., 2008). The ESN applied immediately prior to hilling performed significantly better than urea applied at the same time for US No. 1, marketable, and total yield, with increases of 5.6, 5.3, and 4.4 Mg ha^{-1}, respectively. The N release from ESN closely matches the N uptake needs of *Russet Burbank* potato under field conditions (Wilson et al., 2009). This effectively reduces the time that NO_3^- is exposed to environmental loss from the soil, thus improving NUE. Unlike most other CRN (as well as SRN) fertilizers, costs for ESN are 25-30% greater than uncoated urea. Although costs are higher, they are not 2-10 times higher that has been common for SRN and CRN materials in the past. ESN may prove to be economical if total NUE is improved and rate of N applied can be reduced and/or yields and/or tuber quality are improved.

This PCU technology has the potential to meet the needs of increased NUE by increasing yields, maximizing net returns to the grower, and decreasing loss of N to the environment, and in addition improve sustainability of potato production, as well as other crops. The objective of this study was to compare the effects of ESN and uncoated urea applications on NUE in irrigated *Russet Burbank* potato production systems. The focus this paper is to look at petiole NO_3-N, NDVI, yield per unit of N applied (ΔY/N), and seasonal change in residual soil NO_3-N (ΔNO_3-N) as they relate to NUE.

Materials and Methods

Three trials were conducted in commercial potato fields evaluating the effectiveness of ESN on *Russet Burbank* potatoes. The fields were located in southern Idaho, USA near Blackfoot (Bannock loam) and Aberdeen (Declo loam) in 2006 and in Aberdeen (Declo loam) in 2007. In general, the soils were low in organic N and highly calcareous with medium to high concentrations of most nutrients (Table 3.1). All fields were irrigated with 0.56-0.66 m water that contained 5-6 mg kg^{-1} of NO_3-N. The previous crop was spring wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) with approximately 2 Mg ha^{-1} of residual grain stubble. It should be noted that two additional trials were performed on growers' fields near Rupert, Idaho in 2006 and 2007 with the same treatments and methods. However, the data from these locations were omitted from data analysis because of problems with irrigation and N contamination from irrigation sources (Appendix A).

Individual plots were 3.6 m wide (four 0.91 m rows) by 12.2 m in length with treatments established in a randomized complete block design (RCBD) with 4 replications/blocks. Thirteen treatments were evaluated, including: an untreated check and four rates of N (33%, 67%, 100%, and 133% of recommended N) applied as: 1) ESN applied pre-emergence, 2) uncoated urea (46-0-0) applied pre-emergence, or 3) uncoated split-applied urea. The four rates of N were 33%, 67%, 100%, and 133% of recommended N rate based on University of Idaho fertilizer recommendations for *Russet Burbank* potatoes using soil test values, yield potential, and previous crop information for each location (Stark et al., 2004).

The recommended N rate for both 2006 locations was within 10 kg N ha^{-1} and, therefore, the rates were rounded up/down to be equivalent within this year. The recommended N rate in 2006 was 303 kg ha^{-1} N. Therefore, the four rates applied were 101, 202, 303, and 404 kg ha^{-1} for the 33%, 67%, 100%, and 133% N rates, respectively. The recommended N rate in 2007 was 269 kg ha^{-1} N. Therefore, the four rates applied were 90, 179, 269, and 359 kg ha^{-1} for each N rate, respectively.

The pre-emergence applications occurred just prior to cultivation and plant emergence. The timing of the single application of ESN or urea was determined based upon research conducted at the University of Idaho (Hopkins et al., 2008) and the University of Minnesota (Wilson et al., 2009) showing that ESN applied before planting may release N too early for Russet Burbank potato needs and result in a substantial delay in tuber initiation and, thus, yield losses. The University of Minnesota data shows that the N release curve from ESN closely followed that for plant N need when it was applied at plant emergence (Wilson et al., 2009). From these data it was determined that ESN should be applied at or just prior to plant emergence and just prior to cultivation/hilling to ensure fertilizer was incorporated into the soil. This is a common application timing use to supply at least part of the N needs for potatoes in Southern Idaho. The treatments applied pre-emergence were incorporated into the soil 1-2 days after application. Cultivation occurred on June 3 for both Aberdeen and Blackfoot in 2006, which was 28 and 16 days after planting (DAP). In 2007, cultivation occurred on May 21 for Aberdeen, which was 23 DAP.

The split-applied treatment at the 100% recommended rate represented the grower standard practice. The split-applied treatments had 50% of the N applied pre-emergence (as described previously); with the remainder applied in three equal applications throughout the growing season. Timing of the first in-season application was based on University of Idaho in-season N recommendations (Stark et al., 2004) based upon petiole NO_3^--N analysis of composite samples from the grower standard practice plots. The composite petiole and Normalized Difference Vegetative Index (red NDVI; GreenSeeker, N-Tech Industries, Ukiah, Cal, USA) results were used to guide petiole sampling from all plots in an effort to identify the optimum date to document maximum petiole NO_3 -N differences by treatment. In 2006, the first in-season application took place on July 15 for Aberdeen and Blackfoot. In 2007, the first in-season application took place on July 10 in Aberdeen. The subsequent two in-season applications were applied every two weeks thereafter. All N applications were made using a rotary hand spreader to apply pre-weighed fertilizer uniformly across the plot area.

The NDVI measurements were taken in the center of each plot and integrated over ~5 s. Petiole tissue samples were taken from each plot in 2006 on August 16 for Aberdeen and Blackfoot. Plant tissue samples were taken in 2007 on August 15 for Aberdeen. Samples were taken from the fourth fully emerged petiole from the top of each plant (Stark et al., 2004). Thirty-five petioles were sampled from each plot, dried and ground to pass through a 1 mm screen and were analyzed for NO_3-N using the chromotropic acid analysis (Sims and Jackson, 1971). The analysis for nitrate is done using an automated colorimetric produce using flow injection analysis (FIA; Quick Chem 8500, Lachat Instruments, Hach Company, Loveland, Col., USA).

The overall yield and tuber quality is discussed in a companion paper (Taysom et al., 201x). Yield data was used to calculate yield per unit of N applied ($\Delta Y/N$). This was done for US #1, marketable, and total tuber yield as discussed in the companion paper. Calculated values represent NUE with respect to yield.

Soil samples were taken just prior to initial fertilization (composite for each of the four blocks; Table 3.2) and again after harvest (from each of the 52 plots) at each location from within (0-0.46 m) and below (0.46-0.76 m) the primary rooting zone on November 1 and October 20, 2006 for Aberdeen and Blackfoot, respectively; and on November 1, 2007 for Aberdeen. These samples were taken with an eight cm diameter soil auger. Two samples were taken randomly from the center of each plot and composited and were analyzed for post-harvest NO_3-N. Results were then used to calculate ΔNO_3-N by subtracting the pre-plant soil NO_3-N from the post-harvest NO_3-N.

Because of missing data points due to lost samples and some plots being damaged from irrigation problems, the data was analyzed with analysis of variance using GLM (General Linear Model) with a $P=0.05$ criteria using SAS (Version 9.1, SAS Institute, 2003, North Carolina, USA). Means were separated by LSD (Least Significant Difference) test with an alpha of 0.05.

Results

Statistical analysis of treatment effects across location, N rate, and fertilizer source and all possible interactions of these parameters are shown in Table 3.3 with data for soil ΔNO_3-N, petiole NO_3-N and NDVI, and ΔY/N, shown in Tables 3.4, 3.5, and 3.6, respectively. Field averages for each measured parameter are found at the bottom of Tables 3.4-3.6. As stated above, this study originally included two additional field location that were likely compromised by excess in-season N fertilizer and improper irrigation due to grower error, which is why they were not included in this paper. Data for these locations is included in Appendix A.

The US No. 1 and Marketable ΔY/N response was the same regardless of location (Tables 3.3 and 3.6). However, when the tuber quality parameters were removed, the Total ΔY/N varied significantly by location with AB2 > AB1 > BF1 (Tables 3.3 and 3.6). In addition, differences across locations were highly significant for surface (BF1 = AB2 > AB1) and subsurface (BF1 > AB1 = AB2) soil ΔNO_3-N and petiole NO_3-N (BF1 > AB2 > AB1), NDVI (BF1 > AB1 = AB2) (Tables 3.3-3.5). Location did not affect the N rate or source response for NDVI, petiole NO_3-N, or ΔY/N (Table 3.3) and, therefore, values were averaged across locations for evaluation of the N rate and fertilizer source responses for these parameters.

In contrast, location did affect the N rate response for surface and subsurface soil ΔNO_3-N. The soil ΔNO_3-N values were similar for all fields at the first two rates of N, with values increasing as N rate increased (Table 3.4; Fig. 3.1). However, the final soil ΔNO_3-N values at the highest N rate were over three times greater at the BF1 and AB2 locations than the AB1 site for surface soil. For subsurface soil, the BF1 location had more than twice the soil ΔNO_3-N than AB1 and AB2 at the high rate. More importantly, with regard to the objectives of this study, there was no location by fertilizer source interaction for the soil ΔNO_3-N and, as such, values were also averaged across locations as was done for the other measured parameters in this study.

Rate of fertilizer N had highly significant effects on all measured parameters (Table 3.3). Fertilizer N tended to increase soil ΔNO_3-N, petiole NO_3-N, and NDVI (Tables 3.3-3.5;

Figs. 3.1-3.2). Conversely, N fertilizer rate had a tendency to decrease ΔY/N as N rate increased (Tables 3.3 and 3.6; Fig. 3.3). The rate effect is similar to what has been observed by other researchers (Biemond and Vos, 1992; Errebhi et al., 1998; Errebhi et al., 1999; Kleinkopf et al., 1981; Miller and Hopkins, 2007; Stark et al., 2004; Vos, 1999; Waddell et al., 1999; Westermann, 2005) and is consistent regardless of location or fertilizer source for petiole NO_3-N and NDVI (Fig. 3.2) and all ΔY/N measurements (Fig. 3.3). It is noteworthy that all possible correlations for independent and dependent variables with NDVI and petiole NO_3-N were calculated (data transformed relative to the untreated control at each site) and that only N rate and petiole NO_3-N had any reasonable level of correlation ($R^2 = 0.624$). All other relationships were poorly correlated ($R^2 < 0.360$), including a poor correlation between NDVI and petiole NO_3-N (Fig. 3.2; $R^2 = 0.136$).

Although the rate response was consistent across locations and fertilizer sources for the canopy and tuber measurements, there was, as discussed previously, a location by N rate interaction for both surface and subsurface soil ΔNO_3-N (Table 3.3; Fig. 3.1) and an interaction between N rate and fertilizer source for surface soil ΔNO_3-N. This N rate by fertilizer source interaction for surface soil ΔNO_3-N shows that urea applied at emergence resulted in a nearly linear increase in ΔNO_3-N and the split-applied urea and the PCU resulting in a strong curvilinear response, with values increasing in near exponential fashion as N rate increased (Fig. 3.4). The surface soil ΔNO_3-N values were similar at the 33% N rate. At the 67 and 100% rates, the split-applied urea N application had higher surface soil ΔNO_3-N than both PCU and urea at emergence. This trend changed at the 133% rate, with the PCU and the split-applied urea applications having equivalent ΔNO_3-N, but both being significantly higher than urea applied at emergence. The magnitude of the difference was dramatic at the highest level where N application substantially exceeded plant need/uptake. This is likely a result of the differences in the timing of N availability the between early and late season applications. The N applied as urea all at emergence was resident in the soil for a much longer period than the other treatments and, as such, the excess N applied at the highest rates was more likely to be lost to leaching, volatilization, and nitrification/denitrification, especially at the highest N rate. Fertilizer source effects were not significant for subsurface soil ΔNO_3-N, which is below the effective rooting zone for the shallow rooted Russet Burbank potato.

As previously discussed, surface soil ΔNO_3-N (Table 3.3) was the only measured parameter with interactions with fertilizer source and, therefore, the results for the other measured parameters are averaged across locations and N rates as discussed below.

Fertilizer source had a significant impact on mid to late season petiole NO_3-N concentrations (Tables 3.3 and 3.5; Fig. 3.5). The grower standard practice of split applying N during the season resulting in the highest petiole NO_3-N values, followed by PCU and then urea applied all at emergence (Fig. 3.5). All fertilized treatments resulted in significant increases in petiole NO_3-N and NDVI when compared to the unfertilized control. However, in contrast with petiole NO_3-N, there were no differences in NDVI readings between fertilizer sources (Fig. 3.5).

The ΔY/N values for US No. 1, marketable, and total tuber yield were also significantly impacted by fertilizer source (Tables 3.3 and 3.6; Fig. 3.6). In general, PCU fertilized potato resulted in the highest ΔY/N (Fig. 3.6). PCU had significantly higher ΔY/N than both split-applied urea and urea applied at emergence for US No. 1 and marketable yields. For total ΔY/N, PCU was statistically greater than urea applied at emergence and trended in this same way for split-applied urea, although the means were not significantly different. Surprisingly, split-applied urea was statistically similar to urea applied at emergence for all ΔY/N measurements.

Discussion

Petiole NO_3-N concentrations are a popular method of assessing potato N needs throughout the growing season (Porter and Sission, 1991; Westerman, 1993; Belanger et al., 2002; Rodrigues, 2004; Stark et al., 2004; Rosen and Eliason, 2005). Our results show that the petiole NO_3-N for urea applied all at emergence was lower than when it was split applied. In addition, PCU applied at emergence resulted in petiole NO_3-N concentrations between those for urea applied at emergence and split-applied urea. It is interesting to note that the PCU fertilized potato had an overall average petiole NO_3-N concentration ~2 g kg^{-1} less than the split applied urea (Fig. 3.5), which is consistent with other field observations (Hopkins and

Taysom, unpublished data). These data are in agreement with observations made by farmers and researchers that petiole NO_3-N concentrations for potato fertilized with PCU's tend to be less than petiole concentrations under conventional potato nitrogen management. However, our results were based on a late season (around August 1st) sampling and do not reflect or track levels over the growing season.

Wilson et al. 2009 showed that early in the growing season soluble N treatments, such as our urea applied all at emergence, resulted in significantly higher petiole NO_3-N concentrations than for ESN, whereas later in the season the opposite was observed. This is in contrast to what we observed late in the season. Pack et al. (2006) showed no effect between soluble N and PCU in terms of petiole NO_3-N. Zebarth et al. (2012) observed higher petiole NO_3-N concentrations with PCU in one of three years, with the other two years showing no differences between fertilizer sources. However, if PCU results in lower petiole NO_3-N concentrations, new guidelines are needed for managing PCU fertilizers in potato. Furthermore, the question remains regarding how differing PCU fertilizers may affect potato N response.

In a study examining response to different PCU rates, Cambouris et al. (2014) suggests that established critical petiole NO_3-N concentrations for conventional soluble N sources may not be applicable when PCU fertilizers are used. We used ESN, but there are other brands of PCU available and are likely unique in their release patterns. Despite the lower petiole NO_3-N concentrations for PCU, yields were significantly higher than either urea treatment (Taysom, 201x; Taysom et al., 201x). This is an indication of increased NUE.

As with petiole NO_3-N, NDVI was strongly correlated with fertilizer rate (Fig. 3.2). This response is similar to what other researchers have seen with NDVI and N rate (Bowen et al., 2005; Jain et al., 2007; Wu et al., 2007). Using NDVI as an indicator for petiole NO_3-N differences was successful and could relate to plant N needs. However, there was a weak correlation between petiole NO_3-N and NDVI as stated above. One possible explanation is that NDVI is more a measurement of leaf N content and may not reflect petiole NO_3-N concentrations. Although PCU fertilized plots had lower petiole nitrates, the NDVI was similar to urea and split-applied urea (Fig. 3.5). This suggests that the greening of the canopy as assessed by the NDVI was the same for PCU fertilized plots as it was for split-applied urea, regardless of petiole NO_3-N concentration. NDVI and other types of spectral indices may be useful tools in assessing potato N needs (Bowen et al., 2005; Jain et al., 2007).

The PCU used in these trials increased marketable, US No. 1, and total tuber $\Delta Y/N$ (Fig. 3.6). More yield per unit of N applied ($\Delta Y/N$) and lower petiole NO_3-N concentrations suggest that the plants were more efficient in utilizating N fertilizer. The greatest benefit of PCU in terms of N efficiency, as measured by $\Delta Y/N$, was with increased tuber quality (higher US No. 1 and Marketable $\Delta Y/N$), rather than Total yield. Other studies have shown improved NUE with respect to PCU (Bero et al., 2014; Ziadi et al., 2011; Zvomuya et al., 2003), while Wilson et al. (2010) did not see an effect of source on NUE. In spite of improved NUE, it has been well documented that as N rate increases, NUE decreases regardless of the source (Gagnon and Ziadi, 2010; Wilson et al., 2010; Ziadi et al., 2011; Zvomuya et al., 2003). Fageria and Baligar (2005) suggest that this decrease in NUE at higher N rates is due to the inability of the plant to use N at higher rates or that N losses exceed the rate of plant uptake. These data suggest that the greatest benefit of PCU in terms of N efficiency, as measured by $\Delta Y/N$, was with increased tuber quality (higher US No. 1 and Marketable $\Delta Y/N$), rather than Total yield.

Another way to look at N efficiency is to look at soil residual NO_3-N following harvest. Nitrate is the form of N most likely to be lost due to leaching, which is common in areas of high rainfall and irrigation and especially problematic with potato and other crops with shallow, inefficient root systems. Despite the interaction observed in the surface soil (0-46 cm; effective rooting zone) of the present study (Fig. 3.4), maximum yields were observed between the 33 and 100% N rates (Taysom, 201x; Taysom et al., 201x). At these rates, PCU had lower residual soil NO_3-N than the grower standard practice of split-applied urea (Fig. 3.4). Other studies found somewhat differing results with respect to soil residual NO_3-N (Zebarth et al., 2012). Ziadi et al. (2011) observed lower soil residual NO_3-N with PCU compared to soluble N sources in only one out of three years, but it was statistically similar to the equivalent rate of soluble N. This was surprising as these researchers further found improved NUE with respect to yield without reducing soil residual NO_3-N. Wilson et al. (2010) did not see statistical differences in residual NO_3-N at equivalent rates as well. However, under conditions in Idaho over the three locations evaluated in these studies, PCU seemed to have lower residual NO_3-N at standard fertilizer rates.

Even though some researchers did not observe differences in soil residual NO_3-N, others have shown reduced or similar NO_3-N leaching (Venterea et al., 2011; Wilson et al., 2010) and reduces nitrous oxide emissions (Hyatt et al., 2010; LeMonte et al., 2011; Venterea et al., 2011) when using PCU fertilizers. Results from Zebarth et al. (2012) suggest that this may not always be the case as PCU may even increase the risk of nitrous oxide emissions in some cases.

Although our study did not measure either of these parameters, the similarities of our work with others would suggest that we may see similar results as the former studies. The combination of all these results further confirms improved efficiency of N with use of the PCU (ESN) used in these studies.

Conclusions

The Results of this study show that when using PCU (ESN) fertilizers provided greater NUE as shown by higher yields per unit of N. In addition to yield, the lower petiole N concentrations observed with PCU also suggests that the plants used fertilizer N more efficiently than with urea. PCU fertilizers have the potential to improve the efficient use of N fertilizer while maintaining or improving yields and reducing losses to the environment. Petiole concentrations, soil residual NO_3-N measurements, and reduced losses as shown by other studies all indicate that PCU fertilizers have the potential to be more efficient in supplying N to the potato crop. This is important in a time when fertilizer and application costs are higher in the last decade. PCU can help reduce those costs and may even improve profits with increased yields and quality, at the same time reducing loss to the environment.

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Tables

Table 3.1. Pre-plant soil test data and nutrient levels for three Idaho locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) for N fertilizer response trials on Russet Burbank potato.

	-------------Location-------------		
Soil Test Data‡	AB1	BF1	AB2
Soil pH	8.4	8.0	8.3
Excess Lime, %	5.7	1.0	7.2
Organic Matter, %	1.7	1.8	1.4
Nitrate-N, mg kg^{-1}	1	5	7
Phosphorus, mg kg^{-1}	13	16	24
Potassium, mg kg^{-1}	170	160	215
Calcium, mg kg^{-1}	4168	2906	2365
Magnesium, mg kg^{-1}	267	401	352
Sodium, mg kg^{-1}	23	23	69
Sulfate-S, mg kg^{-1}	14	8	11
Zinc, mg kg^{-1}	1.2	1.8	1.4
Iron, mg kg^{-1}	5.0	9.6	2.5
Manganese, mg kg^{-1}	6.0	8.4	4.5
Copper, mg kg^{-1}	0.4	0.6	0.9
Boron, mg kg^{-1}	0.4	0.5	0.9

†Soil test methods include: 2:1 (pH), titration (Lime), Walkley-Black (OM), KCl (nitrate), bicarbonate Olsen (P), ammonium acetate (K, Ca, Mg, S, and Na), DTPA (Zn, Fe, Mn, Cu), and hot water (B) (Gavlak et al., 2003)

Table 3.2. Pre-plant† soil NO_3-N at two depths for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of an N fertilizer response trial in 2006-2007.

	-------- Soil NO_3-N mg kg^{-1} --------	
Location	0-46 cm	46-76 cm
AB1	11	7
BF1	17	13
AB2	10	8

†Pre-plant soil samples were taken from each block and values were averaged across blocks for each location.

Table 3.3. Significance (*Pr* > *F*) of overall model and model components, including: block, location (L), N rate (R), fertilizer source (S), with all possible interactions on seasonal changes in residual soil NO_3-N concentration (ΔNO_3-N), petiole NO_3-N concentration, NDVI, and yield per unit of N applied ($\Delta Y/N$) for Total, US No. 1, and Marketable yields for three locations of a N fertilizer response trial on Russet Burbank potato in 2006-2007. Values in bold face type are significant at *Pr* < 0.10.

Parameter Measured	Model	Block	L	R	S	L*R	L*S	R*S	L*R*S
Seasonal Change in Surface and Sub Soil NO3-N									
0-46 cm	**<0.0001**	**0.0130**	**<0.0001**	**<0.0001**	**0.0001**	**0.0105**	0.5415	**0.0007**	0.9633
46-76 cm	**<0.0001**	0.7529	**0.0888**	**<0.0001**	0.8886	**0.0117**	0.3845	0.8747	0.5266
Canopy Measurements									
Petiole NO3-N	**<0.0001**	0.1615	**<0.0001**	**<0.0001**	**<0.0001**	0.1536	0.8781	0.1103	0.2641
NDVI	**<0.0001**	**0.0416**	**<0.0001**	**<0.0001**	**0.0842**	0.2910	0.3907	0.8718	0.6599
Tuber Yield Increase per Unit of Fertilizer N Applied									
Total	**<0.0001**	**0.0227**	**0.0061**	**<0.0001**	**0.0412**	0.1705	0.2236	0.9631	0.9749
US No. 1	**0.0015**	**0.0149**	0.5802	**<0.0001**	**0.0037**	0.7125	0.5587	0.2791	0.7689
Marketable	**0.0009**	**0.0031**	0.1700	**<0.0001**	**0.0300**	0.7904	0.7094	0.6628	0.7926

Table 3.4. Seasonal change in residual soil NO_3-N (ΔNO_3-N) at 0-46 cm, 46-76 cm, and total NO_3-N (mg kg^{-1}) for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	--- 0-46 cm Soil NO_3-N ---			-- 46-76 cm Soil NO_3-N --			--- Average Soil NO_3-N ---		
Rate, %†	AB1	BF1	AB2	AB1	BF1	AB2	AB1	BF1	AB2
	-- mg NO_3-N kg^{-1} soil --								
				unfertilized check					
0	-4	-5	-3	-5	-7	-4	-4	-6	-3
				PCU at emergence					
33	-4	-2	-2	-4	-6	-4	-4	-3	-3
67	-1	5	1	-2	0	-2	-1	3	0
100	-2	9	10	5	9	4	0	9	8
133	15	31	22	15	16	3	15	25	14
				Urea at emergence					
33	-3	-1	-2	-3	-5	-3	-3	-3	-3
67	-2	3	-1	-1	1	-4	-1	2	-2
100	-2	12	10	-1	6	4	-1	9	7
133	0	16	9	1	24	6	1	19	8
				Split-applied urea ‡					
33	-3	4	0	-4	-4	-2	-3	1	-1
67	2	11	6	0	-1	-2	1	6	3
100	2	13	15	-1	6	0	1	10	9
133	7	32	32	7	18	13	7	26	24
				Average across all treatments					
	0	10	8	1	4	1	0	8	5

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for AB1, and BF1 and 269 kg ha^{-1} for AB2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table 3.5. Petiole NO3-N and NDVI for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	--------- Petiole NO3-N (mg kg^{-1}) ---------			------------------ NDVI ------------------		
Rate, %†	AB1	BF1	AB2	AB1	BF1	AB2
			unfertilized check			
0	1041	4925	1672	0.598	0.767	0.576
			PCU at emergence			
33	1252	3888	2987	0.745	0.821	0.707
67	4053	9573	8153	0.818	0.837	0.806
100	6212	17695	13995	0.848	0.847	0.822
133	12213	19387	14964	0.825	0.846	0.851
			Urea at emergence			
33	1825	5093	3542	0.684	0.806	0.705
67	3470	10888	5452	0.811	0.819	0.773
100	4852	8225	13506	0.782	0.833	0.807
133	4316	15735	12408	0.804	0.828	0.845
			Split-applied urea ‡			
33	2740	6455	7647	0.721	0.791	0.761
67	8059	13803	12462	0.755	0.839	0.789
100	9489	16615	14475	0.721	0.834	0.830
133	13350	18212	15829	0.807	0.844	0.797
			Average across all treatments			
	5606	11576	9776	0.763	0.824	0.774

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for AB1, and BF1 and 269 kg ha^{-1} for AB2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table 3.6. Total, US No. 1, and Marketable yield (Mg ha^{-1}) increase per kg N ha^{-1} (converted to g g^{-1}) applied relative to the untreated control (ΔY/N) for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of an N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	----- Total Yield per kg^{1} N -----			-- US No. 1 Yield per kg^{1} N --			- Marketable Yield per kg^{1} N -		
Rate, %†	AB1	BF1	AB2	AB1	BF1	AB2	AB1	BF1	AB2
				PCU at emergence					
33	66	38	103	79	52	116	89	54	89
67	69	33	58	63	33	49	79	41	79
100	43	22	32	25	19	22	47	28	47
133	23	12	26	23	13	17	34	18	34
				Urea at emergence					
33	24	49	73	26	51	33	36	67	36
67	28	26	47	26	18	46	50	32	50
100	10	9	35	21	7	16	26	14	26
133	13	13	17	15	13	-10	23	17	23
				Split-applied urea ‡					
33	51	49	91	37	32	36	49	27	49
67	27	37	49	23	31	27	38	38	38
100	21	21	35	36	8	10	39	12	39
133	17	14	15	20	14	8	26	21	26
				Average across all treatments					
	30	25	45	30	22	28	41	28	43

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for AB1, and BF1 and 269 kg ha^{-1} for AB2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Figures and Figure Descriptions

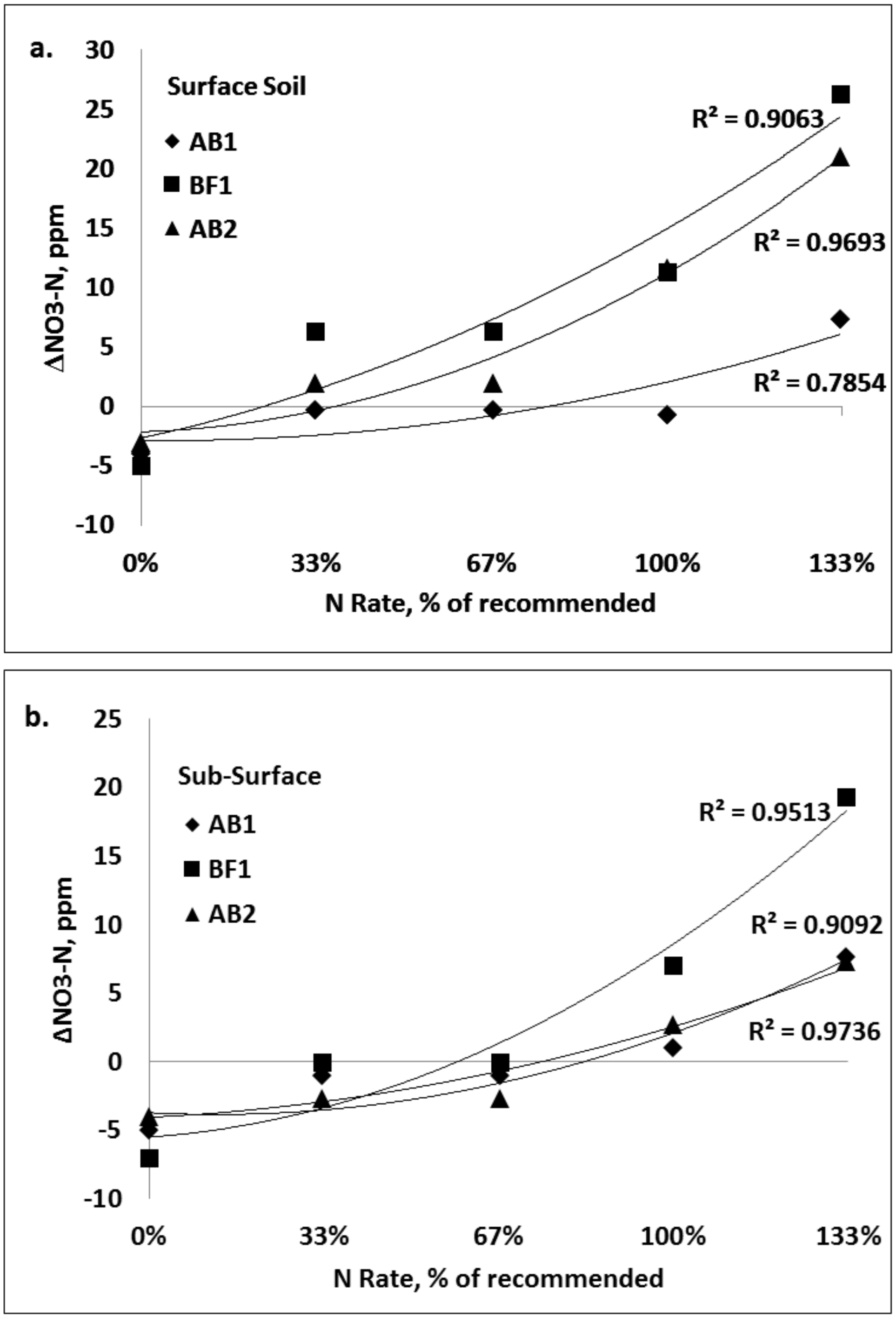

Figure 3.1. Changes in seasonal (a) surface and (b) sub soil nitrate (ΔNO_3-N) for three locations (Aberdeen 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen 2007 = AB2) of a nitrogen (N) fertilizer response trial on Russet Burbank potato in 2006-2007 with five rates of fertilizer N applied (averaged across N sources/timings).

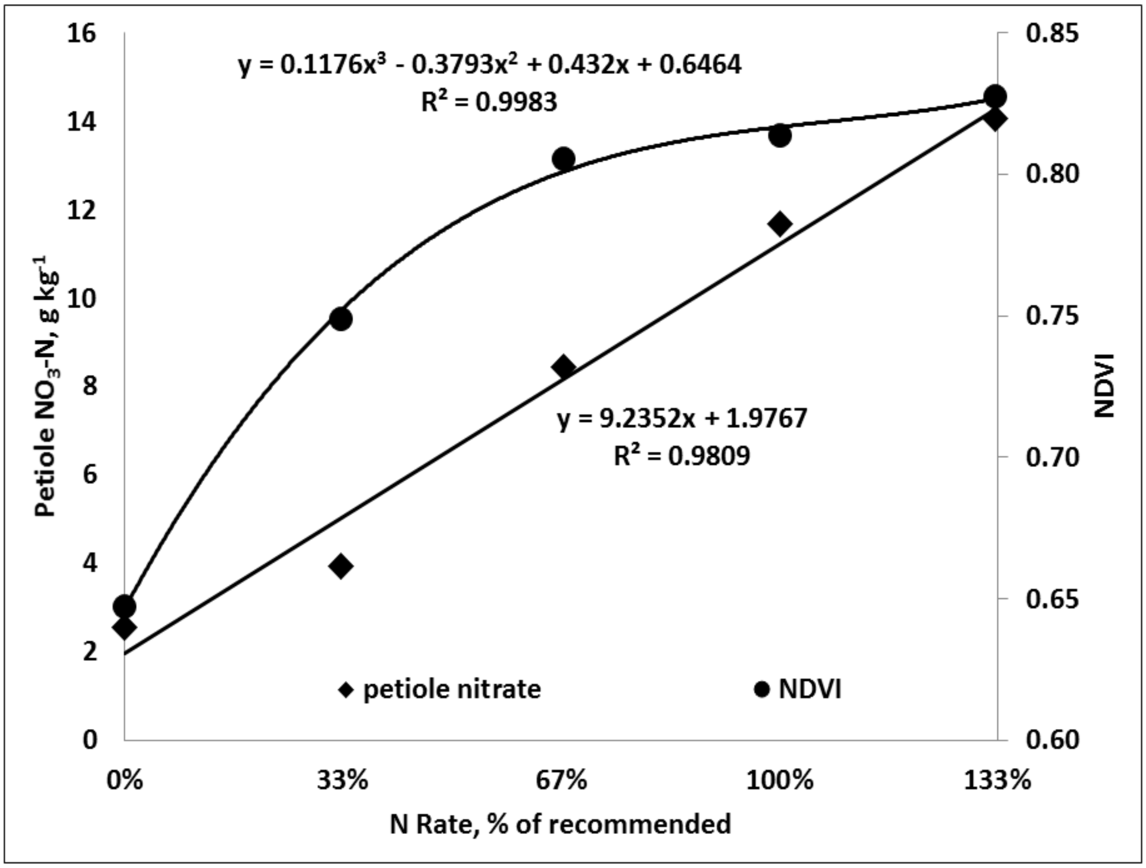

Figure 3.2. Petiole nitrate (NO_3-N) and NDVI response to 5 rates of a nitrogen (N) fertilizer trial across three locations in southern Idaho on Russet Burbank potato in 2006-2007 (averaged across locations and N sources/timings).

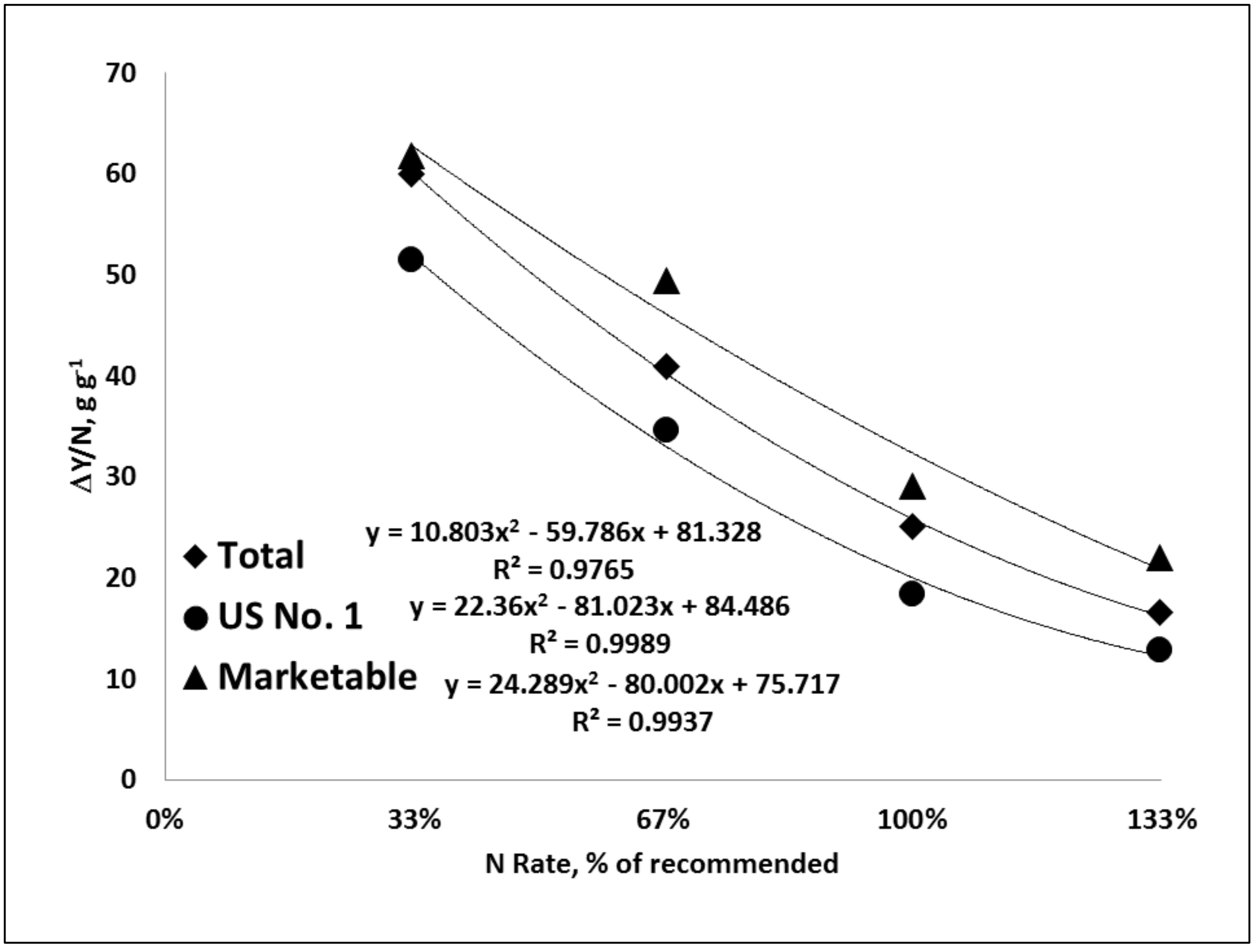

Figure 3.3. Russet Burbank tuber yield increase per unit of nitrogen (N) applied (ΔY/N) for Total, US No. 1, and Marketable yields of an N fertilizer trial across three locations in southern Idaho in 2006-2007 (averaged across locations and N sources/timings).

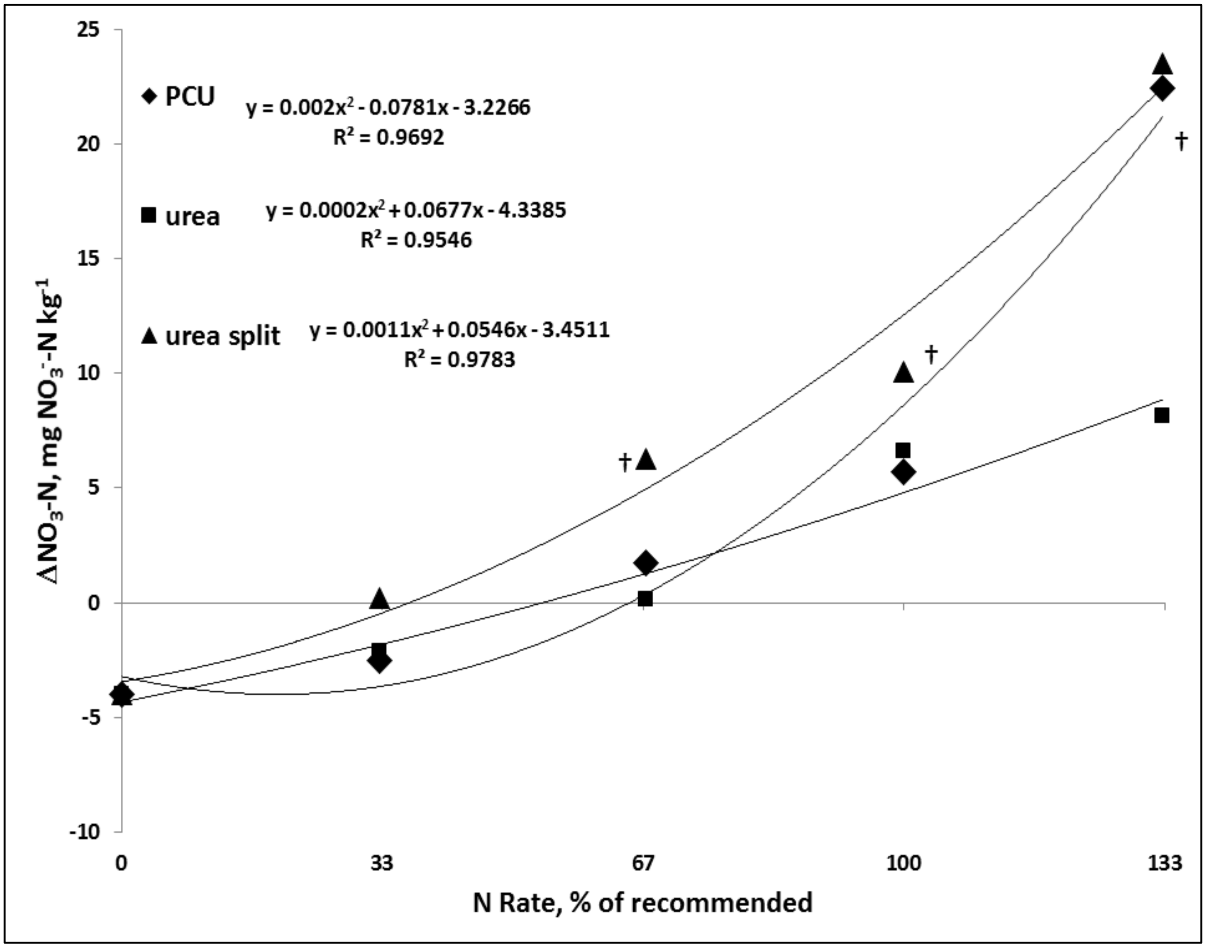

Figure 3.4. Effect of fertilizer source on the seasonal change in soil nitrate (ΔNO_3-N) across three locations in southern Idaho of an N fertilizer trial in 2006-2007 with five rates of fertilizer N applied. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications.

†Indicates that the point next to the symbol is significantly greater than the other fertilizer sources/timings not similarly marked at the given N rate. ($P < 0.10$)

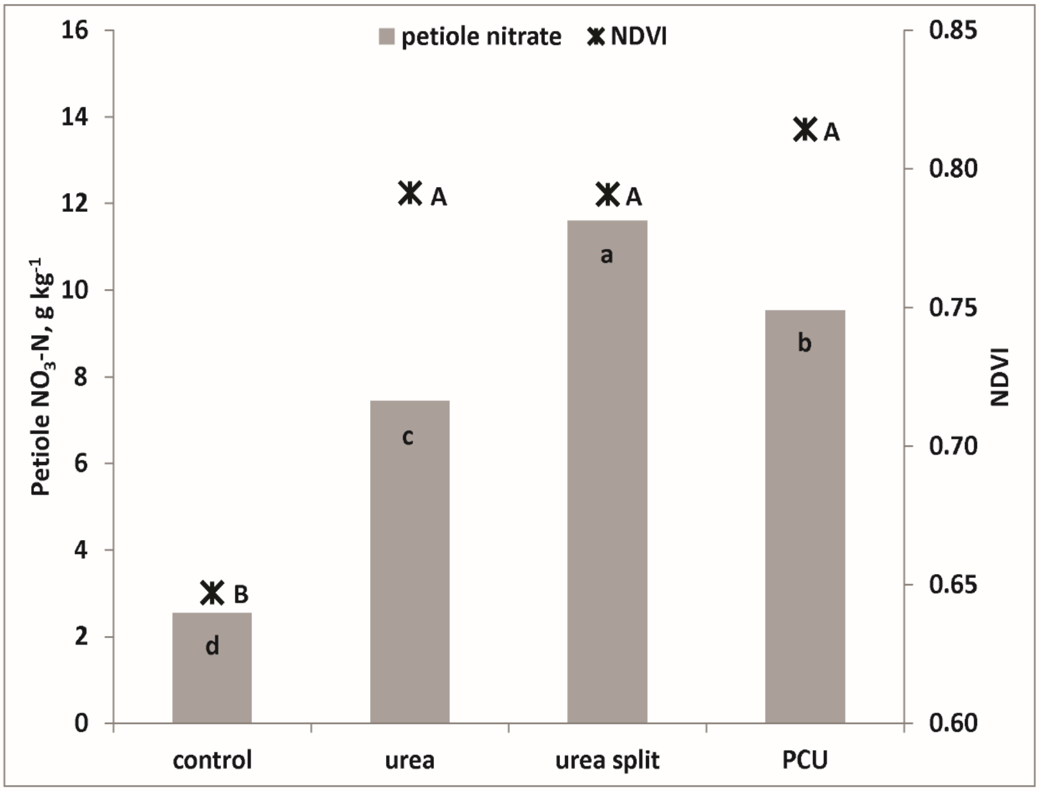

Figure 3.5. Effect of fertilizer source on petiole nitrate (NO_3-N) and NDVI across three locations in southern Idaho of an N fertilizer trial in 2006-2007 with five rates of fertilizer N applied. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars or points with the same letters (uppercase for NDVI and lowercase for petiole NO_3-N) are not significantly different. ($P < 0.10$)

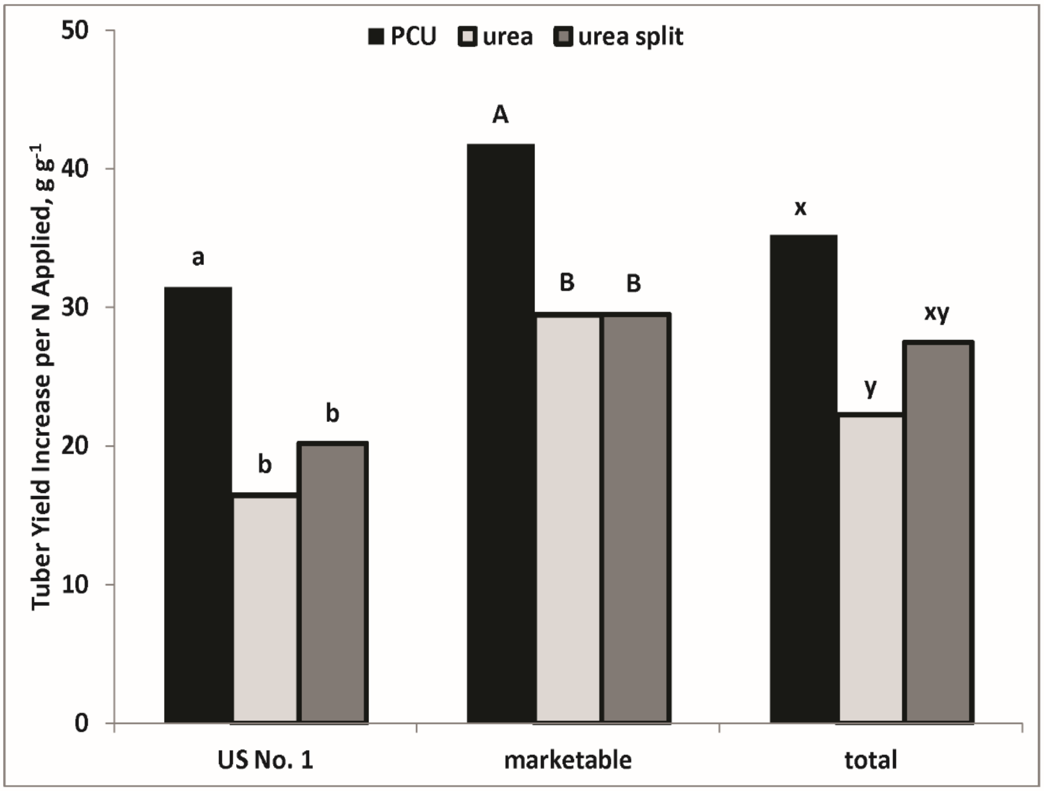

Figure 3.6. Effect of fertilizer source on yield increase per unit of nitrogen (N) applied (ΔY/N) for US No. 1, marketable, and total tuber yields across three southern Idaho locations of an N fertilizer trial in 2006-2007. An untreated control was compared to four rates (values shown averaged across N rates) of N fertilized plots applied as polymer coated urea (PCU) or uncoated urea applied just prior to plant emergence from the soil or as split-applied urea with 50% applied pre-emergence and the remaining in three equal in-season split broadcast applications. Bars with the same letters are not significantly different within a yield grouping. ($P < 0.10$)

Appendix A

Non-Responsive Location Data and Information

Discussion of Non-responsive Fields

Data from two additional locations was collected but were not analyzed as part of the main data analysis. These two locations were located near Rupert, Idaho in 2006 and 2007. These sites were located on grower's fields and it was difficult to control outside agronomic variables such as irrigation and water management.

The reason(s) behind why the RP1 2006 and RP2 2007 fields did not respond to N fertilization and yet had excellent total yields is not completely known. Previous crop credits/debits, residual inorganic soil N, and nitrate in the irrigation water were accounted for in the calculating of fertilizer need and do not explain the lack of response. No manure had been applied in recent years and soil organic matter was low. For the RP2 2007 field, we are fairly certain that N was inadvertently applied through the irrigation due to leakage from a shared system with another field. We assume a similar grower error for the other field as well, as well as under irrigation.

Because the very different responses for the RP1 2006 and the RP2 2007 fields in relation to the other fields, an additional analysis was performed to compare N responsive to N unresponsive fields. It was found that there was a significant interaction with fertilizer source (Pr > F 0.0134). For the reasons listed above and because total yield is the parameter of greatest interest in this study, it was decided to examine the source response for these three fields and eliminate the two non-responsive ones from the following discussion. However, it is interesting to note that there was significantly less yield reduction (difference of 3.0 Mg ha^{-1}) for controlled release (PCU) urea as compared to urea applied at emergence for the RP2 2007 field and a similar trend was observed in the other non-responsive field as well (Table A.1-A.2). All data collected is summarized in tables A.1-A.6.

Table A.1. Russet Burbank potato yields (Mg ha^{-1}) for a fertilizer trial near Rupert, ID in 2006 with five rates of nitrogen (N) applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	----------------- US No. 1 -----------------					US No. 2	Marketable§	------------ Culls -----------			Total Tuber Yield
Rate, %†	114-170 g	170-284 g	284-397 g	>397 g	total			<114 g	malformed	total	
						unfertilized check					
0	0.7	1.3	0.7	0.2	2.9	12.3	15.1	0.0	34.0	34.0	49.2
						PCU at emergence					
33	0.6	1.6	0.9	1.3	4.3	11.3	15.6	0.0	34.6	34.6	50.2
67	0.5	1.0	0.8	0.5	2.7	10.4	13.1	0.0	36.6	36.6	49.8
100	0.1	0.4	0.4	0.3	1.2	7.3	8.5	0.0	37.6	37.6	46.1
133	0.3	0.3	0.3	0.0	1.0	7.8	8.8	0.0	33.1	33.1	41.9
						Urea at emergence					
33	0.3	0.6	0.6	0.5	2.0	6.1	8.0	0.0	36.6	36.6	44.6
67	0.1	0.3	0.2	0.0	0.6	5.4	6.0	0.0	39.2	39.2	45.3
100	0.2	0.4	0.4	1.2	2.1	10.8	12.9	0.0	36.9	36.9	49.8
133	0.3	0.2	0.1	0.3	0.9	7.3	8.2	0.0	34.9	34.9	43.1
						Split-applied urea‡					
33	0.9	2.7	1.2	0.8	5.6	14.9	20.5	0.0	28.0	28.0	48.5
67	0.3	0.8	0.7	0.1	1.9	8.7	10.6	0.0	40.8	40.8	51.4
100	0.1	0.3	0.3	0.3	1.0	9.1	10.1	0.0	34.7	34.7	44.7
133	0.1	0.8	0.5	0.1	1.5	8.8	10.3	0.0	36.5	36.5	46.7
						Average across all treatments					
	0.3	0.8	0.5	0.4	2.1	9.2	11.4	0.0	35.7	35.7	47.0

† Recommended N rate of 100% based on yield goal, residual nitrogen, soil type, etc. equaled = 303 kg ha^{-1} for this field.

†Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

§ Marketable = Total US No. 1 + US No. 2 tuber yields

Table A.2. Russet Burbank potato yields (Mg ha^{-1}) for a fertilizer trial near Rupert, ID in 2007 with five rates of nitrogen (N) applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	----------------- US No. 1 -----------------					US No. 2	Marketable§	------------ Culls -----------			Total Tuber Yield
Rate, %†	114-170 g	170-284 g	284-397 g	>397 g	total			<114 g	malformed	total	
						unfertilized check					
0	6.1	11.7	3.3	4.7	25.8	12.8	38.6	5.0	2.6	7.6	46.1
						PCU at emergence					
33	4.5	10.7	2.6	9.9	27.8	13.8	41.6	4.6	4.0	8.6	50.1
67	3.4	9.5	4.4	8.7	26.0	14.1	40.1	3.9	3.1	7.0	47.1
100	3.8	7.1	2.7	6.4	19.9	14.3	34.2	4.1	4.0	8.1	42.3
133	3.3	8.5	2.1	7.2	21.1	14.7	35.9	4.8	4.5	9.2	45.1
						Urea at emergence					
33	3.4	8.4	2.9	8.6	23.3	14.5	37.8	4.6	3.4	8.0	45.8
67	5.0	9.6	2.6	7.7	24.9	13.2	38.1	3.7	3.6	7.3	45.4
100	5.1	8.6	4.1	6.1	24.0	14.0	38.0	4.0	3.1	7.1	45.0
133	4.1	9.3	2.5	7.0	22.9	14.5	37.4	4.0	4.7	8.8	46.2
						Split-applied urea‡					
33	4.3	9.3	2.7	8.2	24.5	13.0	37.5	4.0	3.6	7.6	45.1
67	4.6	10.5	2.9	6.7	24.7	11.2	35.8	4.6	2.0	6.6	42.4
100	4.6	9.9	3.1	5.6	23.2	11.2	34.4	4.0	3.1	7.1	41.5
133	4.0	7.8	2.1	5.9	19.9	14.4	34.3	6.6	2.8	9.4	43.8
						Average across all treatments					
	4.3	9.3	2.9	7.1	23.7	13.5	37.2	4.4	3.4	7.9	45.1

†Recommended N rate of 100% based on yield goal, residual nitrogen, soil type, etc. equaled = 269 kg ha^{-1} for this field.

‡ Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

§Marketable = Total US No. 1 + US No. 2 tuber yields

Table A.3. Specific gravity, % hollow heart, and % brown center for two non-responsive locations (Rupert 2006 = RP1; Rupert 2007 = RP2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	-- Specific Gravity --		- % Hollow Heart -		% Brown Center	
Rate, %†	RP1	RP2	RP1	RP2	RP1	RP2
			unfertilized check			
0	1.089	1.078	1.6	0.0	0.0	1.6
			PCU at emergence			
33	1.091	1.076	0.0	0.0	0.0	0.0
67	1.088	1.073	7.8	0.0	0.0	1.6
100	1.087	1.072	0.0	0.0	0.0	0.0
133	1.093	1.073	0.0	0.0	0.0	0.0
			Urea at emergence			
33	1.091	1.072	3.1	0.0	0.0	0.0
67	1.090	1.075	4.7	0.0	0.0	0.0
100	1.090	1.074	0.0	0.0	2.1	0.0
133	1.092	1.074	0.0	0.0	0.0	0.0
			Split-applied urea‡			
33	1.092	1.074	0.0	0.0	0.0	0.0
67	1.089	1.074	0.0	0.0	0.0	0.0
100	1.088	1.073	0.0	0.0	0.0	0.0
133	1.091	1.074	0.0	1.6	0.0	0.0
			Average across all treatments			
	1.090	1.074	1.3	0.1	0.2	0.2

†Recommended N rate of 100% based on yield goal, residual nitrogen, soil type, etc. equaled = 303 kg ha^{-1} for RP1 and 269 kg ha^{-1} for RP2.

‡ Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table A.4. Seasonal change in residual soil NO_3-N (ΔNO_3-N) at 0-46 cm, 46-76 cm, and total NO_3-N (mg kg^{-1}) for two non-responsive locations (Rupert 2006 = RP1; Rupert 2007 = RP2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	- 0-46 cm Soil NO_3-N -		46-76 cm Soil NO_3-N		-- Average Soil NO_3-N --	
Rate, %†	RP1	RP2	RP1	RP2	RP1	RP2
	------------------------------------- mg NO_3-N kg^{-1} soil -------------------------------------					
			unfertilized check			
0	-7	0	-10	10	-8	4
			PCU at emergence			
33	-6	6	-9	10	-7	8
67	0	11	-2	21	-1	15
100	15	13	2	28	10	19
133	19	17	4	35	13	24
			Urea at emergence			
33	-7	10	-7	16	-7	13
67	-1	6	-7	23	-3	13
100	18	11	17	32	18	19
133	31	34	21	28	27	32
			Split-applied urea ‡			
33	-7	7	-8	16	-7	10
67	3	11	-7	27	-1	18
100	15	18	2	43	9	28
133	22	15	12	37	18	24
			Average across all treatments			
	7	12	1	25	5	17

†Recommended N rate of 100% based on yield goal, residual nitrogen, soil type, etc. equaled = 303 kg ha^{-1} for RP1 and 269 kg ha^{-1} for RP2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table A.5. Petiole NO3-N and NDVI for two non-responsive locations (Rupert 2006 = RP1; Rupert 2007 = RP2) of a N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	Petiole NO3-N (mg kg^{-1})		----------- NDVI -----------	
Rate, %†	RP1	RP2	RP1	RP2
		unfertilized check		
0	1084	10896	0.779	0.854
		PCU at emergence		
33	2934	13824	0.864	0.899
67	9044	14241	0.873	0.901
100	16833	16028	0.881	0.899
133	15593	15630	0.873	0.859
		Urea at emergence		
33	1749	13803	0.863	0.878
67	7363	15036	0.870	0.860
100	12557	14656	0.877	0.884
133	14107	14199	0.868	0.882
		Split-applied urea ‡		
33	4916	15641	0.862	0.888
67	15639	17747	0.869	0.870
100	18507	18776	0.874	0.878
133	21053	19764	0.877	0.854
		Average across all treatments		
	10875	15403	0.864	0.877

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for RP1 and 269 kg ha^{-1} for RP2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.

Table A.6. Total, US No. 1, and Marketable yield (Mg ha^{-1}) increase per kg N ha^{-1} (converted to g g^{-1}) applied relative to the untreated control (ΔY/N) for two non-responsive locations (Rupert 2006 = RP1; Rupert 2007 = RP2) of an N fertilizer response trial on Russet Burbank potato in 2006-2007 to five rates of N applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only).

	Total Yield per kg^{1} N		US No. 1 Yield per kg^{1} N		Marketable Yield per kg^{1} N	
Rate, %†	RP1	RP2	RP1	RP2	RP1	RP2
PCU at emergence						
33	10	45	14	22	5	34
67	3	5	-1	1	-10	8
100	-10	-14	-6	-22	-22	-16
133	-18	-3	-5	-13	-16	-7
Urea at emergence						
33	-45	-3	-9	-28	-70	-8
67	-19	-4	-11	-5	-45	-3
100	5	-4	-4	-7	-13	-2
133	-13	-0	-6	-8	-22	-3
Split-applied urea ‡						
33	-6	-12	27	-15	53	-12
67	11	-21	-5	-6	-22	-15
100	-15	-17	-6	-10	-17	-15
133	6	-7	-3	-16	-12	-12
Average across all treatments						
	-8	-3	-1	-8	-15	-4

†Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for RP1 and 269 kg ha^{-1} for RP2.

‡Urea applied as 50% at emergence with remaining applied in three uniform rates during the season.