IRRIGATED POTATO (*SOLANUM TUBEROSUM* L.) YIELD, QUALITY RESPONSE AND NITROGEN LOSSES AS INFLUENCED BY NITROGEN FERTILIZER MANAGEMENT AND CULTIVARS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Field studies were conducted in 2015 and 2016 growing season at Northern Plains Potato Growers' Association Irrigation site near Inkster, ND to evaluate the effectiveness of enhanced efficiency fertilizers (EEFs) in maintaining yield, quality and reducing environmental nitrogen (N) losses in irrigated potatoes (*Solanum tuberosum*). Two types of EEFs i.e. SuperU (urea with urease and nitrification inhibitor) and ESN (polymer coated urea); grower's standard fertilization and unamended urea were applied in three late-sown russet potato cultivars.

Our findings suggested that yield responses vary widely with respect to years, length of growing season and cultivar type. Among EEFs, ESN consistently maintained yield compared to conventional fertilization practices. In shorter growing season (114 days), no yield benefit over N rate of 225 kg ha^{-1} was obtained with higher N rates (280 kg N ha^{-1}) and different N sources in all three cultivars. Determinate cultivars can be a better choice to get good yield with lower N rate in shorter growing seasons.

Both of the EEFs significantly reduced N losses through ammonia (NH_3) volatilization and nitrous oxide (N_2O) emission compared to unamended urea and grower's standard fertilization practice. SuperU did not reduce residual soil nitrate (NO_3^-) compared to unamended urea while ESN reduced residual soil NO_3^-. Overall, ESN or polymer coated urea (PCU) is a promising choice for reducing N losses from irrigated potatoes.

Plant N status assessment is important for yield prediction. Despite of being time consuming, total N concentration in petioles gave the better estimate of crop N status compared to standard petiole NO_3-N concentrations. For early season quick N status measurement, ground based active optical sensors should be used in a cultivar specific way. Nitrogen fertilization recommendation for irrigated potatoes in North Dakota should be recalibrated considering length of growing season and cultivar type.

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DEDICATION

This work is dedicated to my mother Ms. Nabanita Majumdar

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AFR	Apparent fertilizer recovery
DAP	Days after planting
EEFs	Enhanced efficiency fertilizers
N	Nitrogen
N_2O	Nitrous oxide
NDRE	Red edge normalized difference vegetation index
NDVI	Normalized difference vegetation index
NH_3	Ammonia
NI	Nitrification inhibitor
$NO3^{-}$	Nitrate
NUE	Nitrogen use efficiency
PCU	Polymer coated urea
UI	Urease inhibitor
VI	Vegetation indices

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GENERAL INTRODUCTION

Limitations to produce food for an ever growing global population have been a burning topic of debate for ages. The world population projections indicate that the total population would reach 9.15 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2013). Expansion of agricultural lands through land clearing and intensive use of existing croplands were the primary solutions to meet the nutritional demands of rapidly increasing human population for a long time (Cassman and Wood, 2005). However, agricultural intensification and expansion are no longer feasible options to meet global food demand as land clearing threatens biodiversity; crop production and fertilization tremendously; increase greenhouse gas (GHG) production as well as destroy marine, freshwater and terrestrial ecosystems (Tilman et al., 2001). The biggest challenge faced by the agriculture in the 21st century is to produce more food and fiber to feed a growing population with a smaller labor force, in which nitrogen (N) fertilization is an inevitable factor. Agricultural lands are inherently deficient in N because soil does not contain any direct source of N and the usable portion of environmental N is very low. Atmospheric N_2 stock is extremely large i.e. 3.9×10^{15} Mg (N), but unavailable for plant use. In 100000 Mg terrestrial organic N stock 96% is in the form of dead organic matter, but only 15% of organic N is labile (easily mineralizable) (Socolow, 1999). The discovery and synthesis of ammonia through Haber-Bosch process in 1909 and later its use in N fertilizer production was the pathway to agricultural intensification also known as green revolution in 1960s (Matson et al., 1997). In 2010-2011 the world consumption of fertilizer reached 172 million Mg of which 104 Mg was N (Heffer, 2013). Unfortunately, only less than 50% of the applied fertilizer N is utilized by the crop and the rest either resides in soil or subjected to loss to off-farm environment where it contributes to various environmental hazards

(Mosier et al., 2005). The main pathways of N losses to environment are nitrate (NO_3^-) leaching, ammonia (NH_3) volatilization, NO_x [nitric oxide (NO), nitrous oxide (N_2O)] and dinitrogen (N_2) gas emissions (Galloway et al., 2004). Ammonia volatilization contributes to acid rain and serves as an indirect source of N_2O emission (Cameron et al., 2013) and its subsequent deposition to soil and aquatic systems cause eutrophication (Erisman et al., 2007). Nitrate being soluble in water easily contaminates groundwater through leaching and other aquatic systems through run off which in turn causes eutrophication (Cameron et al., 2013; Davidson et al., 2015). Nitrate-N concentration in drinking water over 10 mg L^{-1} (USGS, 1998) causes serious health hazards like infantile methamoglobanemia (‘blue baby syndrome’) and gastrointestinal cancer (Alva et al., 2004). Among the gaseous emissions leading to N losses, return of N_2 to atmosphere is safe, but N_2O is a potent greenhouse gas and strong stratospheric ozone depleting substance (Cameron et al, 2013) and NO is a precursor of N_2O emission. Since human population and per capita consumption rate continues to increase, N fertilizer use in the near and distant future would certainly increase globally. With the increase of fertilizer application rate the N use efficiency of crops generally decreases, which would result in greater losses of N per additional unit of N fertilizer used (Mosier et al., 2004).

For a high N-demand, low nitrogen use efficiency (NUE), shallow-rooted crop like potato (*Solanum tuberosum*), localized BMP for N are necessary as the responses are extremely variable with soil, weather, fertilizer and water input. Modifying the fertilizer N release pattern to synchronize with crop N demand is one of the options for improving NUE (Munoz et al., 2005; Waddell et al., 2000). When applied at planting, conventional soluble fertilizers (urea, urea ammonium nitrate, ammonium nitrate etc.) get mineralized and lost too quickly to meet up crop N demand in later growth stages. Split application of fertilizers throughout the growing season requires a lot of labor and energy cost (Munoz et al., 2005; Zvomuya et al., 2003). Enhanced efficiency fertilizer products (EEFs) are developed in order to synchronize N release from applied fertilizers with the crop N demands and minimize the environmental losses even with one time (preplant) application (Trenkel, 2010; Halvorson et al., 2014).

In our study, among a broad group of EEFs, we used two commercially available EEF products i.e. SuperU (Koch Agronomic Services) and ESN® (Agrium Inc). SuperU is granular urea blended with urease inhibitor (UI) N-(n-butyl)-thiophosphoric triamide (NBPT) and the nitrification inhibitor dicyandiamide (DCD). Urease inhibitor temporarily blocks the urease enzyme binding site and thus delays urea hydrolysis or ammonification (Trenkel, 2010). A nitrification inhibitor blocks the conversion of NH_4^+ to NO_2^- (first step of nitrification) by inhibiting the activity of nitrifiers and thus delays NO_3^- formation (Trenkel, 2010). Environmentally smart nitrogen (ESN) is urea coated with a microthin polymer semi permeable to water, and thus slows down N mineralization by protecting the urea from immediate hydrolysis (Blaylock et al., 2004).

This dissertation is divided into four parts (i) Literature review (ii) Chapter 1 ('Influence of enhanced efficiency fertilizers on late sown irrigated potato yield and quality response') (iii) Chapter 2 (Effectiveness of enhanced efficiency fertilizers and split application to minimize nitrogen losses after planting delays in irrigated russet potatoes) and (iv) Chapter 3 (Petiole nitrate, total petiole nitrogen and vegetation indices for estimating N status and yield prediction). In the literature review, the importance of N management in potato crop, environmental losses of N, types of EEFs, the performance of different N management practices focusing on EEFs, split application and N status assessment methods in potato crop have been discussed. In chapter 1, effectiveness of the EEFs in maintaining yield, tuber quality, N uptake, NUE and apparent fertilizer recovery (AFR) in three russet potato cultivars compared to unamended urea and grower's standard fertilization practice have been discussed. In the second chapter, N losses through NH_3 volatilization, N_2O emission and NO_3^- leaching with each N fertilizer treatment under three different cultivars have been estimated to evaluate the performance of the EEFs in reducing N losses compared to conventional fertilization. In Chapter 3, in season N status assessment and prediction of yield from N status of the crop have been evaluated with different methods i.e. petiole NO_3^- concentration, total N concentration in petiole, and vegetation indices (VI) calculated from crop reflectance measured with ground based active optical sensors.

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REVIEW OF LITERATURE

Best management practices for N in potato production

Maintenance of productive soil through fertilization is essential for successful production (Foth and Ellis, 1996). Excessive nutrient application also has detrimental environmental consequences (Davenport et al., 2005; Hopkins et al., 2007). Environmental impacts of N loss definitely dominate research priorities; however, enhancement of yield and NUE are also equally important priorities for both producers and the world food demand. Furthermore, enhancing NUE reduces fertilizer manufacture, transport, and application costs. Nearly 20% of the production cost is for fertilizers of which N fertilizers has the maximum share (Munoz et al. 2005; Zvomuya et al., 2003). Potatoes have high nutrient demand and a shallow rooting system, so potatoes need steady nutrient supply through proper fertilization (Munoz et al. 2005; Stark et al., 2004; Westermann, 2005). As potatoes are grown on sandy soils with low water holding capacity and extremely sensitive to moisture stress, a high rate of irrigation is often required in semi-arid regions. Nitrogen management in irrigated potato crop becomes more challenging due to nutrient leaching (Shock et al., 2007).

Synchronizing N availability and crop demand is the key for potato BMP and fertilizer recommendation (Errebhi et al., 1998b; Munoz et al., 2005; Stark et al., 2004; Waddell et al., 2000; Westermann and Kleinkopf, 1985). Multiple split application of N fertilizers is a common recommendation for potato production (Rosen and Bierman, 2008). Irrigated potato growers supply about 50% of N through fertigation throughout the growing season, but it is unsuitable for non-irrigated cropping systems and some irrigators. In that situation, growers apply N in one pre-plant application or split into two or more applications through side dress or aerial broadcast (Hopkins et al, 2008). Controlled-release N (CRN), slow release N (SRN) and stable fertilizer

(SF) sources are other options for judicial N management and broadly called enhanced efficiency fertilizers (EEFs). Enhanced efficiency fertilizers are designed to release N in soil over an extended period to match up crop demand and to reduce labor and cost intensive in-season N fertilizer application (Alva, 1992; Hutchinson et al., 2003a; Munoz et al., 2005; Shoji et al., 2001; Zvomuya et al., 2003). Controlled release fertilizers are coated or encapsulated with compounds (polymer, polyolefin, resin) semi permeable to water; SRNs are long-chain reduced solubility molecules such as sulfur-coated urea (SCU), urea-formaldehydes (UF), methylene urea, isobutylidine diurea (IBDU), triazine compounds and SFs are fertilizers impregnated with urease and/or nitrification inhibitor (Black et al., 1987; Slater, 2010; Trenkel, 1997; Trenkel, 2010; Zaman et al., 2013a, Zaman et al., 2013b).

Among various urease inhibitors, NBPT has been reported to be one of the most efficient (Gioacchini et al., 2002; Hopkins et al., 2008; Zaman et al., 2008). This compound is effective with urea at very low concentration and it was observed to reduce the pH rise as well as promote nitrification (Christianson et al., 1993). Dicyandiamide has been reported to be an efficient NI (Barneze et al., 2015; Di and Cameron, 2002; Liu et al., 2013; Zaman and Blennerhasset, 2010). Dicyandiamide is one of the most convenient NI as it is nonvolatile, nonhygroscopic, partially water soluble and chemically stable (Prasad et al., 1971; Reidar and Michaud, 1980). Several researchers (Soliman and Abdel Monem, 1996; Zaman and Blennerhassett., 2010) found that fertilizer-N recovery increased when DCD was used with a urease inhibitor (NBPT). Some of the previous works suggested that EEFs like SCU, IBDU were unsuccessful in potato cultivation due to higher cost and unpredictability of release (Elkashif et al., 1983; Hutchinson et al, 2003a; Liegel and Walsh, 1976; Waddell et al., 1999;). Liegel and Walsh (1976) found that SCU performed better in severe leaching conditions, but was not effective in normal condition.

Trenkel (1997), Shaviv (2000) mentioned that N release pattern from PCU is much more predictable than SCU. In recent studies it has been observed that PCU increased or maintained yields compared to soluble N fertilizers at same rates (Hutchinson et al., 2003b; Hyatt et al., 2010; Pack et al., 2006; Shoji et al., 2001; Zvomuya and Rosen, 2001; Zvomuya et al. 2003; Wilson et al., 2009).

Importance of irrigation in potatoes

According to Farm Service Agency, total area under irrigated potato production in North Dakota in 2014 was 9510 ha, which was 30% of the total area planted with potatoes (www.ag.ndsu.edu/irrigation). The prime advantages of production of irrigated potatoes over rain-fed potatoes in ND are higher yields, early maturity and drought protection. Average irrigated potato yield in North Dakota has been reported to be almost double of average non-irrigated potato yield (Scherer et al., 1994). Potatoes are very sensitive to water stress, and even short periods of stress can significantly negatively affect tuber yield and quality (Lynch et al., 1995; Shock et al., 1992; Wright and Stark, 1990). Eldredge et al. (1996) reported a decrease in number of US No 1 tubers and increased internal disorder with short period of irrigation deficit during tuber bulking of ‘Russet Burbank’ potatoes. Fabeiro et al. (2001) examined the effects of irrigation deficit in different growth stages (vegetative growth, tuber bulking, tuber ripening) of potatoes and found that water stress at tuber ripening period affects tuber yield the most. In their experiment, the most deficit irrigation (i.e. 0.4 fold of evapotranspiration throughout the growth period) did not affect the number of tubers but there was a significant reduction in dry matter production. The optimum soil moisture for potatoes to be maintained up to tuber ripening stage is 65 to 85% of available water capacity (AWC) and should be decreased to 60% at vine kill/ before harvesting (King and Stark, 1997). Water deficit condition mainly degrade tuber yield and quality, while over-irrigation lead to disease susceptibility, seed piece or matured tuber decay, NO_3^- leaching, soil erosion and extra input cost for pumping (King and Stark, 1997).

Potato yield, quality, N uptake and N recovery influenced by N fertilization (split application and enhanced efficiency fertilizers)

Potato is a high N demand crop and requires a continuous but variable rate of supply of N in different growth stages. According to North Dakota State University Extension fertilizer recommendation, N requirement for a yield goal of 60 Mg ha^{-1} is 280 kg ha^{-1}, but there is evidence of growers' applying higher rates of N (personal communication with growers). Lauer (1986) conducted a study using cv. 'Russet Burbank' on a Quincy fine loamy sand where he used up to 610 kg N ha^{-1} treatment. Saffigna and Keeney (1977) applied up to 440 kg N ha^{-1} in their experiment.

Potato sprout emergence takes 20 to 30 days after planting (DAP), and during that period sprout nutrition is primarily dependent on the seed piece as then roots are not completely developed. Emergence is followed by the vegetative stage lasting for about 20 to 25 days and then tuber initiation (TI) starts (Alva, 2004). The amount of available N controls the balance between the onset and length of vegetative and reproductive growth stages. Although adequate N is required for TI, excess amount of N application prior to that may result into late season vegetative growth, delay in initiation, secondary tuber growth and low specific gravity (SG) (Allen and Scott, 1980, Ojala et al., 1990). Maximum N uptake and dry matter accumulation occur during tuber bulking to tuber maturity period and tubers plus foliage is the sink for about 80% of the total N uptake throughout the growing period (Greenwood and Draycott, 1995). The N utilization rate and growth rate of tubers vary widely in different cultivars (Westermann and Davis, 1992). Considering minimum 60 days for tuber bulking, the total N required during that period for optimal growth was reported to be about 180 kg N ha^{-1} (Westermann and Davis, 1992). For early tuber development and to increase fertilizer N uptake efficiency, one third to one half of recommended N application is made before or at planting in addition with small amounts through fertigation during the growing season is suggested. Clear understanding of the N uptake pattern is necessary to properly schedule N fertilization rate and timing (Alva, 2004).

Luxury consumption of N quickly at early growth stages is very likely to occur to support high growth rate during periods of N unavailability. Under very high N rates, the vine becomes the dominant sink of N and at lower N rate tuber accumulates maximum portion of N (Millard et al., 1989; Saffigna and Keeney, 1977; Saffigna et al., 1977). Lauer (1986) showed that, with the application of 610 kg N ha^{-1}, except for more N partitioning (60%) in vines, the treatment could not increase yield over 210 kg N ha^{-1} and in fact was slightly lower. Maidl et al. (2002) showed that tuber N recovery increased significantly when N was applied at mid growing period compared to that applied in early growing period.

Nirogen use efficiency is generally low (40 to 50%) for annual crops (Craswell and Godwin, 1984; Hallberg, 1987) and for potatoes grown in sandy soils with intensive irrigations, NUE is about 33% (Errebhi et al., 1998a). The primary reason is that potato has a shallow root system extending up to 60 cm in the soil profile and 90% of the effective roots remain in upper 25 cm of the soil (Tanner et al., 1982) and NO_3^- leaching potential is high in irrigated potato production system (Chu et al., 1997). Management of N fertilization and irrigation are critical in potato production system to attain optimum yield while minimizing environmental hazards.

Response of potatoes to N fertilization, even with recommended management practices, is extremely variable and the best management practice is yet to be developed. Errebhi et al (1998a) showed an increase in yield of smaller tubers and decreased yield of larger tubers when the proportion of N applied at planting was high. Burton et al. (2008), Joern and Vitosh (1995), Westermann and Kleinkopf (1985) did not find any yield benefit of the split application of N over single pre-plant application. Lauer (1985, 1986) showed that tuber yield decreases with no N application at planting (replenished in season) as well as excessive (300 kg N ha^{-1}) N application at planting. Nitrogen is reported to both positively and negatively affect tuber size and quality. Several researchers (Belanger et al., 2002; Waterer, 1997; Zvomuya and Rosen., 2001) reported that N application increased the number of larger-sized tubers suitable for processing, but that can also be a negative attribute for seed potatoes or fresh market potatoes where smaller tubers are preferred.

Some studies showed that PCU has potential for increasing yields of irrigated potatoes compared to multiple split applications of conventional N fertilizers (Hopkins et al., 2008; Hyatt et al., 2010; Wilson et al., 2010; Zvomuya et al., 2003). Rosen et al. (2013) showed that at the rate 258 kg N ha^{-1}, both total and marketable tuber yield were highest with the blend of two PCU (Duration and ESN) followed by ESN and then uncoated urea. LeMonte et al. (2009) showed that 67% of PCU applied at emergence produced higher total and marketable tuber yields consistently over the years and marketable tuber yield was significantly higher than standard grower’s practice. Ziadi et al. (2011) reported significant increase in marketable tuber yield of potatoes with controlled release urea as compared to CAN (calcium ammonium nitrate).

Specific gravity is an important quality parameter for potatoes as processing quality degrades with decrease in SG (Genet, 1992). Tubers with high SG are preferred by crisp manufacturers as oil content and yield of crisps are greatly affected by low SG (Lisinska and Leszczynski, 1989). Lulai and Orr (1979) found that 0.005 unit increase in SG increased yield of chips 1%. With increasing N application SG has been reported to decrease linearly (Belanger et al., 2002; Zebarth et al., 2004). Long et al. (2004) reported that SG increased increasing N rate and decreased when N rate was above the optimum N requirement. Maier et al (1994), Zvomuya et al. (2003) showed a decrease in SG under N deficiency. Joern and Vitosh (1995) reported no effect of N fertilization on SG. Polymer coated urea also did not influence SG and internal disorder of potatoes compared to conventional urea (Ziadi et al., 2011; Rosen et al., 2013).

Wilson et al. (2010) reported that in an irrigated potato production system apparent fertilizer N recovery with PCU was higher (65%) compared to that of soluble N fertigation treatments (55%), but NUE was not influenced by N source. Zvomuya et al. (2003) showed that in an irrigated potato production system, fertilizer N recovery with PCU was higher (50%) compared to split application of urea (43%).

Environmental losses of N influenced by N management practices (split application and enhanced efficiency fertilizers)

Adequate supply of plant available N is required to meet the targets of optimum yield, size and quality, but all of the plant-available N is not used by the crop (Zebarth and Rosen, 2007). The target of any N fertilization program for potatoes should be to recover maximum (typically 75 to 80% of total uptake) N in tubers as well as some in vines (Li et al., 2003; Zebarth et al., 2004b; Zvomuya et al., 2002). High fertilizer N application with improper management leads to various environmental hazards through unutilized N loss and is very common in potato cultivation (Zebarth and Rosen, 2007). For N unrecovered in tubers, there are three main pathways of loss that causes greatest environmental concern i.e. NO_3^- leaching, NH_3 volatilization and N_2O emission from denitrification and nitrification (Mosier et al., 2004; Socolow, 1999).

Nitrate leaching

Nitrate (anion), the ultimate product of N mineralization and most suitable form of crop uptake, is extremely soluble in water and poorly retained in soil due to negatively charged clays. The portion of NO_3-N leached below the rooting zone is generally transported with the moving water front into the deeper soil layers, and eventually may reach to a shallow aquifer (Alva, 2004).

Excessive application of water and fertilizer in modern mechanized agriculture was started as a cheap insurance premium to combat the risk of yield reductions associated with potentially unfavorable and uncontrollable factors like weather condition. Agriculture is the largest user of fresh water and accounting for about 75% of human water use. With the projected ~65% increase in world population by 2050, the additional food requirement will put further enormous pressure on freshwater resources (Wallace, 2000). The need of saving water resources and water use restriction nowadays compel growers for judicial water use and to increase crop water use efficiency by implementing improved irrigation management practices. Besides that, excessive use of irrigation increase the likelihood of NO_3^- leaching and groundwater contamination. As potato has a shallow root system and grown in coarse textured soil with low water holding capacity irrigation is often necessary to meet water demand of the crop (Zvomuya et al., 2003). Under favorable conditions, most soil N is rapidly converted to NO_3^- and moves with the wetting front of the soil (Bock and Hergert, 1991).

Nitrate leaching in sandy soils is intrinsically linked with soil water dynamics, N source, rate of application, crop removal and water displacement below effective root zone (Zotarelli et al., 2007). Excessive rainfall and/or irrigation combined with high rate of N application in easily drained sandy soils with low water holding capacity greatly enhances the risk of N leaching

(Knox and Moody, 1991). The NO_3^- content in groundwater sources of potato growing regions often exceeds the USEPA 10 ppm limit for NO_3-N in drinking water. Several researchers (Gallus and Montgomery, 1998; Saffigna and Keeney, 1977; Hill, 1986)) measured NO_3-N in groundwater sources exceeding 10 ppm in different parts of USA and Canada. Madramootoo et al. (1992) measured concentrations of up to 40 ppm in subsurface water from potato field in Quebec, Canada. Estimate of NO_3- leaching loss beyond root zone in commercial potato field ranged from as low as 10 to as high as 171 kg N ha^{-1} (Milburn et al., 1990; Jensen et al., 1994; Gasser et al., 2002). In experimental trials researchers reported NO_3^- leaching range from 4 to 257 kg N ha^{-1} (Deldago et al., 2001; Vos and van der Putten, 2004; Zvomuya et al., 2003). Nitrate leaching is inevitable with N fertilizer application over optimum rate, but Martin et al. (2001) reported significant NO_3^- leaching even with no fertilizer N application.

Errebhi et al. (1998a) in an irrigated potato production system, showed that NO_3^- leaching increased linearly with increased proportion of N applied at planting. Venterea et al. (2011) reported that in an irrigated potato production system, one type of PCU (PCU-1) significantly reduced the cumulative NO_3^- leaching over the year compared to that of conventional split fertilizer application and another type of PCU (PCU-2) and was statistically similar to that in control. Pack et al. (2006) showed that in a potato production system in Florida, NO_3^- leaching with soluble N fertilizer (ammonium nitrate) was significantly higher than that with CRFs. In an irrigated potato production system, LeMonte et al. (2009) reported 6 mg kg^{-1} decrease in residual soil NO_3^- with 67% PCU at emergence compared to split urea application. Wilson et al. (2010) reported that at equivalent N rate PCU resulted similar leaching as compared to soluble N fertigation treatment in an irrigated potato production system. Some researchers suggested that in irrigated potatoes grown on sandy soils, application of majority of N fertilizer after emergence reduced NO_3–N leaching (Prunty and Greenland, 1997; Errebhi et al., 1998a). Zvomuya et al. (2003) reported 34 to 49% reduction in NO_3^- leaching with PCU compared to three split application of urea when applied at the same rate (280 kg N ha^{-1}). Di and Cameron (2002) estimated that, DCD when applied with urine decreased NO_3-N leaching by 59% compared to no DCD application in a simulated irrigated grazed grassland. Gioacchini et al. (2002) reported an increase in NO_3^- leaching with inhibitor use compared to unamended urea because of real priming effect (addition of fertilizer and amendment increasing soil organic matter mineralization and N release). Liu et al. (2013) also reported increased N mineralization in soil with the application of NI (DCD and DMPP).

Nitrous oxide emission

Nitrous oxide is the fourth most important GHG with 120 year lifetime in atmosphere, and 320 times greenhouse potential than CO_2 (IPCC, 1996; Wrage et al., 2001). About 40% of the global N_2O emissions has anthropogenic sources (USEPA, 2010). Agriculture is the largest anthropogenic source of N_2O emission and accounts for 67% excluding agricultural transportation. Direct agricultural emissions come from fertilized soils and livestock manure (42%), while indirect agricultural emissions come from leaching and runoff of fertilizers (25%) (Denman et al., 2007). Within the United States, 72% of anthropogenic N_2O emissions originate from agricultural practices (USEPA, 2008). In the pre-industrial period, the concentration of N_2O in the atmosphere was 275 ppbv (Prather et al., 1995). The increased use of N fertilizers, conversion of tropical forest land from agriculture and increased fossil fuel burning increased the N_2O concentration in the atmosphere to 322.5 ppbv (WMO, 2010) Nitrous oxide emission from fertilized soil occurs through nitrification, denitrification and nitrate ammonification pathways depending upon the substrate availability and environmental conditions, especially soil moisture

(Baggs et al., 2010). Coarse-textured soils are unlikely to promote denitrification driven N_2O loss; but, high amount of N application in potato production increase the possibility of N_2O production through nitrification (Venterea, 2007).

Burton et al. (2008) showed that split application significantly reduced N_2O emission compared to all N fertilizer application at planting when substrate for N_2O emission (NO_3^-) availability coincided with high amount of rainfall. Hyatt et al. (2010) reported 64% decrease in cumulative N_2O emission in potato production system with PCU compared to conventional split application. Di and Cameron (2002) estimated an 82% reduction in N_2O emission with DCD application with urine in a simulated irrigated grazed grassland compared to no DCD application. Skiba et al. (1993) reported that N_2O emission was reduced by 40% application of DCD. Vallejo et al. (2006) reported that DCD reduced N_2O emission from pig slurry by 83% through the partial inhibition of nitrification. Haile-Mariam (2008) in a two-year experiment reported that in an irrigated potato crop about 0.3% fertilizer N was lost through N_2O emission while in irrigated corn the loss was greater i.e. 0.5 to 0.6%.

Ammonia volatilization

Crop production systems with high amount of fertilizer inputs are subjected to NH_3 volatilization and it is one of the most prominent pathways for fertilizer N loss (Fenn and Hossner 1985; Gezgin and Bayrakll, 1995). According to FAO (2001), about 14% of total mineral N fertilizer applied worldwide annually was lost through NH_3 volatilization. Ammonia volatilization emerged as an environmental issue after being recognized as the cause of soil and water acidification, eutrophication and forest dieback (Ellenberg, 1985; Fangmeier et al., 1994; Roelofs et al., 1985; van Breemen et al., 1982). Besides that, the NH_3-N loss increase the cost of production and NH_3 gas also has potential for ozone layer depletion (Damodar and Sharma, 2000; Fenn and Hossner 1985; FAO 2001).

Ammonia volatilization is most likely to occur in calcareous soils, soils with low buffering capacity and soils with high organic C (Fenn and Hossner, 1985). When urea is surface applied, NH_3 volatilization may lead to loss of 50% of the fertilizer N applied (Catchpoole 1975; Terman 1979). Several researchers reported that NBPT reduces urea hydrolysis and NH_3 volatilization in a wide range of soils (Bremner and Chay, 1989; Bronson et al. 1990; Vittori et al. 1996; Watson et al. 1994). Rawluk et al. (2001) reported that in a fine sandy loam soil NBPT reduced NH_3 volatilization by 30% to 75% compared to an untreated control. Gioacchini et al. (2002) reported that, compared to unamended urea NBPT reduced NH_3 volatilization by 89% and 47% in sandy loam and clay loam soils respectively. In their experiment, in both soils DCD amended urea significantly increased NH_3 volatilization compared to NBPT amended urea but when both DCD and NBPT were applied with urea, NH_3 volatilization was significantly lower than unamended urea. Effectiveness of NBPT in reducing NH_3 volatilization is positively correlated with sand percentage in soil while negatively correlated with clay and organic C content (Bremner and Chay, 1986; Watson et al., 1994). Several researchers suggested that, as NH_3 volatilization is affected by several factors such as pH, temperature and placement of N fertilizer (surface or subsurface), only the use of DCD may or may not increase NH_3 volatilization (Clay et al. 1990; Prakasa Rao and Puttanna 1987). Liu et al. (2007) showed that NH_3 volatilization increase by 2 to 3-fold at 20% field capacity (FC) compared to 80% FC and suggested to maintain the soil moisture to reduce NH_3 volatilization. Blaise and Prasad (1995) reported that in an alkaline sandy soil, in both aerobic and anaerobic conditions, 3% and 6% polymer coated urea (PCU-3 and PCU-6) significantly reduced NH_3 volatilization compared to prilled urea, gypsum coated urea and neem-cake coated urea. Between PCU-3 and PCU-6, PCU-6 significantly reduced NH_3 volatilization compared to PCU-3.

Potato N status assessment

Diagnostic test for nutrient status assessment is required in order to optimize fertilizer rates (Errebhi et al., 1998b). Although combination of soil and plant analyses have been used to generate adequate information in developing fertilizer N recommendations, soil tests in coarse textured soils are generally unreliable (Dow and Roberts, 1982; Vitosh, 1986). However, petiole NO_3-N alone has been reported to be a reliable test for assessing N status in plants (Roberts et al., 1989). Pehrson et al. (2011) reported that in a survey during 2006 to 2007, more than 96% of the potato growers of Idaho relied on petiole NO_3^- test as a mean of N status assessment. Petiole NO_3-N content analysis is a rapid, convenient method and critical limits for petiole NO_3-N concentration in different growth stages have been established for some potato cultivars (Alva, 2004). Total N and acetic acid extractable NO_3-N in petioles were successfully correlated with N status since 1970s (Geraldson et al., 1973). Zebarth and Rosen (2007) stated that post-emergence N fertilizer application in potatoes can reliably be based on petiole NO_3-N concentrations. Critical petiole NO_3-N status for all growth stages in different potato cultivars have been established using the dry weight basis NO_3-N level estimation (Rodrigues, 2004; Stark et al., 2004; Wescott et al., 1991). Zhang et al. (1996) mentioned that petiole NO_3-N concentration has been successfully used to make in season N recommendation for irrigated potatoes in New Mexico. Wu et al. (2007) reported that N deficiency in potatoes could be detected with petiole NO_3-N concentration two weeks after emergence while SPAD (Soil-Plant Analyses Development) chlorophyll meter (Minolta Camera Co., Japan) reading detected the deficiency one month after emergence; and the differences between N rates were also better identified with petiole NO_3-N than SPAD reading. Anderson et al. (1999) showed that both total N and NO_3-N concentration in tomato (*Solanum lycopersicum*) petiole sap are significantly correlated with yield ($R^2 = 0.69$ to 0.74 and $R^2 = 0.78$ to 0.82 respectively).

The reflected light by vegetation in the visible wavelength range is mainly influenced by chlorophyll, which directly relate to the N concentration as N is one of the main components of chlorophyll (Haboudane et al., 2002). Red (~670 nm) and blue (~450 nm) portions of the visible wavelength are absorbed by Chlorophyll a and b (Gates et al., 1965). Besides that, leaf cell structure influences near infrared (NIR) reflectance from the vegetation i.e. healthy, well hydrated mesophyll cells reflect more IR wavelength than dehydrated or diseased cells (Gates et al., 1965). The reflectance pattern from the red-edge (~730 nm) wavelength of the spectrum changes position and shape if the plant is N deficient (Jain et al. 2007). So, reflectance measurements of crop canopy can give an estimate of chlorophyll concentration and thus a measure of N status (Haboudane et al. 2002; Jain et al. 2007). The contrast of absorption and scattering of radiation in red, red edge and near-infrared wavelengths can be mathematically combined into different quantitative indices indicating condition of the vegetation and termed as vegetation indices (VI) (Pnada et al., 2010). Among various VIs, normalized difference vegetation index (NDVI) has been proved to be strongly correlated to total aboveground green biomass as well as yield (Bala and Islam, 2009; Gat et al. 2000; Groten 1993; Liu and Kogan 2002; Rasmussen 1997).

In recent years, different types of remote sensing technologies including space, aerial and ground based sensors have been widely used for assessing plant N status and in season crop yield prediction (Bala and Islam, 2009). Most of the aerial sensors detect passive reflectance while the ground based sensors measure reflectance from active polychromatic light source and thus can be used during day or night and is not affected by cloud cover (Gehl and Boring, 2011; Sultana et al., 2014). Satellite imagery are time-bound, imagery processing is time consuming, weather conditions may interfere with reflectance detection and spatial variability may not be accounted with low resolution (Muñoz-Huerta et al., 2013; Wu et al., 2007). Ground based sensors (i.e. Yara N-sensor, GreenSeeker, CropScan) are cost and time effective and have been successfully used to measure crop reflectance in visible and NIR wavelengths (Muñoz-Huerta et al., 2013).

Conclusion

From all the reviewed studies, it can be concluded that the potato BMP development is still in progress. Growers use N fertilizer in potatoes in excess amount which leads to a tremendous amount of N losses. Stable fertilizers are not in focus anymore as their performance with potatoes had not been extremely successful. Apart from split application PCU, NI and UI are mainly being used recently for the BMP development of potatoes. There are more evidences of PCU in achieving the target yield and maintaining tuber quality is than the NI and UI. Ammonia volatilization loss has been successfully reduced by both PCU and inhibitors (NI, UI). Nitrate leaching is dependent more on untimely fertilizer application and heavy rainfall than irrigation. Nitrous oxide emission can be better controlled by the inhibitors by slowing down the urea hydrolysis and nitrification and thus reducing the substrate availability for both nitrification and denitrification.

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CHAPTER 1. INFLUENCE OF ENHANCED EFFICIENCY FERTILIZERS ON LATE SOWN IRRIGATED POTATO YIELD AND QUALITY RESPONSE

Abstract

Field studies were conducted in 2015 and 2016 growing season at Northern Plains Potato Growers' Association Irrigation site near Inkster, ND to evaluate the effectiveness of EEFs in maintaining tuber yield, quality, N uptake, apparent fertilizer recovery (AFR) and nitrogen use efficiency (NUE) in an irrigated potato production system. Two types of EEFs (SuperU, ESN), unamended urea and grower's standard fertilization at the rate of 280 kg N ha^{-1} and unamended urea at the rate of 225 kg N ha^{-1} were applied as N treatments in three russet potato cultivars ('Russet Burbank', 'Dakota Trailblazer' and 'ND8068-5 Russ') following a factorial randomized complete block design with four replications. In 2015, the maximum marketable tuber yield (42.3 Mg ha^{-1}) was obtained with urea 225 kg N ha^{-1} which was statistically similar to that in ESN 280 kg N ha^{-1} (41.6 Mg ha^{-1}). In 2016, maximum marketable yield was obtained with ESN 280 kg N ha^{-1} (38.7 Mg ha^{-1}) which was statistically similar to that in urea 280 kg N ha^{-1} (37.5 Mg ha^{-1}). In a shorter growing period (2015) cultivation of determinate cultivar like 'ND8068-5 Russ' may be beneficial with respect to tuber yield as the full capacity of the indeterminate cultivars could not be exploited. Specific gravity with all N fertilizer treatment reached the requirement (1.08) for processing quality tubers in both the years. Effect of N treatments and cultivars on AFR and NUE were extremely variable over the years. Considering the yield benefit and consistency of performance, ESN can be recommended for irrigated russet potato cultivars in a short growing season.

Introduction

Potato is a high-value crop and commonly cultivated in coarse-textured soils ensuring proper tuber growth (Kelling et al., 2011; Wilson et al., 2010). Potato is a shallow rooted crop (Lesczynski and Tanner, 1976) which requires a large amount of nitrogen (N) over a short period of rapid growth and is adversely affected by moisture stress (Alva et al., 2002; Dalla Costa et al., 1997). Potato cultivation in the Northern Great Plains is shifting from clayey soils of Red River Valley to the sandy glacial outwash soils because of an ample irrigation water supply which results in high and consistent potato yield (Waddell et al., 1999). To exploit the full economic benefit of potato production, growers are obliged to produce good quality commercial potatoes in a cost-efficient manner, but with increasing concern about the environmental safety, the accompanying challenge is to minimize the hazardous effects associated with cultivation.

Among the macronutrients, N generally represents the greatest limitation in potato production. Insufficient available N leads to reduced growth, reduced light interception, early senescence and limited yields (Hendrickson and Douglass, 1993; Kleinkopf et al., 1981; Millard and Marshall, 1986). Fertilizer N input accounts for a relatively minor proportion of total input costs of production (Zebarth and Rosen, 2007). The economic risk associated with insufficient N fertilization such as loss of tuber yield, undersized tuber production are of far greater concern than the economic risk associated with excessive N fertilization i.e. low specific gravity (SG) and fertilizer price (Zebarth and Rosen, 2007). Fertilizer-N is often over-applied in potato production to ensure against loss of yield and tuber quality and N is considered as a cheap insurance premium for potato production (Waddell et al., 1999).

Nitrogen fertilizer recommendation in potatoes is predominantly based on target yield, soil N availability and previous crop credit (Errebhi et al., 1998). In some areas, application of most of the N at or just before planting was a common practice (Harris 1992) which has been changed to fertilizer application in several splits recently (Prasad et al., 2015). Earlier researchers suggested that applying part of N fertilizer during tuber initiation may increase the tuber bulking and thus enhance tuber yield and quality (Ivins, 1963). Application of full fertilizer dose during planting is not a smart decision as potato seed germination takes at least 15 to 20 days and during that period potato plants rely on the reserve of the seed tuber (Ewing, 1978). Gunasena and Harris (1968, 1969, 1971) through a series of experiments observed that the application of all or part of N fertilizer during tuber initiation achieved yield benefit if followed by heavy rainfall after fertilizer application, but that also lead to high leaching loss. In low rainfall years delay in N application might not increase yield (Ngugi, 1972).Nitrogen losses depend on a dynamic and complex interaction among soil properties, soil hydrology, weather, crop N uptake and management practices (Melkonian et al., 2008). Successful best management practices acquiring high yield with minimal N loss and maximum NUE for potatoes grown on irrigated sandy soil is yet to be developed. To increase NUE, experiments on potato fertilizer-N management in irrigated sandy soils were mainly focused on irrigation management, N fertilizer rates, placement and timing (Zvomuya et al., 2003). However, even with properly-timed N management and appropriate irrigation plans controlling N losses were difficult due to unpredictable precipitation (Sexton et al., 1996).

Urea is the most popular N fertilizer and accounts for about 54% of total N fertilizer consumption in the world (IFA, International Fertilizer Association, 2017). However, N recovery by plant from applied urea is often < 50%, as urea fertilizer is associated with losses through ammonia (NH_3) volatilization, nitrate (NO_3^-) leaching and denitrification (Bayrakli and Gezgin, 1996; Burton et al., 2008; Maharajan et al., 2014; Ruser et al., 2001; Soares et al., 2012; Khan et al., 2014; Zvomuya et al., 2003). Available options to increase the efficiency of urea are matching N mineralization with plant N demand include application in several splits and fertigation, coating urea with sulphur or with polymers semipermeable to water, blending urea with urease inhibitor and/or nitrification inhibitor (Black et al., 1987; Trenkel, 1997; Zaman et al., 2013). The broad group of controlled release, slow release, and stabilized fertilizers were commonly termed as enhanced efficiency fertilizers (EEFs) (AAPFCO, 1995).

Nitrogen release from traditional N fertilizer products such as sulfur-coated urea (SCU) has been unpredictable or resulted in lower yield (Liegel and Walsh 1976; Lorenz et al., 1974; Trenkel, 1997). Recently over past few years of research showed that coated urea fertilizers like ESN (Environmentally Smart Nitrogen, Agrium, Inc.) has been successfully used to reduce N losses, increase potato tuber yield and applying in planting and/or hilling becomes cost effective as compared to multiple split application of conventional fertilizers [urea, ammonium nitrate, ammonium sulphate] or fertigation with urea ammonium nitrate (UAN) (Pack et al., 2006; Rosen et al., 2013). Coating urea with a urease inhibitor (UI) such as NBPT has very good potential to slow down urea hydrolysis and increase potato tuber yield (Khan et al., 2014; Watson et al., 2008). Among various natural and synthetic UIs, NBPT has been widely used, because of its effectiveness at a very low concentration (0.025 to 0.1% of applied fertilizer) and stability after coating (Watson et al., 2008). Nitrification inhibitors (NI) improve N recovery by reducing N loss through nitrate (NO_3^-) leaching as it slows down the conversion of ammonium (NH_4^+) to NO_3^-. Nitrification inhibitors can block nitrification for 35 to 50 days on sandy soil (Hendrickson et al., 1978; Martin et al., 1994). Yield and quality response as well as fertilizer N recovery of potato tubers with the use of NI were not consistent in the previous studies (Hendrickson et al., 1978; Kelling et al., 2011; Martin et al., 1993; Penny et al., 1984; Vendrell et al., 1981; Vos, 1994). Dicyandiamide has been successfully used as a NI in agriculture for a long time and several advantages of DCD including low cost, high water solubility, low volatility and complete decomposability in the soil makes it a suitable choice to use with solid N fertilizers (Di and Cameron, 2002). SuperU is a stabilized fertilizer product developed by Koch Agronomic Services which is actually granular urea blended with NBPT and DCD and had been successfully used in many studies to reduce N losses and increase N recovery (Sistani et al., 2011).

'Russet Burbank' is one of the most popular and commercially grown cultivars in the United States. Fertilizer recommendations in North America has historically been based on the nutrient requirements of the 'Russet Burbank' cultivar (Lang et al., 1999; Rosen and Bierman, 2017; Stark et al., 2004). Previous researchers demonstrated that N uptake, NUE and optimal response to N differ by cultivars (Johnson et al., 1995; Love et al., 2005; Porter and Sisson 1991). Dry matter production rates of tubers are also influenced by variety and seasonal differences (Smith, 1977). Determinate type cultivars (shorter growing period and lesser vegetative growth) may need a different N fertilizer management program than indeterminate (longer growing period and vigorous vegetative growth) cultivars as the tuber initiation of determinate cultivars occur earlier in the season and they complete their life cycle with 80 to 90 DAP while indeterminate cultivars are capable of continued leaf development and nutrient uptake for a longer growing period when other environmental conditions are not limiting (Kleinkopf et al., 1981). In northeastern North Dakota potato plantings are often delayed due to early season heavy rainfalls and as a result, a shorter growing period is available, which may also change the fertilizer N availability and uptake pattern.

The North Dakota Agricultural Experiment Station developed an indeterminate russet potato cultivar 'Dakota Trailblazer' (released in 2009) and a determinate russet potato cultivar

‘ND8068-5 Russ’ (not released) (personal communication with Dr. Asunta Thompson). The release of these new potato cultivars necessitates additional researches for better understanding to cultivar specific N response as well as the development of site and season specific appropriate fertilizer recommendations. Although in North Dakota, the recommended fertilizer rate for a yield goal of 62 Mg ha^{-1} is 225 kg N ha^{-1}, growers always use at least 280 kg N ha^{-1} (personal communication with Dr. Harlene Hatterman-Valenti).

The primary objective of our study was to observe the yield and quality response of the two newly developed potato cultivars and ‘‘Russet Burbank’’ with the application of ESN, SuperU, unamended urea and conventional fertilization practice in two consecutive growing seasons. Secondly, the AFR and NUE of the fertilizer products and the cultivars were also calculated to understand the performance of the EEFs and the cultivars. It was hypothesized that the EEFs may have yield benefit and consistency in maintaining yield and quality over conventional fertilization and unamended urea in a late sown irrigated potato production system of North Dakota. The results will also inform if there is a necessity of developing different fertilizer management practices for different cultivars.

Materials and methods

Site description and experimental design

Field trials were conducted during 2015 and 2016 growing season at Northern Plains Potato Growers’ Association (NPPGA) Irrigation site near Inkster, ND (48° 09′ 57.3″ N, 097° 43′ 12.9″ W; 313 m above mean sea level). Soil type of the site was Inkster sandy loam (Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls). The previous crop in both years was soybean (*Glycine max* L.). The soil in the experimental site is coarse textured (sandy loam), slightly acidic with low bulk density (BD), cation exchange capacity (CEC), electrical conductivity (EC) and a significant amount of organic matter (Table 1.1.). The soil before planting had very low available N (25.8, 22.4 kg N ha^{-1}) and adequate amount of P (27.0, 40.0 mg P kg^{-1} soil) and K (214, 210 mg K kg^{-1} soil) in both growing seasons (Table 1.1.).

Table 1.1. Basic physical and chemical properties of the soil in experimental site

Parameters	2015	2016
Texture	Sandy loam	Sandy loam
Sand (g kg^{-1})	663	695
Silt (g kg^{-1})	217	177
Clay (g kg^{-1})	120	128
Bulk Density 0-15 cm (Mg m^{-3})	1.12	1.07
pH	6.02	5.80
Electrical conductivity (dS m^{-1})	0.17	0.21
Cation exchange capacity	10.6	11.5
Available N (0 to 61 cm) kg N ha^{-1}	25.8	22.4
Available P (mg ka^{-1})	27.0	40.0
Available K (mg kg^{-1})	214	210
Organic matter (g kg^{-1})	331	319

In both years, field experiments were laid out in a factorial randomized complete block design (RCBD) with four replicates (blocks). In 2015, the experiment was comprised of eighteen treatment combinations including three potato cultivars and six N treatments. The three Russet potato cultivars were (i) 'Russet Burbank', (ii) 'Dakota Trailblazer' and (iii) 'ND8068-5 Russ' and the six N treatments were (i) Grower's Standard i.e. 10-34-0 (34 kg N ha^{-1}) at planting+ urea (168 kg N ha^{-1}) at hilling + UAN (79 kg N ha^{-1}) at tuber initiation; (ii)Urea i.e. urea (225 kg N ha^{-1}) at planting; (iii) UreaSplit i.e. urea (112 kg N ha^{-1}) at planting and urea (168 kg N ha^{-1}) at hilling; (iv) SuperU [urea stabilized with NBPT and DCD (Koch Agronomic Services)] i.e. SuperU (112 kg N ha^{-1}) at planting and SuperU (168 kg N ha^{-1}) at hilling; (v) ESN [a micro thin polymer polyurethane coated slow release urea (ESN®, Agrium Inc)] i.e. ESN (112 kg N ha^{-1}) at planting and ESN (168 kg N ha^{-1}) at hilling and (vi) control (No fertilizer N). In 2016, another N treatment was added and experiment was laid out in a factorial RCBD with twenty-one treatment combinations (three cultivars × seven N treatments). The added treatment was ESN+AS i.e. ESN (112 kg N ha^{-1}) at planting and AS (56 kg N ha^{-1}) with ESN (112 kg N ha^{-1}) at hilling.

Cultivation

Individual plot dimension was 6.09 by 3.66 m with four hills or rows per plot. Hand cut potato seeds weighing between 60-80 g were planted in 0.3 m in row spacing and 0.9 m between row spacing with a two row assist feed Harriston planter (Harriston Industries, Minto, ND, USA). Dry N fertilizers (urea, SuperU, ESN) were applied uniformly and incorporated into the soil before planting and hilling and liquid UAN fertilizer was sprayed at tuber initiation following the treatment requirements. Planted rows were hilled up 15 DAP with a double row Harriston Hiller (Harriston Industries, Minto, ND, USA). Throughout the growing period, supplementary irrigation was provided through an overhead irrigator (Reinke Manufacturing Company, Inc, Deshler, NE, USA) according to the checkbook method to maintain adequate soil moisture (Wright, 2002). At physiological maturity, the middle two rows of each plot were harvested using a small plot single row Hassia harvester (Hasia-Redatron GmbH, Butzbach, Germany). The relevant important dates of cultivation practices are listed in Table 1.2.

Table 1.2. Important dates regarding cultivation practices and fertilization in two growing seasons

	2015 (DOY)	2016 (DOY)
Planting+ 1st Fertilizer application	10 June	6 June
Hilling+ 2nd Fertilizer application	25 June	20 June
Third Fertilizer application	15 July	18 July
Harvesting	2 October	10 October

Sampling and analyses

Tuber yield, tuber grading, plant biomass and specific gravity

After harvesting, tubers were brought back to NDSU potato storage unit and stored at 5ºC. Tubers were graded in a Hagan single row potato grader (Hagan Electronics Inc., United Circle Parks, NV, USA) following the US No. 1 potato standard (USDA, 2011), where the tubers were graded in 4 weight ranges i.e. 0-113 g, 113-170 g, 170-340 g and >340 g. Culls and damaged tubers were hand-picked and weighed before size grading of each plot. Total tuber yield was calculated by summing up culls and all grade weights. Marketable tuber yield is the sum of 113-170 g, 170-340 g and >340 g grade tuber weights. Aboveground part or vines of two plants from each plot were cut and collected from each plot at the start of senescence stage ('ND8068-5 Russ') or before harvest ('Russet Burbank' and 'Dakota Trailblazer'). The vines were dried for 3 days at 60ºC and then the dry weight was recorded. Tuber SG tuber samples from each plot were determined following the Weight in air / Weight in water method (Zebarth et al., 2004).

Plant N uptake

Six randomly sampled tubers from each plot were sliced with a chipper and dried at 60ºC. Dried tuber and vine samples were grounded in a Wiley mill plant sample grinder (Thomas Scientific, Swedesboro, NJ, USA). Total N in plant materials were determined following the procedure described by Nelson and Somner (1973). Ground plant sample (0.2 g) was weighed in a cigarette paper, placed in a Folin-Wu digestion tube and 5 mL of the salicylic acid H_2SO_4 mixture (5.0 g salicylic acid per 200 mL of H_2SO_4) was added and kept overnight. After that, 1.1 g of a salt-catalyst mixture (10: 1 K_2SO_4 and $CuSO_4.5\ H_2O$ mixture by weight) and 0.5 g $Na_2S_2O_3.\ 5H_2O$ were added. The tube was swirled and the mixture was digested in the aluminum heating block at 300ºC. A small glass funnel was placed in the mouth of the tubes for refluxing of the digestion mixture. The sample was digested until at least 60 mins past clearing. The digest is diluted to 50 mL with distilled water after cooling. The NH_4^+ in the aliquot (10 mL) was then determined by capturing the NH_4^+ in a 4% boric acid mixed indicator solution through an alkaline steam distillation using 10 N NaOH followed by a titration with 0.005 N HCl. A blank was run following the same procedure.

$$\%\ \text{N sample} = \frac{(\text{S}-\text{B}) * \text{Normality of titrant} * 1.4007 * \text{dilution factor of aliquot}}{\text{weight of plant sample}} \qquad \text{(Eq 1.1.)}$$

where, S= mL of acid consumed for sample titration, B= mL of acid consumed for blank titration.

Apparent fertilizer recovery and nitrogen use efficiency

Apparent fertilizer recovery (%) was calculated following the formula (Delogu et al., 1998)

$$\text{AFR} = \frac{(\text{Total N uptake in } N_f - \text{Total N uptake in control})}{\text{Applied fertilizer N}} \times 100 \qquad \text{(Eq 1.2.)}$$

where, N_f = N fertilizer treatments.

Nitrogen use efficiency (kg marketable tuber kg^{-1} of applied N) was calculated following the formula. (Ziadi et al., 2011)

$$\text{NUE} = \frac{(\text{Marketable tuber yield in } N_f - \text{Marketable tuber yield in control})}{\text{Applied fertilizer N}} \qquad \text{(Eq 1.3.)}$$

where, N_f = in N fertilizer treatments.

Statistical analysis

The effect of different N treatments and cultivars and their interaction effect on total tuber yield, marketable tuber yield, SG, N uptake, AFR and NUE were determined using a factorial randomized complete block design model. The means of the parameters were analyzed separately for each year using analysis of variance (ANOVA) in R 3.2.0. For each response (total tuber yield, marketable tuber yield, SG, N uptake, AFR and NUE), the validity of model assumptions (normal distribution, constant variance, and independence of the error terms) were verified by examining the residuals as described in Montgomery (2013). When violated, appropriate (log or reciprocal) transformation was applied to the response measurements, but the means reported in the tables and in figures were back-transformed to the original scale to facilitate easier interpretation. If any effect was significant on the responses, the multiple means comparison was done using Fisher's least significant difference (LSD) at the 5% level of significance ($P<0.05$).

Results and discussion

Environmental conditions and irrigation

The environmental conditions and irrigation are illustrated in Fig 1.1. and Fig 1.2. The cumulative rainfall in 2015 growing season (June 10 to October 2) was 383 mm which was lower than the cumulative rainfall in 2016 growing season (June 6 to October 10) i.e. 485 mm. In both the years, the water requirement of the crop was complemented with irrigation. The total irrigation applied over the growing seasons of 2015 and 2016 were 320 and 220 mm, respectively. In 2015 growing season, the average daily air temperature ranged from 9.89ºC to 28.09ºC with an average of 19.35ºC. In 2016 growing season, the average daily air temperature (0-15 cm) ranged from 1.77ºC to 24.83ºC with an average of 18.18ºC. The daily average soil temperature in 2015 growing season ranged from 12.43ºC to 28.03ºC with an average of 21.09ºC. The daily average soil temperature in 2016 growing season ranged from 7.18ºC to 26.28ºC with an average of 20.23ºC. Overall, the 2015 growing season was warmer than the 2016 growing season. The average wind speed in 2015 growing season was 3.03 ms^{-1} (maximum

7.51 ms^{-1} and minimum 1.31 ms^{-1} which were higher than that of 2016 growing season i.e. 2.55 ms^{-1} (maximum 6.27 ms^{-1} and minimum 0.54 ms^{-1}).

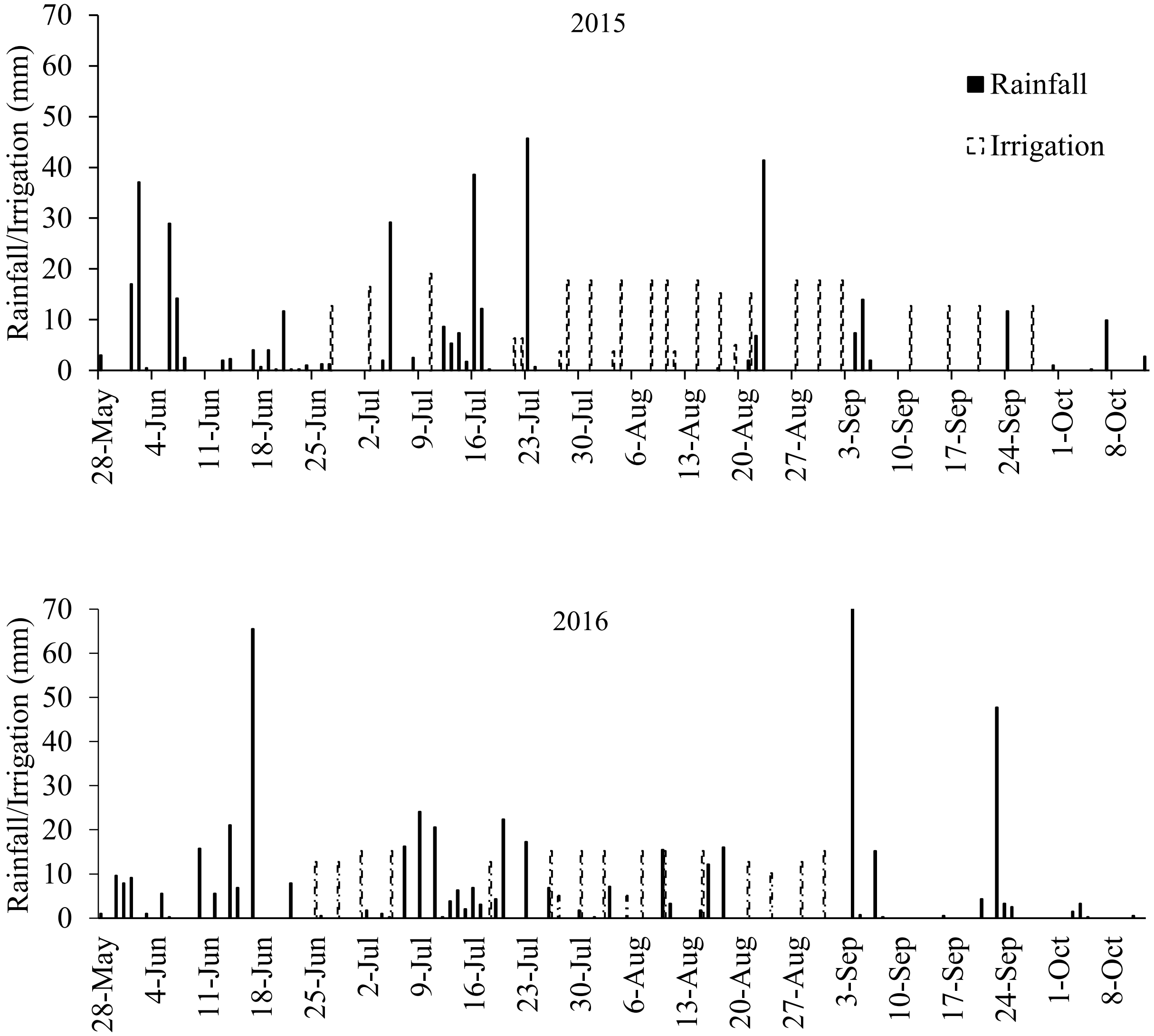

Fig 1.1. Daily mean precipitation (rainfall) or irrigation (mm) in 2015 and 2016 growing season

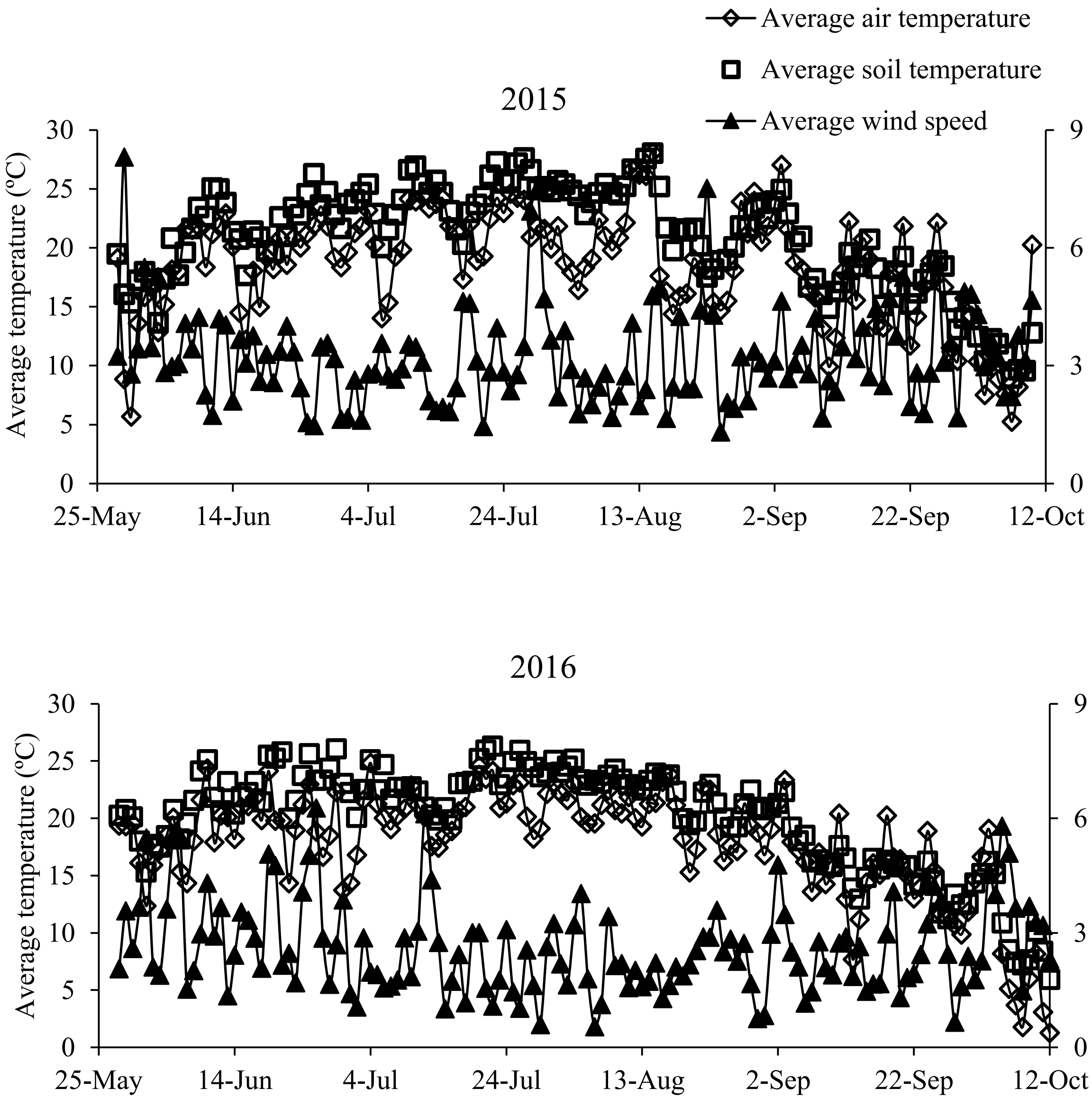

Fig 1. 2. Daily average air temperature (ºC), daily average soil temperature (ºC) and average wind speed (m s^{-1}) in 2015 and 2016 growing season

Description of the cultivars

In this study, we used three russet potato cultivars i.e. ‘Russet Burbank’, ‘Dakota Trailblazer’, and ‘ND8068-5 Russ’. ‘Russet Burbank’ is one of the most popular cultivars in the USA, ‘Dakota Trailblazer’ and ‘ND8068-5 Russ’ is the two newly developed cultivars by ‘The

North Dakota Agricultural Experiment Station' and 'North Dakota State University'. 'Dakota Trailblazer' was released in 2009 and 'ND8068-5 Russ' is still in the procedure of release.

Russet Burbank

'Russet Burbank' was identified back in 1914 and has been cultivated as one of the most popular commercial varieties for a long time. It is a late maturing cultivar that requires a growing season of 140 to 150 days for maximum tuber production. The indeterminate type vines are vigorously spreading with medium growth. The above ground stems are thick with long and medium leaflets of light to medium green color. The flowers are white and not fertile and tubers are large, long, and cylindrical with deep brown skin and white flesh. 'Russet Burbank' is excellent for baking, processing, and table stock with long-term storability (www.potatoassociation.org).

Dakota Trailblazer

'Dakota Trailblazer' was developed by the North Dakota Agricultural Experiment Station and North Dakota State University and was released in 2009. It is a medium to late maturing cultivar with high yield potential. The indeterminate type vines are vigorously spreading with medium to dark green leaflets and fertile white flowers. The tubers long blocky with medium dark russet skin and creamy white flesh. 'Dakota Trailblazer' is suitable for both frozen processing and table stock. It has medium to long storability with low sugar accumulation in storage (www.ndsuresearchfoundation.org).

ND8068-5 Russ

'ND8068-5 Russ' was developed by The North Dakota Agricultural Experiment Station and the North Dakota State University and not yet released but applied for plant variety protection certification. It is a very early maturing variety with medium to high yield potential. It has a medium spreading determinate type vine with medium to light green leaflets and white non-fertile flower. The tubers are long blocky with golden russet skin with white flesh. It is suitable for both frozen processing and table stock. The tubers have good storability and low sugar accumulation in storage (www.ndsuresearchfoundation.org).

Total tuber yield and marketable yield

2015 growing season

Total tuber yield and marketable yield were significantly influenced by both N treatments and cultivars and their interaction effect during 2015 and 2016 growing seasons. In 2015, averaged across all cultivars, all N treatments significantly increased total tuber yield over control (Table 1.3.). Total tuber yield was maximum (50.4 Mg ha^{-1}) with Urea followed by ESN (49.9 Mg ha^{-1}), which were not significantly different from each other (Table 1.3.). Averaged across all N treatments total tuber yield of ‘Russet Burbank’ and ‘ND8068-5 Russ’ were significantly higher than that of ‘Dakota Trailblazer’ (Table 1.3.). In 2015 growing season ‘Russet Burbank’ had highest tuber yield with Urea closely followed by ESN and were not significantly different (Fig 1.3.). In ‘Dakota Trailblazer’, maximum yield was obtained with ESN closely followed by Urea and SuperU, and were not significantly different from each other (Fig 1.3.). However, only ESN increased ‘Dakota Trailblazer’ total tuber yield over control (Fig 1.3.). All N fertilizer treatments increased ‘ND8068-5 Russ’ total tuber yield over control (Fig 1.3.). Maximum total tuber yield in ‘ND8068-5 Russ’ was obtained with Grower’s standard, closely followed by Urea and ESN and were not significantly different from each other (Fig 1.3.).

Table 1.3. Effect of N treatments and cultivars on total tuber yield, marketable yield and specific gravity of potatoes in 2015 and 2016 growing seasons

	Total tuber yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Specific gravity
N treatment		2015	
Grower's	48.7 (1.40)ab	39.8 (1.33)bc	1.094 (0.002)
Urea	50.4 (0.83)a	42.3 (0.29)a	1.099 (0.003)
UreaSplit	46.7 (0.85)b	39.2 (0.66)c	1.097 (0.002)
SuperU	46.7 (0.84)b	38.2 (0.91)c	1.092 (0.001)
ESN	49.9 (0.74)a	41.6 (0.85)ab	1.094 (0.003)
Control	43.4 (0.79)c	36.1 (0.87)d	1.082 (0.011)
Cultivar			
‘Russet Burbank’	48.4 (0.60)a	38.8 (0.65)b	1.086 (0.004)
‘Dakota Trailblazer’	45.9 (0.73)b	39.2 (0.65)ab	1.096 (0.004)
‘ND8068-5 Russ’	48.6 (0.65)a	40.6 (0.86)a	1.097 (0.004)
		Analysis of variance	
N treatment	***	***	NS
Cultivar	**	*	NS
N treatment X Cultivar	*	***	NS
N treatment		2016	
Grower's	49.7 (1.60)[ϕ]a[†]	34.7 (1.86)bc	1.100 (0.003)
Urea	46.5 (1.83)b	33.6 (0.89)c	1.102 (0.002)
UreaSplit	48.7 (2.14)a	37.5 (1.94)a	1.102 (0.003)
SuperU	49.1 (2.39)a	37.2 (2.83)ab	1.099 (0.003)
ESN	50.0 (2.44)a	38.7 (1.69)a	1.098 (0.003)
ESN+AS	49.1 (1.82)a	36.7 (1.89)ab	1.100 (0.002)
Control	40.0 (1.21)c	25.0 (1.60)d	1.103 (0.003)
Cultivar			
‘Russet Burbank’	55.2 (1.16)a	37.4 (1.68)a	1.094 (0.001)c
‘Dakota Trailblazer’	45.7 (0.89)b	37.9 (1.69)a	1.110 (0.001)a
‘ND8068-5 Russ’	41.9 (0.57)c	28.9 (1.70)b	1.098 (0.001)b
		Analysis of variance	
N treatment	***	***	NS
Cultivar	***	***	***
N treatment X Cultivar	***	***	**

*, **, ***Significant at $P < 0:05$, $P < 0:01$, and $P < 0:001$, respectively.

NS, not significant

[ϕ] Parenthesis include standard error

[†] Values followed by the same letter in each column are not significantly different

Averaged across all cultivars in 2015, maximum marketable yield was obtained with Urea (42.3 Mg ha^{-1}) followed by ESN (41.6 Mg ha^{-1}) and were not significantly different (Table 1.3.). Although marketable yields were significantly increased with all N fertilizer treatments over control, UreaSplit and SuperU had significantly lower marketable tuber yield compared to Urea and ESN (Table 1.3.). Averaged across all N treatments in 2015 marketable tuber yield was maximum with 'ND8068-5 Russ', and 'Russet Burbank' marketable yield was significantly lower compared to that of 'ND8068-5 Russ' (Table 1.3.). For 'Russet Burbank', highest marketable yield was obtained with Urea, which was statistically similar to UreaSplit and ESN (Fig 1.3.). For 'Dakota Trailblazer', marketable yield was not significantly increased over control with any N fertilizer treatment, however, maximum marketable yield was obtained with Urea and ESN (Fig 1.3.). 'ND8068-5 Russ' maximum marketable yield was obtained with Grower's standard and not significantly different from Urea and ESN treatments (Fig 1.3.).

The total tuber yield in our study is similar to the previous studies with similar fertilizer-N application rates conducted by Kelling et al. (2011), Rosen et al. (2013); comparatively lower than the result found by Errebhi et al. (1998), and comparatively higher than the results found by Pack et al. (2006), Ziadi et al. (2011). Total tuber yield with SuperU and UreaSplit were significantly lower than Urea, ESN and Grower's standard. Higher N fertilizer dose (280 kg N ha^{-1} applied with EEFs, Urea and Grower's practice) had no beneficial effect on total tuber yield over the lower N dose (urea 225 kg N ha^{-1}) because of the significant soil N supply (total N uptake in control was considered as soil N supply) i.e. 190 kg N ha^{-1} during the growing season (Xing et al., 2016). Kelling et al. (2011) showed that nitrification inhibitor treated ammonium releasing fertilizer reduced tuber yield due to NH_4^+/ NO_3^- imbalances in plant and slow release of N in a short growing season. In our study, the same effect was observed in the case of SuperU while ESN did not create any NH_4^+ and NO_3^- imbalance. Shoji et al. (2001) reported that controlled release fertilizers (CRF) increased tuber yield in potatoes but nitrification inhibitor (NI) application had no yield benefit.

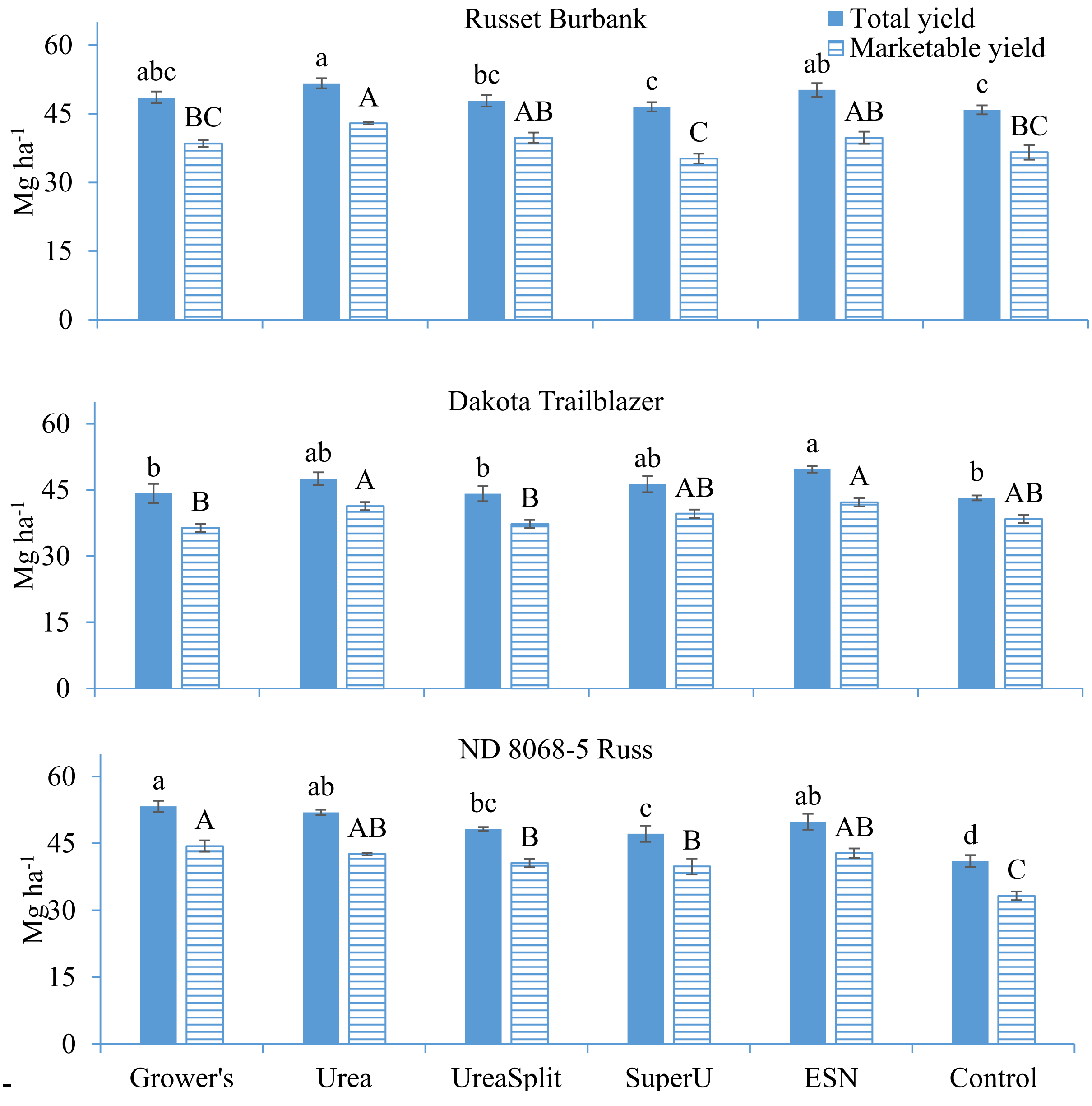

Fig 1.3. Interaction effect of N treatments and cultivars on total tuber yield (Mg ha^{-1}) and marketable yield (Mg ha^{-1}) in 2015 growing season.
The effect of N treatments on total tuber yield and the marketable yield under each cultivar is denoted by the lowercase letters and uppercase letters respectively.

Kleinkopf et al. (1981) stated that determinate cultivars complete their growth cycle within 60 to 80 days after emergence (DAE) while indeterminate cultivars need more than 100 days. They also suggested that with higher N rate, the tuber yield of the indeterminate cultivar (‘Russet Burbank’) could have significantly increased over the determinate early maturing cultivar (Norgold Russet) in a longer growing season. ‘Russet Burbank’ maintains active leaf area and translocate dry matter to tuber for a longer time period. With a simulation study Kooman and Rabbinge (1996) showed that with limiting conditions for tuber growth, crop earliness influence dry matter allocation in tuber the most, but with optimal condition leaf longevity is most important. In our study, a short growing season with high soil N supply facilitated the determinate early maturing ‘ND8068-5 Russ’ to produce total tuber yield and marketable tuber yield more than the indeterminate cultivars (‘Russet Burbank’ and ‘Dakota Trailblazer’).

2016 growing season

In 2016, averaged across all cultivars, all N fertilizer treatments significantly increased total tuber yield over control (Table 1.3.). Total tuber yield with all N fertilizer treatments was statistically similar except for that of Urea which was significantly lower (Table 1.3.). However, maximum total tuber yield (50.0 Mg ha^{-1}) was obtained with ESN (Table 1.3.). Averaged across all N treatments, ‘Russet Burbank’ total tuber yield was maximum followed by ‘Dakota Trailblazer’ and that followed by ‘ND8068-5 Russ’ (Table 1.3.). All N fertilizer treatments significantly increased ‘Russet Burbank’ total tuber yield over control and maximum yield was obtained with ESN which was statistically similar to all other N fertilizer treatments except for Urea (Fig 1.4.). All N fertilizer treatments significantly increased ‘Dakota Trailblazer’ total tuber yield over control and maximum yield was obtained with ESN+AS which was statistically similar to Grower's standard and ESN (Fig 1.4.). 'ND8068-5 Russ' total tuber yield was significantly higher than control only with Grower's standard and UreaSplit (Fig 1.4.).

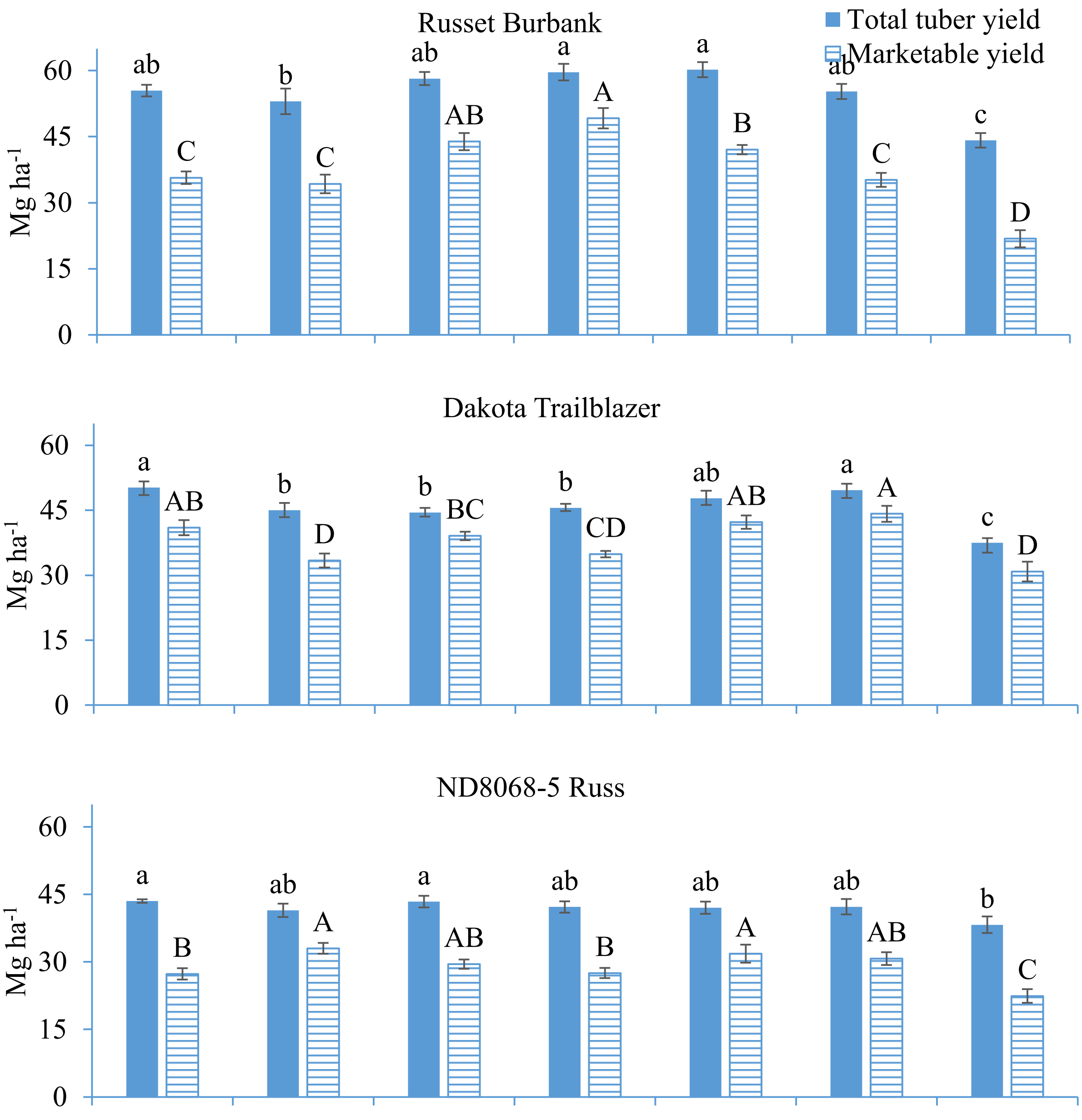

Fig 1.4. Interaction effect of N treatments and cultivars on total tuber yield (Mg ha^{-1}) and marketable yield (Mg ha^{-1}) in growing season 2016.

The effect of N treatments on total tuber yield and the marketable yield under each cultivar is denoted by the lowercase letters and uppercase letters respectively. Vertical bars denote standard error.

Averaged across all cultivars, all N fertilizer treatments significantly increased marketable yield over control and maximum yield was obtained with ESN (38.7 Mg ha^{-1}) closely followed by UreaSplit (37.5 Mg ha^{-1}) and were not significantly different (Table 1.3.). Marketable yield was significantly lower with Urea and Grower's standard compared to ESN (Table 1.3.). Averaged across all N treatments maximum marketable yield was obtained with 'Dakota Trailblazer' (37.9 Mg ha^{-1}) followed by 'Russet Burbank' (37.4 Mg ha^{-1}) and were not significantly different, while 'ND8068-5 Russ' marketable yield was significantly lower compared to the other two cultivars (Table 1.3.). 'Russet Burbank' marketable yield was maximum with SuperU followed by UreaSplit and were not significantly different (Fig 1.4.). Grower's standard, Urea, and ESN+AS significantly reduced 'Russet Burbank' marketable yield as compared to other N fertilizer treatments (Fig 1.4.). 'Dakota Trailblazer' marketable yield was maximum with ESN+AS and statistically similar to ESN and Grower's standard (Fig 1.4.). 'ND8068-5 Russ' marketable yield was maximum with Urea followed by ESN and were not significantly different (Fig 1.4.).

In 2016 growing season, the responses of different cultivars to N treatments were completely different from each other which might be due to the complex interaction among several factors like soil N supply, seed dormancy period, vine type, dry matter distribution pattern in relation to time and fertilizer N availability or phasic temperature change patterns. (Cao and Tibbitts 1994; Kleinkoph et al. 1981; Xing et al., 2016). The growing period of 2016 was 13 days longer than 2015 which might have increased the 'Russet Burbank' and 'Dakota Trailblazer' yield significantly over early maturing 'ND8068-5 Russ'. Unlike 2015, Urea treatment had significantly lower yield than other N treatments in 2016. Comparatively lower soil N supply (158 kg N ha^{-1}), more leaching losses due to early season rainfall flushes in 2016

(Fig 1.1.) might have resulted in lower yield response with lower N fertilizer dose (Urea 225 kg N ha^{-1}). Although ESN+AS increased the 'Dakota Trailblazer' yield exceptionally, but overall ESN alone had greater total and marketable tuber yield than ESN+AS.

Despite variable cultivar response in both growing seasons, ESN (280 kg N ha^{-1}) consistently maintained tuber yield. Our observation is consistent with Pack et al. (2006); Rosen et al. (2013); Ziadi et al. (2011) who found greater tuber yield with PCU compared to conventional fertilizers. The variable response to N fertilization in consecutive growing seasons is also very common. Zvomuya et al. (2003) in three years experiment found yield benefit of PCU over common urea in only one year when applied at the same rate and standard irrigation. Similar to our observation in 2015, Biemond and Vos (1992), and Ziadi et al. (2011) did not find any yield benefit with excess N fertilization. Errebhi et al. (1998), and Love et al. (2005) observed variable yield response of N fertilizer timing and rate with respect to different growing seasons and cultivars. Belanger et al. (2000) stated that potato yield response was often limited to N fertilization or variable when cultivated following a legume crop (soybean in our study). Pehrson et al. (2011), in a survey during 2006 and 2007 in Idaho, found a noticeable decrease in number of growers using legume in rotation with potato crop in the past decade. However, the practice is still common in North Dakota and should be modified.

Specific gravity

In 2015 growing season N treatments and cultivars had no significant effect on SG. In 2016, SG was significantly influenced by the main effect of cultivar and N treatments × cultivar interaction effect, but there was no effect of N treatments. Averaged across all N treatments SG of 'Dakota Trailblazer' was maximum and significantly higher than the SG of 'ND8068-5 Russ' which was again significantly higher than that of 'Russet Burbank' (Table 1.3.). The specific gravity of ‘Russet Burbank’ was maximum with SuperU and lowest with ESN (Fig 1.5.). ‘Dakota Trailblazer’ SG was maximum with control and significantly greater than that of Urea, SuperU, ESN and the lowest SG with ESN+AS (Fig 1.5.). ‘ND8068-5 Russ’ SG was lowest with SuperU and was significantly lower than all other N treatments (Fig 1.5.). However, in controls, the SG were always higher or statistically similar to the N fertilizer treatments while yields were significantly lower.

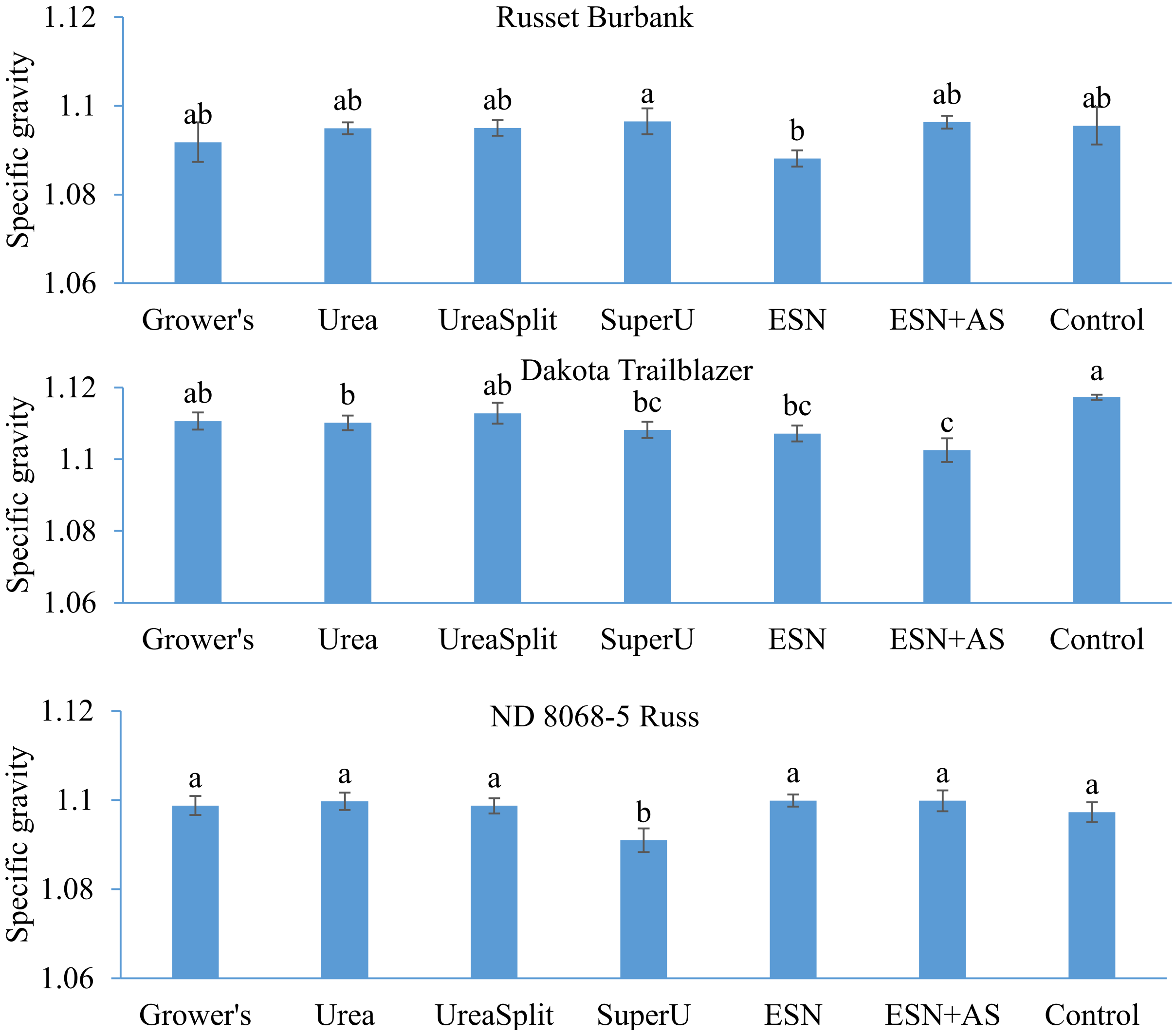

Fig 1.5. Interaction effect of N treatments and cultivars on potato specific gravity in 2016 growing season.
Vertical bars denote standard error.

Specific gravity in 2015 and 2016 growing seasons ranged from 1.082 to 1.099 and from 1.094 to 1.110, respectively. These values are high compared to the values reported in similar previous studies by Rosen et al. (2013); Westermann and Kleinkopf (1985); Ziadi et al. (2011); Zvomuya et al. (2003). Similar to our observation, Porter et al. (1993), Rosen et al. (2013); Wilson et al. (2009); Ziadi et al. (2011) did not find any rate, timing, and source (PCU and urea) effect of N fertilization on tuber SG. Kelling et al. (2011) found no effect of N rate or nitrification inhibitor on tuber SG. Our finding does not match with Westermann and Kleinkopf (1985), who suggested a decrease in SG with tuber yield increase. The positive linear relationship between dry matter yield and SG has been established for a long time by many researchers (Verma et al., 1971). Verma et al (1975) established a strong positive linear relation between starch and SG and the strong negative linear relationship between SG and N content. Although there was an N treatment × cultivar interaction effect in 2016, no significant relationships between SG and tuber yield, SG and tuber dry matter yield and SG and N content were found. This phenomenon was observed possibly due to very high SG of the tubers within a very narrow range of values, while the relationships are established in a wide range of values. However, in 2016, when a significant difference between cultivar SG was found, that could be attributed to the percent marketable tubers of total tuber yield as a strong positive linear relationship (R^2= 0.97) was observed (regression not shown) but cannot be conclusively stated due to very small sample number. As high SG is desirable for processing potatoes to increase the chipping yield, the potatoes produced in the experiment would serve as very good quality processing potato despite the low N treatment and cultivar response.

Vine biomass and nitrogen uptake

Vine dry biomass was significantly influenced by the main effects of N treatments and cultivars in both growing seasons (Table 1.4.). In 2015, averaged across all cultivars, Grower's standard, SuperU, and ESN had significantly higher vine biomass compared to that of control, Urea and UreaSplit (Table 1.4.). Maximum vine dry biomass was obtained with Grower's standard and the lowest was with control (Table 1.4.). Averaged across all N treatments, 'Dakota Trailblazer' had significantly higher dry vine biomass compared to 'Russet Burbank' and 'ND8068-5 Russ' (Table 1.4.). In 2016, averaged across all cultivars, all N treatments increased dry vine biomass over control (Table 1.4.). Maximum dry vine biomass was obtained with Grower's standard and that was only significantly higher than that of Urea among all N fertilizer treatments (Table 1.4.). Averaged across all N treatments 'Dakota Trailblazer' had significantly higher dry vine biomass compared to 'Russet Burbank' which was again significantly higher than that of 'ND8068-5 Russ' (Table 1.4.). The vine growth and vine biomass yield are cultivar-specific and in both years 'Dakota Trailblazer' had, even more, vine biomass than indeterminate 'Russet Burbank' cultivars. Although the number of stolons was not recorded, but from the observation, it can be stated that the besides vigorous vines, a large number of fruits in 'Dakota Trailblazer' must have increased the vine dry biomass compared to indeterminate fruitless 'Russet Burbank' and determinate fruitless cultivar 'ND8068-5 Russ'. The maximum vine growth with Grower's treatment might have been because of the N fertilizer application during tuber initiation period, which leads to increased late season vegetative growth (Ojala et al., 1990).

In 2015, vine N uptake and total N uptake were significantly influenced by the main effects of N treatments and cultivars while tuber N uptake was significantly influenced by N treatments (Table 1.4.). Averaged across all cultivars, Grower's, SuperU and ESN significantly

Table1.4. Effect of N treatments and cultivars on vine dry biomass, vine N uptake, tuber N uptake and total N uptake in 2015 and 2016 growing season.

	Vine dry biomass (Mg ha^{-1})	Vine N Uptake (kg ha^{-1})	Tuber N Uptake (kg ha^{-1})	Total N uptake (kg ha^{-1})
N treatments	2015			
Grower's	7.02 (0.88)[ϕ]a[†]	140 (15.8)a	180 (12.3)a	320 (14.0)a
Urea	3.54 (0.86)b	81.4 (21.9)bc	163 (9.35)ab	244 (22.9)c
UreaSplit	3.57 (0.75)b	77.3 (14.1)bc	191 (16.3)a	269 (19.7)bc
SuperU	6.24 (0.85)a	137 (19.5)a	174 (15.4)a	310 (21.1)ab
ESN	5.50 (0.78)a	102 (14.4)b	166 (10.9)ab	268 (16.3)bc
Control	3.04 (0.56)b	57.7 (10.0)c	132 (6.88)b	190 (13.0)d
Cultivar				
‘Russet Burbank’	3.77 (0.45)b	79.8 (9.81)b	169 (9.24)a	248 (14.7)b
‘Dakota Trailblazer’	7.25 (0.66)a	148 (13.4)a	157 (6.55)a	305 (14.8)a
‘ND8068-5 Russ’	3.43 (0.34)b	70.1 (7.73)b	177 (11.6)a	247 (15.4)b
	Analysis of variance			
N treatments	***	***	*	***
Cultivar	***	***	NS	***
N treatment × Cultivar	NS	NS	NS	NS
N treatments	2016			
Grower's	4.00 (0.55) a	83.9 (11.0)ab	211 (14.6)bc	295 (23.0)ab
Urea	2.93 (0.27)b	56.7 (7.52)c	187 (13.2)c	244 (14.2)c
UreaSplit	3.93 (0.52)a	71.0 (12.1)bc	201 (13.9)bc	272 (7.75)bc
SuperU	3.86 (0.38)a	100 (9.90)a	206 (15.9)bc	307 (21.0)a
ESN	3.14 (0.19)ab	74.8 (7.69)bc	227 (9.04)ab	302 (8.61)ab
ESN+AS	3.44 (0.57)ab	67.3 (14.1)bc	249 (18.9)a	317 (22.6)a
Control	1.63 (0.25)c	20.7 (3.92)d	137 (11.5)d	158 (12.9)d
Cultivar				
‘Russet Burbank’	3.44 (0.29)b	62.5 (8.22)b	224 (13.8)a	286 (17.9)a
‘Dakota Trailblazer’	4.06 (0.33)a	86.3 (8.01)a	200 (10.9)b	286 (15.0)a
‘ND8068-5 Russ’	2.33 (0.16)c	54.6 (6.31)b	185 (7.08)b	239 (10.7)b
	Analysis of variance			
N treatments	***	***	***	***
Cultivar	***	***	**	***
N treatment × Cultivar	NS	*	*	**

*, **, ***Significant at $P < 0:05$, $P < 0:01$, and $P < 0:001$, respectively.

NS, not significant

[ϕ] Parenthesis include standard error

[†]Values followed by the same letter in each column are not significantly different

increased vine N uptake over control and maximum N uptake was obtained with Grower's (140 kg N ha^{-1}) which was not significantly different than that of SuperU (Table 1.4.). Averaged across all N treatments 'Dakota Trailblazer' had significantly higher vine N uptake (148 kg N ha^{-1}) compared to 'Russet Burbank' and 'ND8068-5 Russ' (Table 1.4.). Averaged across all cultivars, tuber N uptake with UreaSplit, Grower's and SuperU were significantly higher than that of control (Table 1.4.). Averaged across all cultivars, all N treatments significantly increased total N uptake over control (Table 1.4.). Grower's treatment had maximum total N uptake (320 kg N ha^{-1}) followed by SuperU (310 kg N ha^{-1}) and they were not significantly different (Table 1.4.).

Averaged across all N treatments 'Dakota Trailblazer' had significantly higher N uptake than that of 'Russet Burbank' (Table 1.4.). In 2016, vine N uptake, tuber N uptake, and total N uptake were significantly influenced by the main effects of N treatments and cultivar and N treatment × cultivar interaction effect. Averaged across all cultivars, SuperU had maximum vine N uptake and was not significantly different than that of Grower's (Table 1.4.). Averaged across all N treatments 'Dakota Trailblazer' had significantly higher vine N uptake than that of 'Russet Burbank' and 'ND8068-5 Russ' (Table 1.4.). Averaged across all cultivars the tuber N uptake and total N uptake was maximum with ESN+AS (249 kg N ha^{-1} and 317 kg N ha^{-1}, respectively) (Table 1.4..). Total N uptake of ESN, SuperU, and ESN were statistically similar, but with SuperU vine N uptake was more while with ESN the tuber N uptake was more (Table 1.4.).

The N uptake responses in different cultivars were extremely variable. For 'Russet Burbank' total N uptake and vine N uptake were maximum with SuperU while ESN+AS had maximum tuber N uptake (Fig 1.6.). For 'Dakota Trailblazer', both total N and tuber N uptakes were maximum with ESN+AS which were not significantly different than that of Grower's treatment (Fig 1.6.). Total and tuber N uptake in UreaSplit were significantly lower than that of Grower's and ESN+AS (Fig 1.6.). For 'ND8068-5 Russ', total N uptake was obtained with ESN and was not significantly different than that of UreaSplit, SuperU, and ESN+AS (Fig 1.6.). Tuber

N uptake in ‘ND8068-5 Russ’ was maximum with UreaSplit and not significantly different than that of SuperU, ESN, and ESN+AS (Fig 1.6.).

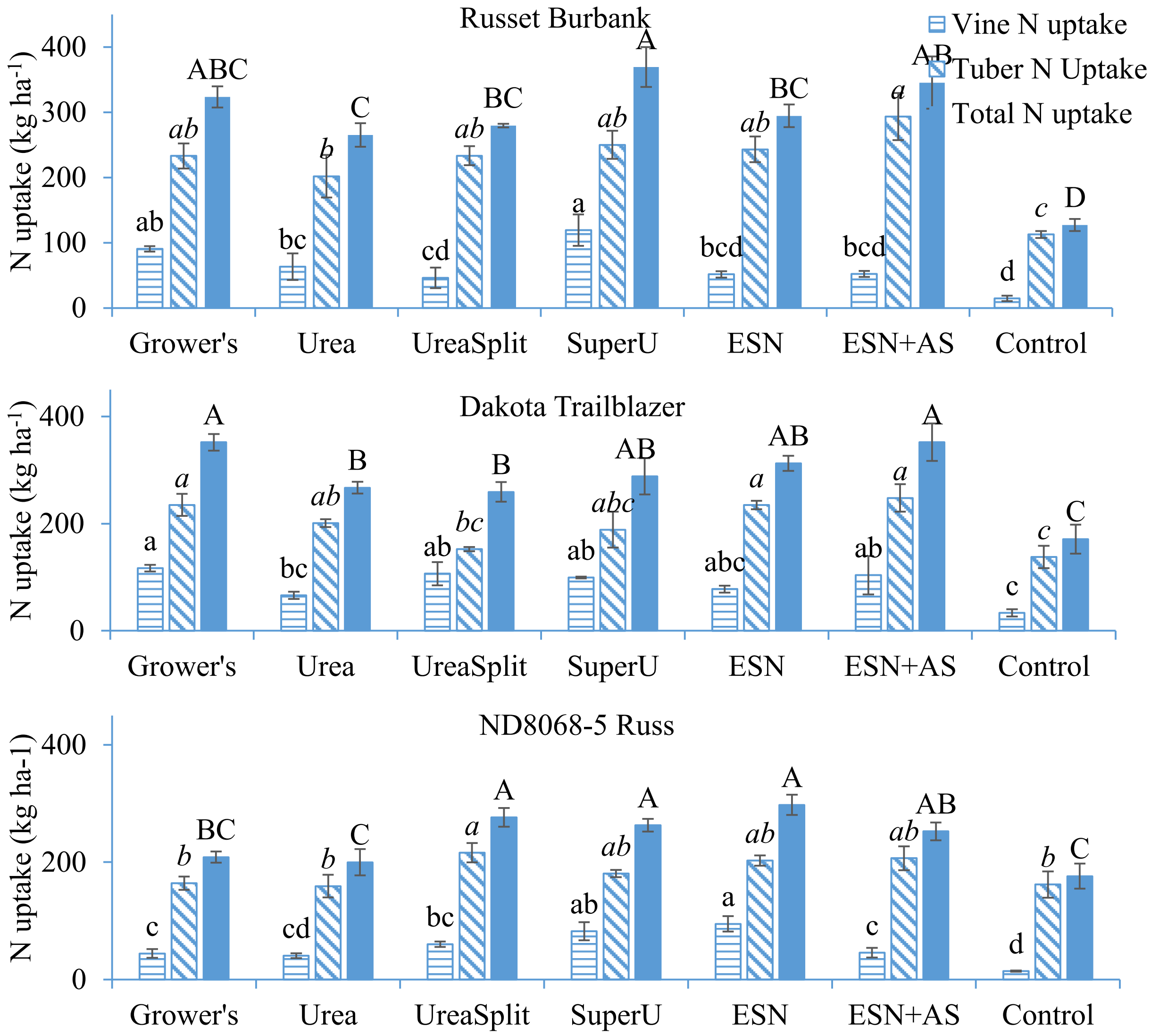

Fig 1.6. Interaction effect of N treatments and cultivars on vine N uptake (kg ha^{-1}), tuber N uptake (kg ha^{-1}) and total N uptake (kg ha^{-1}) in 2016 growing season.
The effect of N treatments under each cultivar on vine N uptake, tuber N uptake and total N uptake are denoted by the lowercase letters, italicized lower case letters and uppercase letters respectively.

The total N uptake found in our study is comparatively higher than the previously reported values with similar N rates by Errebhi et al. (1998); Wilson et al. (2010); Zvomuya et al. (2003). This difference is primarily because of the excessive vine N uptake in our study as the tuber N uptakes were similar to the previous studies. Pack et al. (2006) also reported vine N uptake of 41 to 99 kg N ha^{-1} when N applied at 146 to 225 kg ha^{-1}. Vine N uptake was more related with vine biomass than N concentration; with increased biomass N uptake increased. However, N concentration was significantly lower in control than N fertilizer treatments (data not shown). Hasse et al. (2007) also showed no difference in N concentration with N source and cultivars and the main difference in N uptake was due to dry matter yield. In 2015, as the tuber N uptakes were not significantly different among the cultivars, the higher total N uptake in 'Dakota Trailblazer' also corresponds to the higher vine N uptake. In 2015, tuber fresh yield was apparently inversely related to tuber N uptake. This can be explained by higher N concentration in tubers (data not shown) even with lower fresh tuber yield owing to similar SG resulting dry biomass productions with all N fertilizer treatments. Biemond and Vos (1992) in their experiment observed that although N concentration in tubers during different growth stages may vary with N treatments (rates), but the final distributions of dry matter and N between tubers were not affected by N treatments, just the time and pattern of partitioning of dry matter were different. Although the responses in two growing seasons were variable but in both seasons, the vine N uptake with SuperU was comparatively higher than that in ESN while the tuber N uptake was higher in ESN than SuperU. This suggests that the release of N from ESN can better match up with the N uptake pattern and dry matter distribution for russet potato cultivation in irrigated sandy soil. Hendrickson et al. (1978), Martin et al. (1993) concluded inhibitor use should not be recommended for potatoes on irrigated sandy soils and our work also confirms that as the tuber yields and N uptake patterns were not consistent with SuperU. Wilson et al. (2010) also showed that PCU applied at emergence had more tuber N accumulation than soluble N in two splits.

Although the overall seasonal temperature in two seasons did not differ, the variability in N uptakes and N translocation in response to N treatments might be due to the differences in phasic temperature changes after planting and germination period in two years (Cao and Tibbits, 1994). Errebhi et al. (1998) showed that even in irrigated potatoes difference in rainfall distribution in early growing season lead to different crop response with similar N treatments, which can be attributed to the change in seed dormancy period as well as crop growth and fertilizer N mineralization pattern. Plant N uptake and growth were not only regulated by soil N supply, but also depend upon the relative internal supply of C and N (Lemaire and Millard 1999). More investigations of plant growth parameters and N translocation pattern are required to substitute and explain the agronomic responses in our study.

Apparent fertilizer recovery and nitrogen use efficiency

In 2015 growing season AFR was significantly influenced by N treatments while in 2016 AFR was only influenced by cultivars (Table 1.5.). In 2015, SuperU had maximum AFR (48.9 %) followed by Grower's treatment (46.7 %) and not significantly different from each other (Table 1.5.). Apparent fertilizer recovery with Urea, UreaSplit, and ESN was significantly lower than that of SuperU and Grower's and was statistically similar to each other (Table 1.5.). In 2016, AFR by 'Russet Burbank' (68.3%) was significantly higher than 'Dakota Trailblazer' (49.2 %) which was again significantly higher than that of 'ND8068-5 Russ' (27.3%) (Table 1.5.). The effect of cultivars on AFR in 2016 was also reflected in residual NO_3-N in the soil which showed that with increasing AFR, the residual NO_3- N decreased (Table 2.3). Zebarth et al. (2004) also showed that fertilizer N recovery is higher (77%) with low NO_3^- leaching loss associated with low rainfall year. Errebhi et al. (1998) reported that AFR in higher rainfall year decreased from 40% in control to 25% in 270 kg N ha^{-1} at planting, while in lower rainfall season recovery was more (56%) and AFR was inversely related to soil residual NO_3^-.

The AFR values reported in previous studies fall in a very wide range of fertilizer recovery calculated by difference method is not as accurate as the isotopic method, but Zvomuya et al. (2003) also showed that N fertilizer recovery calculated by different methods reflect the

Table 1.5. Influence of N treatments and cultivars and their interaction effect on apparent fertilizer recovery, nitrogen use efficiency in 2015 and 2016 growing seasons

	2015	
N treatments	AFR (%)	NUE (kg marketable tuber kg^{-1} applied N)
Grower's	46.7 (4.31)[ϕ]a[†]	20.4 (6.00)bc
Urea	30.8 (3.70)b	31.6 (4.82)a
UreaSplit	29.7 (6.20)b	15.0 (4.63)cd
SuperU	48.9 (6.55)a	12.9 (4.90)d
ESN	32.4 (4.27)b	23.1 (3.90)b
Control	-	-
Cultivars		
‘Russet Burbank’	33.9 (4.34)a	16.2 (3.25)b
‘Dakota Trailblazer’	39.5 (3.22)a	8.94 (2.40)c
ND 8065-5 Russ	39.7 (5.42)a	36.6 (2.16)a
	Analysis of variance	
N treatments	**	***
Cultivars	NS	***
N treatments × Cultivars	NS	*
	2016	
N treatments	AFR (%)	NUE (kg marketable tuber kg^{-1} applied N)
Grower's	48.8 (10.8) a	34.4 (5.65)a
Urea	39.6 (9.42)a	38.8 (6.82)a
UreaSplit	40.5 (6.99)a	44.6 (8.15)a
SuperU	53.1 (11.4)a	44.0 (12.1)a
ESN	51.2 (4.87)a	48.9 (6.15)a
ESN+AS	56.6 (10.1)a	41.7 (3.56)a
Control	-	-
Cultivars		
‘Russet Burbank’	68.3 (4.23)a	66.9 (4.34)a
‘Dakota Trailblazer’	49.2 (6.46)b	30.6 (4.25)b
ND 8065-5 Russ	27.3 (4.22)c	28.6 (2.66)b
	Analysis of variance	
N treatments	NS	NS
Cultivars	***	***
N treatments × Cultivars	NS	***

*, **, ***Significant at $P < 0{:}05$, $P < 0{:}01$, and $P < 0{:}001$, respectively.

NS, not significant

[ϕ] Parenthesis include standard error

[†] Values followed by the same letter in each column are not significantly different

same N treatment response as in the isotopic method and the trend of response also did not change. The AFR obtained in our experiment are consistent with several previous studies i.e.

Joern and Vitosh (1995) reported AFR 52%; Errebhi et al. (1998) reported AFR 33 to 56%; Zvomuya and Rosen (2002) reported AFR 42 to 53%. Our observation in 2015 growing season was similar to Kelling et al. (2011) who showed greater N recovery with DCD because of delayed release of N which eventually increased vine N uptake. Similar to our observation in 2016, Wilson et al. (2010) also reported that N source (soluble N and PCU) had no effect on fertilizer N recovery which ranged from 45 to 76%. Pack et al. (2006) in an experiment testing several controlled release fertilizer (CRF) observed that only some (product names were not provided) CRF improves N recovery. Unlike our observation, Zvomuya et al. (2003) observed that in high rainfall years or high leaching loss condition N recovery efficiency with PCU was 93% and 54% higher than urea when applied at 280 kg N ha^{-1}, but in lower rainfall years with low leaching loss condition there were no significant difference between urea and PCU with respect to N recovery.

In 2015, NUE was significantly influenced by main effects of N treatments and cultivars and their interaction effect, while in 2016 it was influenced by the main effect of cultivars and N treatments×cultivar interaction effect (Table 1.5.). In 2015, Urea had maximum NUE which was significantly higher than all other N fertilizer treatments (Table 1.5.). ‘ND8068-5 Russ’ NUE was significantly higher than that of ‘Russet Burbank’ which was again significantly higher than that of ‘Dakota Trailblazer’ (Table 1.5.). In 2016, ‘Russet Burbank’ NUE was maximum and significantly higher than that of ‘Dakota Trailblazer’ and ‘ND8068-5 Russ’ (Table 1.5.). The N treatment × cultivar interaction effects on NUE were extremely variable in both years (Table 1.6.). As the NUE was calculated using marketable yield, the response pattern apparently followed the response of marketable yield. From the data, only it can be surmised that NUE in a shorter growing season with frequent small rainfall flushes can be increased with early maturing determinate type cultivar and lower dose (225 kg N ha^{-1}) of N fertilizer application, while in a longer growing season NUE of indeterminate late maturing cultivars can be increased with EEFs.

Table 1.6. Interaction effect of N treatments cultivars on nitrogen use efficiency in 2015 and 2016 growing seasons

	Russet Burbank	Dakota Trailblazer	ND8068-5 Russ
	NUE (kg of marketable tuber/ kg of applied N)		
N treatments	2015		
Grower's	11.8 (2.65)[ϕ] bc[†]	6.2 (3.68)abc	43.3 (3.30)a
Urea	35.2 (4.82)a	15.2 (3.03)ab	44.3 (4.88)a
UreaSplit	15.3 (5.41)bc	0.16 (0.16)c	29.6 (3.27)b
SuperU	2.56 (2.56)c	4.91 (1.43)bc	31.3 (4.92)b
ESN	16.4 (4.37)b	18.3 (8.00)a	34.5 (0.75)ab
Control	-	-	-
	2016		
Grower's	49.5 (2.54)[ϕ] d[†]	36.2 (12.5)ab	17.5 (4.09)c
Urea	55.3 (10.8)cd	13.9 (7.74)b	47.1 (3.71)a
UreaSplit	78.8 (3.85)b	29.5 (10.5)ab	25.4 (3.99)bc
SuperU	97.8 (5.95)a	15.7 (8.05)b	18.4 (7.59)c
ESN	72.4 (6.05)bc	40.7 (9.37)ab	33.6 (2.73)b
ESN+AS	47.7 (3.33)d	47.6 (6.69)a	29.8 (3.46)bc
Control	-	-	-

[ϕ] Parenthesis include standard error

[†] Values followed by the same letter in each column are not significantly different

Nitrogen use efficiency has been computed using several formulae in different studies using total tuber yield or marketable yield or dry matter yield. So, it is very hard to compare the N uptake efficiency (NUpE) or N utilization efficiency (NUtE) with the NUE calculated using marketable tuber yield in our study. Zebarth et al. (2004) found that NUtE is more related to crop N supply (soil N supply + fertilizer N applied) than soil N supply, but they also mentioned that soil N supply is difficult to estimate as leaching losses cannot be accounted and late season soil N mineralization may not be captured in the plant N accumulation by early senescing crop in control treatment. It is assumed that the N uptake rate and soil N mineralization is not affected by the priming effect of added fertilizer N. However, Westermann and Kurtz (1973) showed that soil N uptake increased 17- 45% with N fertilizer application because of the increase in soil N mineralization. Zebarth et al. (2004) surmised that NUE is independent of climatic and seasonal variation and mostly controlled by the genetics of the cultivar and applied N rate. Similar to our observation in 2016, Wilson et al. (2010) observed no effect of N source on NUE. The values estimated for NUE in our study is consistent with several previous studies i.e. Ziadi et al (2011) reported 44.6 to 84.3 kg tuber kg^{-1} applied N; Shoji et al. (2001) reported 17.3 to 58.4 kg tuber kg^{-1} N applied. Zvomuya et al. (2003) reported a very high NUE of 35-145 kg tuber kg^{-1} applied N with urea and 38-168 kg N kg^{-1} applied N with PCU when applied at 140 kg N ha^{-1}. Many researchers (Errebhi et al., 1999, Wilson et al., 2010) found that NUE decrease with increased N rate and that finding is apparently reflected in our 2015 observation where NUE was maximum with urea @ 225 kg N ha^{-1} and significantly higher than the other N fertilizer treatments applied @ 280 kg N ha^{-1}.

Conclusions

Results from this study indicate that when grown in an irrigated sandy soil and late sowing situation due to early season unpredictable heavy rainfall, potato yield, quality, and NUE may greatly vary between years depending on the number of growing days, rainfall distribution pattern, phasic temperature pattern, cultivars and soil N supply. Delayed sowing due to early season rainfall possibly hinders achieving target yield of 62 Mg ha^{-1} in the case of indeterminate cultivars. Shorter growing season does not allow to exploit full yield and N use potential of the indeterminate cultivars. In a very short growing season as 2015, determinate cultivar (ND 8068-5 Russ) can produce marketable tubers similar to indeterminate 'Russet Burbank' cultivar, but in a comparatively longer growing season, the indeterminate cultivars ('Russet Burbank' and 'Dakota Trailblazer') would produce more marketable tubers than 'ND8068-5 Russ'. Preceded by a legume crop and soil N supply throughout the growing season substantially reduce N fertilizer treatment response in irrigated late sown russet potato cultivation. With a very high soil N supply and smaller rainfall flushes application of 225 kg N ha^{-1} through urea at planting may also produce a higher amount of marketable tubers compared to urea applied @ 280 kg N ha^{-1} in two splits. However, when applied at the same rate, ESN had either yield benefit or over unamended urea. SuperU or urea amended with UI and NI has variable response depending upon the activity of inhibitors and may not match up with plant N uptake and lead to high vine N uptake. Over the year, ESN had a consistent response in maintaining or increasing yield. Application of AS with ESN at hilling did not have any yield benefit over ESN alone. The specific gravity of the tubers was high enough (about 1.09) to meet the processing quality standard with all N fertilization practices in both years. Grower's standard practice and SuperU may increase vine biomass and thus vine N uptake due to greater N availability later in the season, but do not have consistent yield benefit or better NUE than ESN. Regardless of soil N supply and rainfall pattern, polymer coated urea like ESN may be a better option for irrigated late sown russet potato cultivation considering the consistent yield response while reducing N losses (Chapter 2). A different fertilizer management program should be developed at least for the determinate cultivar considering that the shorter growing season allows it to utilize N to its full potential, still leaves greater residual NO_3-N after harvest (Chapter 2).

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CHAPTER 2. EFFECTIVENESS OF ENHANCED EFFICIENCY FERTILIZERS AND SPLIT APPLICATION TO MINIMIZE NITROGEN LOSSES AFTER PLANTING DELAYS IN IRRIGATED RUSSET POTATOES

Abstract

Field studies were conducted in 2015 and 2016 growing season at Northern Plains Potato Growers' Association Irrigation site near Inkster, ND to evaluate the effectiveness of EEFs in reducing N losses through NH_3 volatilization, N_2O emission and NO_3^- leaching in an irrigated potato production system. Two types of EEFs (SuperU, ESN) at the rate of 280 kg N ha^{-1}, unamended urea at the rate of 225 kg and 280 kg N ha^{-1} and grower's standard fertilization at the rate of 280 kg N ha^{-1} were applied as N treatments in three russet potato cultivars following a factorial randomized complete block design with four replications. In both years, NH_3 volatilization were maximum with urea 280 kg N ha^{-1}. When applied at same rate (280 kg N ha^{-1}), ESN significantly reduced NH_3 volatilization compared to urea and grower's standard practice in both growing seasons. All N treatments significantly increased N_2O emission over control in both growing seasons. When applied at same rate (280 kg N ha^{-1}), both EEFs reduced N_2O emission compared to unamended urea in both growing seasons. However, SuperU was most efficient in reducing N_2O emission. Residual NO_3-N was greatly increased and maximum with SuperU in both growing seasons. Although not statistically significant, grower's standard practice also increased NO_3-N leaching over urea @ 280 kg N ha^{-1}. In 2015, ESN did not increase residual NO_3-N concentration over control, but in 2016, significantly increased residual NO_3-N concentration over control. Residual NO_3-N concentration with 'ND8068-5 Russ' were significantly higher compared to 'Russet Burbank' in both growing seasons. In order to reduce environmental losses of N, ESN can be recommended for irrigated late-sown russet potatoes. A

better method for in-season NO_3^- leaching measurement is required. For determinate cultivars like 'ND8068-5 Russ', a modified N management practice and N rate should be developed as the N fertilization recommendations are commonly based on 'Russet Burbank' cultivar.

Introduction

Increasing nitrogenous (N) fertilizer prices and environmental health concerns associated with N losses are forcing us to better manage N fertilizers and improve N use efficiency. Potatoes *(Solanum tuberosum*) need a significant amount of N supply, i.e. 225 kg N ha^{-1} for a yield goal of 62 Mg ha^{-1}, in order to meet target yield and quality of tubers (Franzen, 2010; Zebarth and Rosen, 2007). However, a considerable amount of the N applied are subjected to environmental loss during the stages of low crop uptake. The actual recovery (estimated by tracer technique) of applied N fertilizer by whole plant ranges from 29 to 77% and the apparent recovery (estimated with difference method) commonly ranges from 40 to 60% (Li et al., 2003; Roberts et al., 1991; Zebarth et al., 2004; Zvomuya et al., 2002). The portion of the N which is not recovered by the crop is subjected to loss through three pathways i.e. NH_3 volatilization, gaseous (N_2O, N_2) losses through denitrification and nitrification and NO_3^- leaching below root-zone.

Ammonia (NH_3) is a corrosive gas extremely toxic to biological organisms (Krupa, 2003). Ammonia, produced as an intermediate product during N mineralization, easily gets lost through volatilization and deposited within terrestrial and aquatic systems resulting eutrophication, soil acidification (Zebarth and Rosen, 2007) and pose a threat to human health through particulate matter formation (Aneja et al., 2009). Therefore, efficient N management practices has become one of the greatest challenges in potato production.

Potato has a shallow root system which extends up to 60 cm depth and 90% of the active roots are limited to the 25 cm of the surface soil (Lesczynski and Tanner, 1976; Liegel and

Walsh, 1976)) and commonly cultivated in sandy soils (Wilson et al., 2010) for proper growth of tubers. These factors lead to increased NO_3^- leaching due to the low water holding capacity of sandy soils and low recovery of NO_3^- by the shallow potato roots. The leached NO_3^- have a potential to contaminate groundwater in the shallow groundwater table region. The average NO_3^- concentration of groundwater in Central Sands region of Minnesota, an irrigated potato growing region, was 16.1 mg L^{-1}, which is above the drinking water critical limit of 10 mg L^{-1}(O' Dell, 2007). Nitrous oxide is a potent greenhouse gas with global warming potential 300 times greater than CO_2, and the single most dominant ozone layer depleting substance (Ravishankara et al., 2009). In United States agriculture is the source of 74.8% of the total anthropogenic N_2O emission (USEPA, 2008). Nitrous oxide is produced primarily as an intermediate product of denitrification (Mosier et al., 1998), particularly in humid environments or under irrigation. Coarse textured soils may not facilitate denitrification, but high rates of N applied in potato crop may promote nitrification-driven N_2O production (Venterea, 2007).

The goal of best management practices is to provide the sufficient supply of N to the crop to achieve the target yield of tubers of good quality, while minimizing the risk of environmental losses of N simultaneously. Applied N can be efficiently used if the soil N availability is well synchronized with the crop N demand and uptake. Crop N demand, primarily determined by crop growth, varies with cultivar, soil and climatic conditions and crop management practices while soil N supply depends upon net N mineralization of soil organic matter, manure and crop residues, carry-over of mineral N from the previous growing season and climatic conditions (Zebarth et al., 2005). So, even with the application of right type and dose of fertilizer in right time, sometimes it's very hard to attain a high nitrogen use efficiency (NUE).

Nitrogen applied in several splits throughout the growing season increases N utilization by the crop (Errebhi et al., 1998; Vos, 1999). Three split applications are generally recommended for irrigated potatoes cultivated in coarse textured soils of Northern Great Plains (Lamb et al., 2008). Other viable and emerging option to increase the NUE and reduce N losses is the enhanced efficiency fertilizers (EEFs), which are formulated to release N in sync with the plant uptake generally following three mechanisms. Common inorganic fertilizers are blended with nitrification inhibitor (NI) to suppress the bacterial oxidation of NH_4^+, or urease inhibitor (UI) to delay urea hydrolysis, or coated with sulfur or microthin polymers to slower the rate of nutrient release through coating (Akiyama et al., 2010). Enhanced efficiency fertilizers, have been studied intensively, and the findings indicated that they can increase NUE while reducing labor and fuel costs of split application (Grant, 2005).

The primary objective of this study was to assess the impact of two EEFs (SuperU and ESN) and split application of N on (i) NH_3 volatilization, (ii) N_2O emissions (iii) Below root zone soil water NO_3^- concentration and (iv) residual NO_3-N availability in soil profile (0- 120 cm) throughout the growing season of 2015 and 2016 under an irrigated, late sown, Russet potato production system. As EEFs and split application are supposed to and have been reported to increase N use efficiency and reduce N losses, this study tried to estimate N losses throughout the growing season under conventional fertilization practice (in split), whole fertilization at planting and alternative fertilization i.e. EEFs with three russet potato cultivars to understand which of the fertilization options may consistently and effectively reduce N losses. The secondary objective this study was to observe the responses of three different russet potato cultivars under different N fertilization treatments to comprehend the efficiency of the cultivars in reducing N losses as well as the necessity of adapting different fertilizer management practices with respect to cultivars. From the outcomes of this study, the promise of EEFs as emerging options in reducing N fertilizer loss and environmental hazards coupled with reduced labor and cost of application, can be evaluated.

Materials and methods

Site description and experimental design

Description of the experimental site and experimental design are discussed in Chapter 1.

Sampling procedures for N loss assessment

In both years, due to limited labor force, samples to estimate N losses were collected from three replications of six N treatments i.e. Grower's standard, Urea, UreaSplit, SuperU, ESN and Control under three cultivars. The N treatment ESN+AS was added in 2016 to observe the yield benefit of application of a soluble N fertilizer (AS) just before emergence, combined with a slow release N fertilizer (ESN).

Ammonia volatilization measurements

Ammonia volatilization loss was measured using open chamber ammonia traps (Jantalia et al., 2012). The trap prepared with a 2-L polyethylene terephthalate bottle covers 90 cm^2 surface area of soil. A polyfoam strip of dimension 25 cm × 3.5 cm × 0.5 cm is used as NH_3 traps. Polyfoam strips were rinsed thoroughly twice with deionized water; excess water was removed, and then rinsed with 0.5 M H_3PO_4 + 4% Glycerol solution, finally the excess solution was removed. A single strip was then hung from the bottle lid inside each chamber using a wire hook. The lower end of the polyfoam strip was dipped into 30 mL H_3PO_4 solution in a 60mL plastic cup suspended from the wire hook. Chambers were installed on the second hilltop of each plot toward the center of the plot just after planting.

In 2015, samples for NH_3 volatilization estimation was collected at 5, 12, 19, 26, 34, 50 and 64 DAP and in 2016 the samples were collected at 8, 22, 29, 29 to 36, 44, 51, 58, 71, 86 DAP. The data for 8 to 14 DAP was unavailable because a thunderstorm on June 19 blew away the ammonia traps. At each sampling date, the polyfoam strips and the acid solution in plastic cups from each chamber were collected in 125 mL of 2 M KCl solution. Each trap was replaced with fresh polyfoam strips and H_3PO_4 solution. The solution containing NH_3 traps were transferred to the laboratory, and maintained at 5°C and analyzed within three days. In the laboratory, the solution was brought to 250 mL by further rinsing the strips with KCl solution.

Fifty mL of this solution was then analyzed using Automated Timberline TL2800 Ammonia Analyzer (Timberline Instruments, Colorado). Nitrogen loss through ammonia volatilization during consecutive sampling dates (mg NH_3-N m^{-2}) were obtained by multiplying NH_3-N concentration (μg mL^{-1}) by the total volume of solution (250 mL), divided by the surface area of the soil covered by the trap (90 cm^2).

Field nitrous oxide flux measurements

Nitrous oxide fluxes were measured using static chamber methods described by Parkin and Venterea, (2010). Headspace air sampling to estimate N_2O concentration was done during 0900 to 1200 local hours as the surface soil temperature represents its daily average during that time (Maharjan et al., 2014). After planting, polyvinyl chloride (PVC) rings (25.4 cm internal diameter 8 height) were inserted 5-cm deep into the soil in the middle of each plot. At each sampling day, insulated, vented, and reflective PVC chamber tops were placed above the PVC rings (anchors). Headspace air samples (20 mL) were collected at 0, 30 and 60 min following chamber deployment using 30 mL polypropylene syringe and transferred to 12 mL pre-evacuated glass vials sealed with butyl rubber septa. In 2015, sampling for N_2O flux determination was conducted at 1, 5, 15, 26, 34, 43, 50, 56, and 90 DAP and in 2016 sampling was done at 3, 8, 14, 22, 30, 36, 44, 51, 58, 66, 72, 88 DAP. Each time samples were collected at least 24 hours after irrigation to avoid bias. Air samples were analyzed for N_2O concentration using DGA-42 Master Gas Chromatograph (Dani Instruments, Milan, Italy) fitted with a ^{63}Ni electron capture detector (ECD) and a master SHS headspace autosampler. The Ar/CH_4 (95:5) mixture was used as carrier gas, and the ECD was operated at an oven temperature of 300°C. Analytical gas standards (0.1, 0.5, 2, 5, 10, 100 mg kg^{-1}; Scott Specialty Gases) were included for each sampling day to construct standard curves.

The N_2O fluxes (μL N L^{-1} h^{-1}) were determined from N_2O concentrations vs. time linear regression or quadratic regression (QR) (Wagner et al., 1997). Linear regression was used with linear or convex-upward curves (i.e., when second derivative of QR ≤ 0), while QR was used with convex-downward curves (Venterea et al., 2012). The N_2O fluxes were then converted into μg N_2O-N m^{-2} h^{-1} using ideal gas law equation. Minimum detectable flux of gas chromatograph, estimated by sampling ambient air samples from the experimental site, ranged from 3.5 to 7.5 μg N_2O-N m^{-2} h^{-1}. However, even if the N_2O flux lied below the minimum detectable flux, actually measured N_2O flux data have been reported and used for estimating cumulative N_2O emissions.

Soil water nitrate concentrations below the rooting zone

In 2015, ceramic suction cup lysimeters (130 cm long and 1.60 cm internal diameter) were installed to a depth of 0.9 m one DAP. In 2016, the lysimeters were installed to a depth of 0.6 m after hilling or 15 DAP. Before the installation, the ceramic end of the lysimeters were soaked in deionized water for 24 h at a constant vacuum of 40 kPa. For lysimeter installation, 1-m deep (in 2015) and 0.7 m deep (in 2016) soil hole was bored using a hydraulic probe (3.6 cm inner diameter) at the center of each plot, a slurry of unfertilized field soil with minimum plant residue was poured into the hole prior to lysimeter insertion to ensure a good contact of the ceramic cup wall with the soil. Lysimeter was inserted into the hole, and the gap around the lysimeter was re-filled with excavated soil according to the depth. A continuous vacuum of 40kPa was created inside the lysimeters using hand pump and rubber septum throughout the sampling period. In 2015, Soil water were collected three each week during month during June, July and every two weeks in August. In 2016 soil water was collected twice a month in July, August and September in 50 mL polypropylene tubes and then frozen at 18°C until analysed using Automated Timberline TL2800 Ammonia Analyzer (Timberline Instruments, CO, USA).

Residual soil nitrate

After tuber harvesting, one soil core (3.6 cm inner diameter) was collected from the center of each plot to 120 cm depth with a truck-mounted Giddings hydraulic probe. The soil core was divided and bagged separately at incremental depth intervals: 0-15, 15-30, 30-60 and 60-120 cm. The samples were transferred to laboratory at 5°C, and stored at –18°C until analyzed within a week. After thawing and homogenizing the frozen soil, approximately 6.5 g of field moist soil were extracted with 25 mL of 2 M KCl (1:5 dry soil: extractant ratio) by shaking for 30 min (Manyard and Kalra, 1993). The KCl extracts were analyzed using Timberline TL2800 Ammonia Analyzer (Timberline Instruments, CO, USA). Soil moisture content was determined by oven drying (105 °C) separate subsamples. Bulk density of soil at each depth was measured from an intact soil core in order to convert mg of N kg^{-1} soil to kg N ha^{-1}.

Calculation

Cumulative N_2O emissions (direct soil-to-atmosphere) from each plot were calculated using trapezoidal integration of daily measured N_2O fluxes using the following equation (Venterea, 2013).

$$\text{Cumulative } N_2O \text{ emission (z)} = \sum_i^n \frac{X_i + X_{i+1}}{2} \, (t_{i+1} - t_i) \qquad \text{(Eq 2.1)}$$

where, *Xi* is the N_2O-N flux measurement on day *t*, *Xi+1* is the succeeding N_2O-N flux measurement on day *ti+1* and n is the final date of N_2O-N flux measurement.

Cumulative NH_3 volatilization loss (kg N ha^{-1}) was determined by summing the amount of NH_3 volatilized during each sampling period throughout the growing season. Total residual nitrogen in soil (kg N ha^{-1}) was determined by summing the amount of residual N at each depth.

Statistical analysis

The effect of different N treatments and cultivars and their interaction effect on NH_3 volatilization N_2O emission and residual soil NO_3^- were determined using a factorial randomized complete block design model. The means of the parameters were analyzed separately for each year using analysis of variance (ANOVA) in R 3.2.0. For each response (NH_3 volatilization N_2O emission and residual soil NO_3^-), the validity of model assumptions (normal distribution, constant variance, and independence of the error terms) were verified by examining the residuals as described in Montgomery (2013). When violated, appropriate (log or reciprocal) transformation was applied to the response measurements, but the means reported in the tables and in figures were back-transformed to the original scale to facilitate easier interpretation. If any effect was significant on the responses, the multiple means comparison was done using Fisher's least significant difference (LSD) at the 5% level of significance ($P<0.05$).

Results and discussion

Environmental conditions and irrigation

Environmental conditions and irrigation are discussed in Chapter 1.

Ammonia volatilization

In 2015, N treatment × cultivar interaction had significant effect on NH_3 volatilization during most of the sampling days except for June 15th and July 30th (Fig 2.1.). For all the cultivars NH_3 volatilization tremendously increased with UreaSplit treatment compared

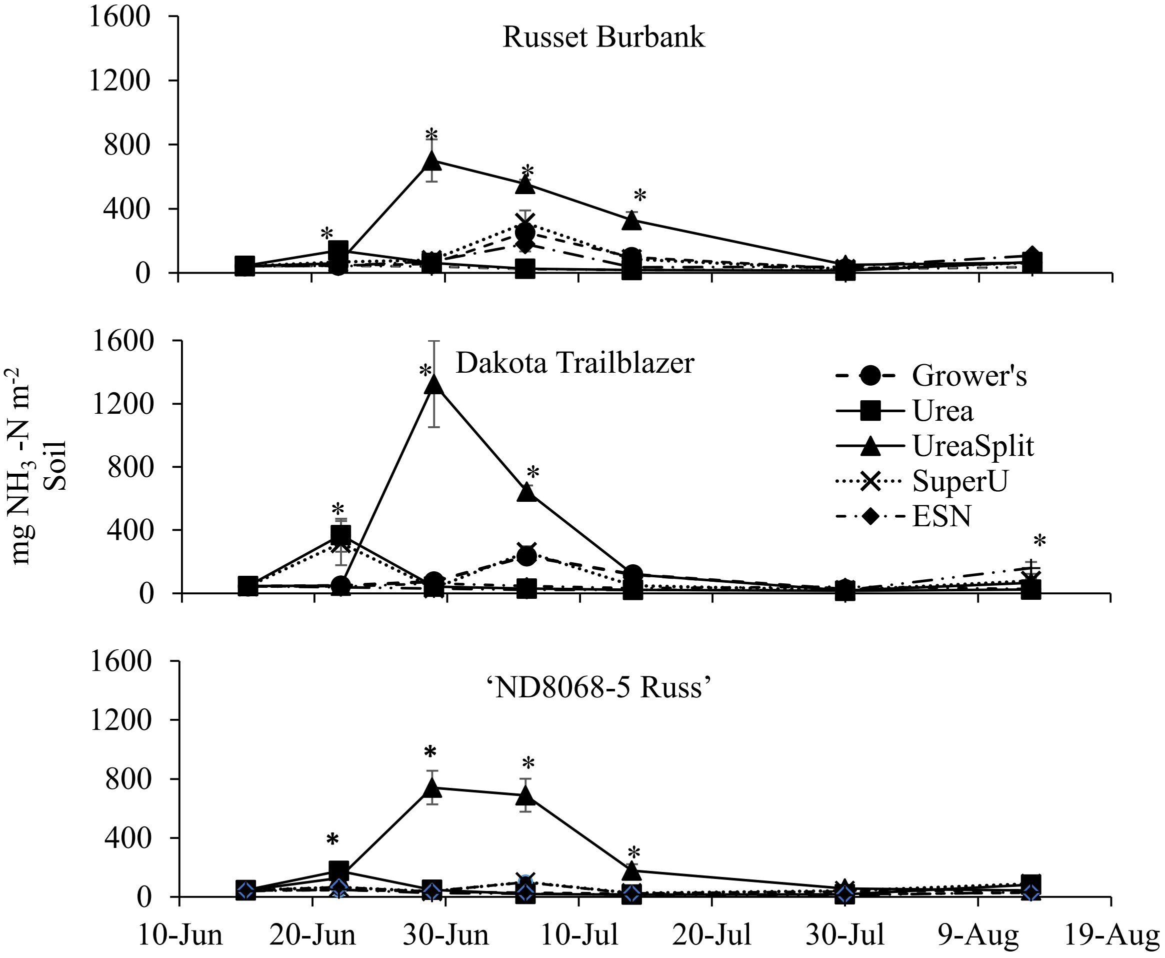

Fig 2.1. Ammonia volatilization loss (mg NH_3-N m^{-2}) measured on each sampling date in 2015 growing season under three cultivars ('Russet Burbank', 'Dakota Trailblazer', 'ND8068-5 Russ') with different N sources (Grower's standard, Urea, UreaSplit, SuperU, ESN and Control). Ammonia volatilization on each sampling day shows the total ammonia volatilized from previous day of sampling to that day of sampling. Vertical bars represent the standard errors (n=3). * indicates significant effect of N treatments ($P < 0.05$) on that particular day of sampling.

to other N treatments from June 29 to July 14 (Fig 2.1.). This increase can be attributed to the second split application of the treatment (168 kg N ha^{-1}) at hilling (June 25) and the higher soil temperature during this period (Fig 1.1.). Ammonia volatilization with ESN was low during the whole sampling period while NH_3 volatilization with SuperU and Grower's standard increased after June 29 (Fig 2.1.). The peak of NH_3 volatilization with Urea treatment was observed earlier (June 22) compared to other treatments but remained lower during the rest of the sampling period (Fig 2.1.). In 2016 also a significant N treatment × cultivar interaction effect on NH_3

volatilization was observed during most of the sampling days (Fig 2.2.). Ammonia volatilization tremendously increased with UreaSplit treatment compared to other N treatments after second split application of the treatment (168 kg N ha^{-1}) at hilling (June 20) (Fig 2.2.). Volatilization loss in 'Russet Burbank' cultivar was higher compared to In 'ND8068-5 Russ' cultivar NH_3 volatilization with ESN treatment increased significantly over control from July 5 to August 5 (Fig 2.2.). Peak volatilization for all N treatments were observed during July 5.

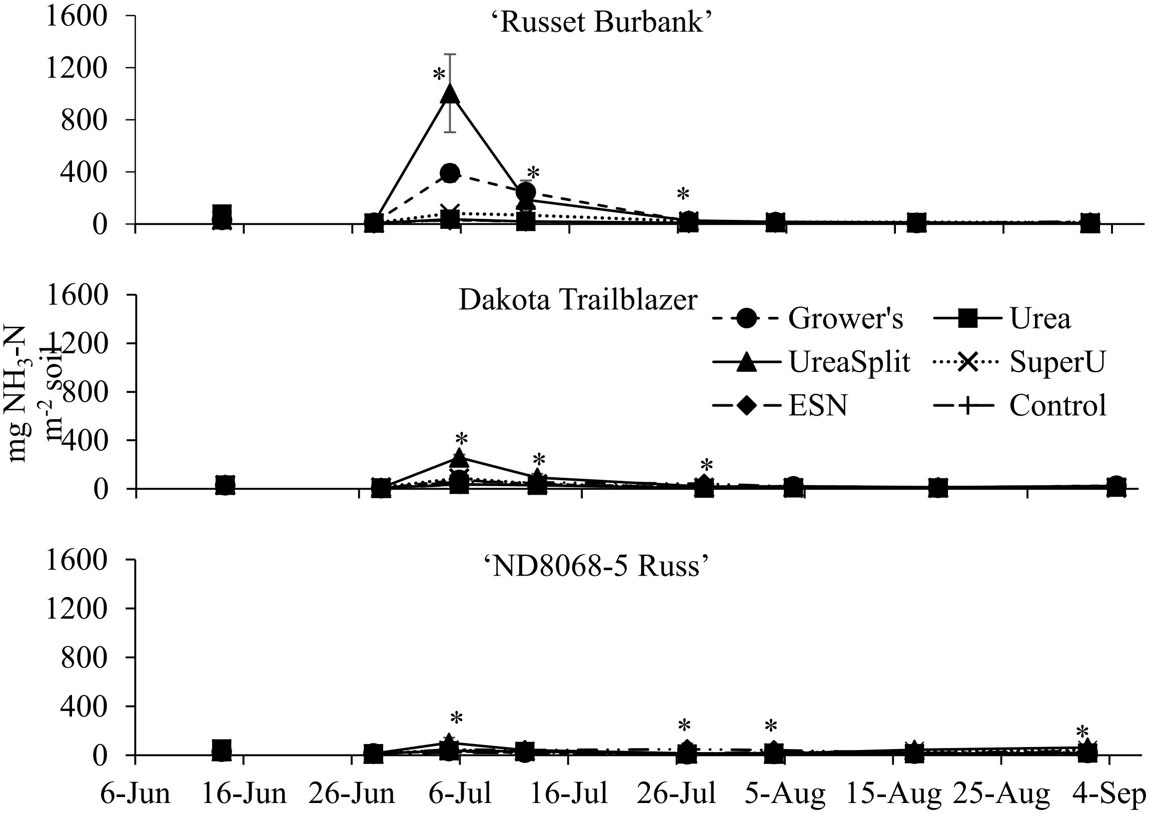

Fig 2.2. Ammonia volatilization loss (mg NH_3-N m^{-2}) measured on each sampling date in 2016 growing season under three cultivars ('Russet Burbank', 'Dakota Trailblazer', 'ND8068-5 Russ') with different N treatments (Grower's standard, Urea, UreaSplit, SuperU, ESN and Control). Ammonia volatilization on each sampling day shows the total ammonia volatilized from previous day of sampling to that day of sampling. Vertical bars represent the standard errors (n=3). * indicates significant effect of N treatments ($P < 0.05$) on that particular day of sampling.

In 2015, N treatments and cultivars significantly influenced cumulative NH_3 volatilization, but no significant interaction between N treatments × cultivars was observed (Table 2.1.). UreaSplit, SuperU and Grower's treatments increased cumulative NH_3 volatilization significantly over control while cumulative NH_3 volatilization with Urea and ESN was statistically similar to control. With UreaSplit treatment cumulative NH_3 volatilization was maximum (20 kg ha^{-1}) and significantly higher than all other treatments. In 2016, cumulative NH_3 volatilization was significantly influenced by main effects of N treatment, cultivars and the N treatment × cultivar interaction effect (Table 2.1.). Across all cultivars, only Grower's standard and UreaSplit treatments significantly increased cumulative NH_3 volatilization over control (Table 2.1.). In 'Russet Burbank' only UreaSplit and Grower's treatment significantly increased cumulative NH_3 volatilization over control and cumulative NH_3 volatilization with EEFs were statistically similar to control (Table 2.2.). In 'Dakota Trailblazer', only UreaSplit significantly increased cumulative NH_3 volatilization over control. In 'ND8068-5 Russ', contrasting to other two cultivars, only ESN increased cumulative NH_3 volatilization

Table 2.1. Effect of N treatments and cultivars on cumulative NH_3 volatilization (kg N ha^{-1}) and N_2O-N emission (kg N ha^{-1}) in two growing seasons of 2015 and 2016

	Cumulative emissions (kg ha^{-1})			
Source of Variation	NH_3-N		N_2O-N	
N treatments	2015	2016	2015	2016
Grower's	6.07 (0.86) [ϕ]b[†]	4.14 (0.95)b	2.28 (0.29)c	2.53 (0.15)b
Urea	3.54 (0.23)c	2.13 (0.17)c	2.93 (0.28)a	1.74 (0.09)c
UreaSplit	20.0 (1.42)a	7.28 (1.66)a	2.72 (0.18)ab	2.95 (0.31)a
SuperU	5.97 (0.77)b	2.61 (0.28)c	1.37 (0.08)d	1.72 (0.15)c
ESN	3.53 (0.47)c	2.59 (0.40)c	2.36 (0.18)bc	2.02 (0.14)c
Control	2.45 (0.29)c	1.84 (0.13)c	0.69 (0.06)e	0.33 (0.01)d
Cultivar				
'Russet Burbank'	6.97 (1.30)ab	4.82 (1.11)a	2.39 (0.26) a	1.81 (0.23)ab
'Dakota Trailblazer'	8.10 (1.80)a	2.73 (0.30)b	2.13 (0.23) a	1.76 (0.17)b
'ND8068-5 Russ'	5.70 (1.45)b	2.76 (0.22)b	1.67 (0.17) b	2.07 (0.27)a
	Analysis of variance			
N treatment	***	***	***	***
Cultivar	**	***	***	*
N treatment X Cultivar	NS	***	NS	***

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. NS is non-significant

[ϕ] Parenthesis include standard error (n=9 for treatment, n=18 for cultivar)

[†] Values followed by the same letter in each column are not significantly different

Table 2.2. Interaction effect of N treatments and cultivars on cumulative NH_3 volatilization (kg N ha^{-1}) and N_2O-N emission (kg N ha^{-1}) in 2016 growing season

N Treatments	NH_3-N kg/ha			N_2O-N kg/ha		
	Russet Burbank	Dakota Trailblazer	ND8068-5 Russ	Russet Burbank	Dakota Trailblazer	ND8068-5 Russ
Grower's	7.76 (0.97)b[†]	2.59 (0.24)b	2.08 (0.18)b	2.50 (0.18)ab	2.45 (0.27)a	2.63 (0.41)b
Urea	2.19 (0.14)c	1.70 (0.13)b	2.51 (0.36)ab	1.59 (0.15)cd	1.87 (0.13)b	1.75 (0.22)c
UreaSplit	13.27 (2.25)a	5.10 (0.59)a	3.49 (0.54)ab	3.10 (0.26)a	1.89 (0.21)b	3.86 (0.31)a
SuperU	2.69 (0.66)c	2.31 (0.45)b	2.83 (0.47)ab	1.21 (0.12)d	2.12 (0.14)ab	1.83 (0.18)c
ESN	1.46 (0.15)c	2.76 (0.46)b	3.56 (0.72)a	2.17 (0.42)bc	1.88 (0.18)b	2.01 (0.09)bc
Control	1.53 (0.14)c	1.90 (0.06)b	2.07 (0.32)b	0.30 (0.01)e	0.35 (0.04)c	0.34 (0.01)d

[ϕ] Parenthesis include standard error (n=3)

†Values with at least one letter in common in each column are not significantly different

significantly over control. This difference might be because the slow release of N from ESN did not match with the N uptake pattern of the early maturing cultivar ‘ND8068-5 Russ’. Rosen et al. (2013) reported that most of the N from ESN is released 60-80 days after application while the ‘ND8068-5 Russ’ is a 90 day cultivar. The ‘Dakota Trailblazer’ responses varied over the years, but in both years cumulative NH_3 volatilization with determinate ‘ND8068-5 Russ’ were significantly lower compared to indeterminate cultivar ‘Russet Burbank’. The early germination, growth and early uptake of the ‘ND8068-5 Russ’ might have reduced the NH_3 volatilization. However, the different response of the ‘Dakota Trailblazer’ cultivar over the years could not be explained.

Although NH_3 volatilization from irrigated potato fields has not been quantified in North Dakota or Northern Great Plains, considering other research works, NH_3 volatilization from our research field in both growing season seems quite low. Cumulative NH_3 volatilization loss in two growing season ranged from a minimum of 0.13% (Urea treatment in 2016) to 6.27% (UreaSplit treatment in 2015) of the applied fertilizer. Liu et al. (2007) reported NH_3 volatilization loss up to 25.7% of the applied fertilizer in four potato growing coarse textured soils of Washington and Florida. Soares et al. (2012) reported 17-44% of the applied Urea fertilizer along with urease inhibitor or nitrification inhibitor or both were lost through NH_3 volatilization in a potato production system in Brazil. Bayrakli and Gezgin (1996) also reported 7.0 to 23.6 % of the N applied through amended Urea fertilizer was lost through NH_3 volatilization in Turkey. Comparatively lower NH_3 loss in our study might be due to the occurrence of rainfall or irrigation following N fertilization. Jantalia et al. (2012) reported that irrigating the fields the day following fertilization could significantly limit NH_3 loss from urea-based fertilizers to < 4%. Zaman et al. (2013) also suggested applying irrigation water soon after urea application to wash the applied urea from surface soil to minimize the risk of NH_3 volatilization. In 2016, NH_3 volatilization was even lower than 2015 because rainfall after first and second fertilizer doze application in 2016 was higher than that in 2015. Besides that, we have lost one data point in 2016 due to thunderstorm which might have underestimated the total NH_3 volatilization. Several researchers (Jantalia et al., 2012; Kim et al., 2012; Zaman et al. 2009) reported that urea applied with both urease and nitrification inhibitor reduces NH_3 volatilization compared to urea alone. Our results also suggest that the inhibitory effect of SuperU on NH_3 volatilization loss was associated with the presence of urease inhibitor, NBPT, which slowed down urea hydrolysis during the initial days following fertilization. The effect of polymer coated urea in reducing NH_3 volatilization is variable. Laboratory incubation project conducted by Hopkins (2016) in Idaho, USA and Blaise and Prasad (1995) in Freising, Germany on potato growing soils showed that polymer coated urea significantly reduced NH_3 volatilization compared to urea while Zavaschi et al. (2014) in Brazil reported no effect of polymer coated urea in reducing NH_3 volatilization. A meta-analysis by Pan et al. (2016) showed that split application of N fertilizer had no effect on mitigating NH_3 volatilization. In our study we observed that urea applied @ 280 kg N ha^{-1} in split had the maximum NH_3 volatilization while urea applied @ 225 kg N ha^{-1} had a very low NH_3 volatilization loss. Tian et al (1998) also suggested that increase in N application rate significantly increased NH_3 volatilization. However, with Grower's treatment, where N was applied in three splits, again reduced NH_3 volatilization compared to UreaSplit. Three split application of N with band placement of 10-34-0 at planting followed by Urea broadcast at hilling and Urea Ammonium Nitrate (UAN) through fertigation at tuber initiation/flowering stage might have helped reducing the NH_4^+ accumulation and subsequent NH_3 volatilization Grant et al. (1996) and Grant and Brandon (2004) also reported reduction in NH_3 volatilization with band application of N fertilizer and UAN application through fertigation compared to surface applied urea.

Nitrous oxide emission

In two consecutive growing seasons, N fertilizer application significantly increased N_2O emission compared to control (Fig 2.3. and Fig 2.4.). This is consistent with previous studies (Burton et al., 2008; Ruser et al., 2001; Smith et al., 1998) in potato production systems. In 2015, significant N treatment and cultivar interaction effect on N_2O emission were observed during most of the sampling days except for June 15, August 5 and September 9 (Fig 2.3.). In 2016, significant N treatment and cultivar interaction effect on N_2O emission were observed in all sampling days except for June 9 and September 2 (Fig 2.4.). In 2015, in all cultivars, N_2O emission from all N treatments attained their maximum during July (Fig 2.3.) and similar to that in 2016, the maximum emissions were observed during July to early August (Fig 2.4.). This phenomenon can be attributed to the increased available N concentration in soil (Appendix figures) coupled with maximum rainfall and irrigation application during July-August, which might have created favorable condition for N_2O emission through both nitrification and denitrification (Clayton et al., 1997; McSwiney and Robertson, 2005; Weitz et al., 2001).

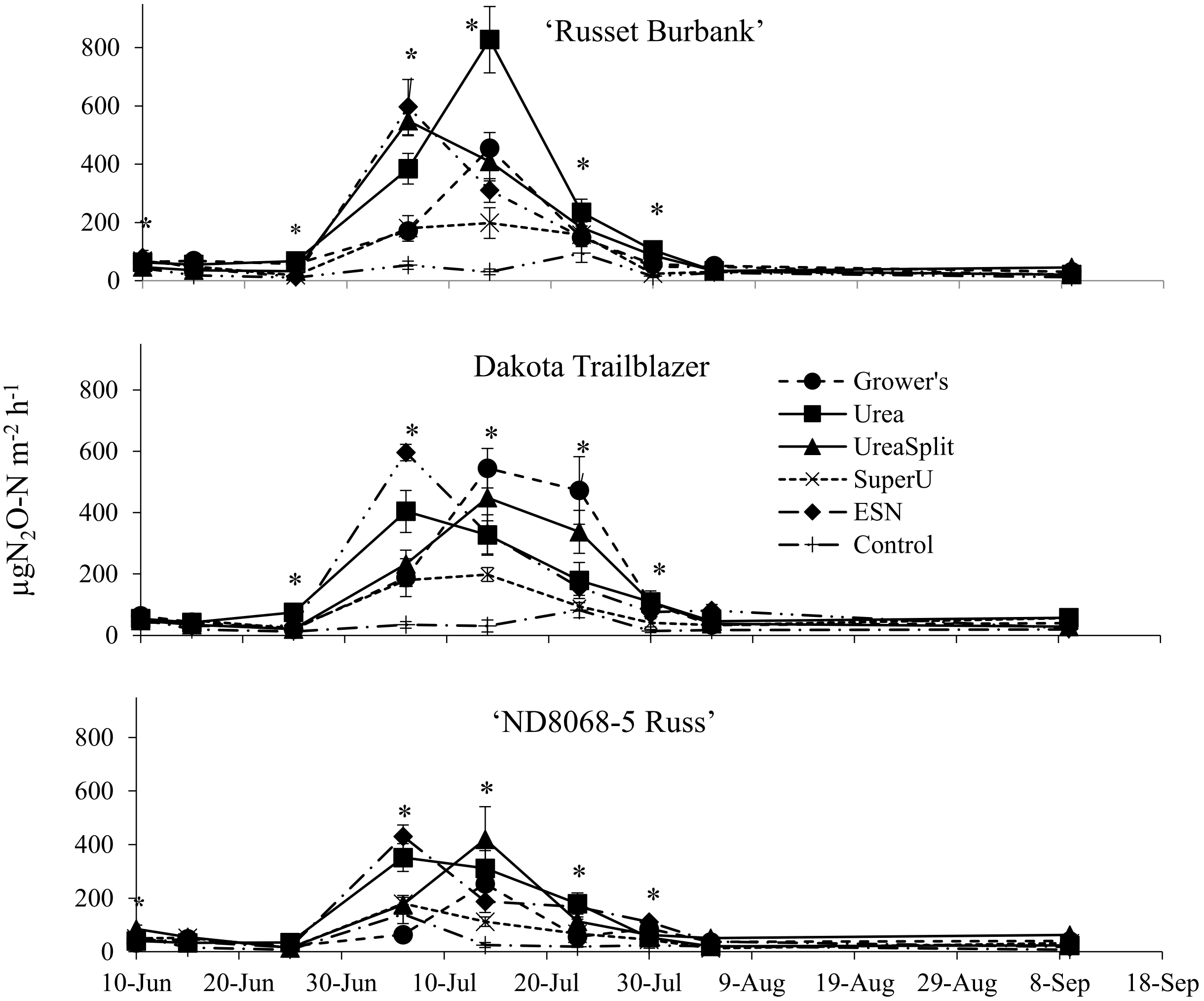

Fig 2.3. Nitrous oxide fluxes (μg N_2O-N m^{-2} h^{-1}) measured on each sampling date in 2015 growing season under three cultivars ('Russet Burbank', 'Dakota Trailblazer', 'ND8068-5 Russ') with different N treatments (Grower's standard, Urea, UreaSplit, SuperU, ESN and Control). Vertical bars represent the standard errors (n=3). * indicates significant effect of N treatments ($P < 0.05$) on that particular day of sampling.

In 2015, N_2O emission from SuperU remained lower compared to other N treatments throughout the sampling period (Fig 2.3.). Unlike 2015, in 2016 N_2O emission with Urea treatment remained low throughout the sampling period (Fig 2.4.). In 2016, the trend of N_2O

emission under ‘Dakota Trailblazer’ cultivar was quite different than the other two cultivars. In ‘Dakota Trailblazer’, although the peak emissions from the N treatments were lower compared to that in other two cultivars, but all N treatments had similar peak emission at different times of the sampling period (Fig 2.4.).

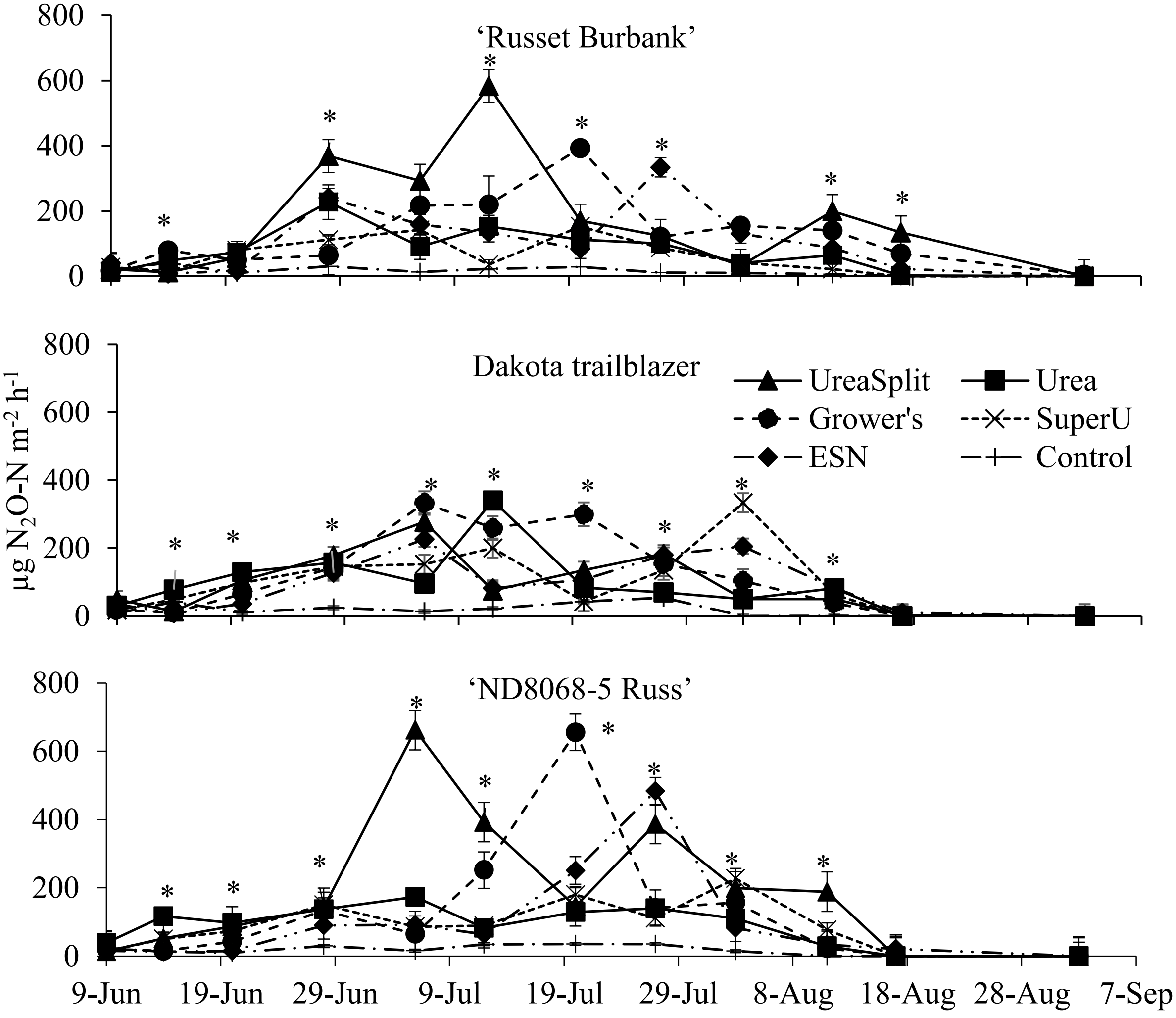

Fig 2.4. Nitrous oxide fluxes (µg N_2O-N m^{-2} h^{-1}) measured on each sampling date in 2016 growing season under three cultivars (‘Russet Burbank’, ‘Dakota Trailblazer’, ‘ND8068-5 Russ’) with different N treatments (Grower’s standard, Urea, UreaSplit, SuperU, ESN and Control). Vertical bars represent the standard errors (n=3). * indicates significant effect of N treatments ($P < 0.05$) on that particular day of sampling

Effect of cultivars on N_2O emission in both years were also different (Fig 2.3. and Fig 2.4.), which might be due to the physiological differences among the cultivars. From our observation, ‘Russet Burbank’ and ‘Dakota Trailblazer’ vines were longer compared to ‘ND8068-5 Russ’ cultivar. ‘Russet Burbank’ vines are comparatively erect while ‘Dakota Trailblazer’ vines were crawling type providing more ground cover. Higher vegetative growth facilitates greater water uptake and transpiration, while the greater ground cover may alter the diurnal temperature variation in surface soil. Schindlebacher et al. (2004) showed that N_2O flux increases with increase in both soil moisture and temperature and soil to air N_2O flux depends upon a complex interaction between N_2O production and gas diffusion. Haile-Mariam et al. (2008) mentioned that crop canopy infrastructure can significantly influence N dynamics in soil by regulating the N uptake pattern and sunlight deflection, which controls the substrate availability for nitrification and denitrification. Burton et al. (2008) also stated that, differences in relative magnitudes of N_2O emission emphasizes the role of different environmental factors such as substrate availability, water filled pore space (WFPS), temperature and N_2O to N_2 conversion rate etc. on N_2O release from soil to air. As the effects of the cultivars were variable in two growing season, evaluation of the cultivars needs further investigation.

In two year’s growing period, cumulative N_2O-N loss with N fertilization in our study ranged from 1.37 to 2.95 kg ha^{-1}. This value is consistent with Hyatt et al., 2010, who previously reported N_2O-N loss monitored over similar period of time in Northern Great Plains irrigated potato system. Burton et al. (2008) reported a lower N_2O-N loss (0.6 to 2.0 kg ha^{-1}) over a longer monitoring period (~200 d) in rain-fed potato production system in Fredericton, Canada, which suggests irrigation triggers N_2O emission through denitrification. Although in both years, all N treatments increased N_2O emission significantly over control (Table 2.1.), N_2O emission pattern was quite different in two growing seasons. In 2015, cumulative N_2O emission was significantly influenced by direct effects of N treatments and cultivars, while a significant N treatment × cultivar interaction effect on cumulative N_2O emission was observed in 2016 (Table 2.1.). In 2015, Maximum N_2O-N loss was observed from Urea (2.93 kg ha^{-1}) followed by UreaSplit treatment (2.72 kg ha^{-1}). Grower's standard and EEFs significantly reduced N_2O-N loss compared to urea fertilizer (Table 2.1.). In 2016, maximum N_2O-N loss in 'Russet Burbank' and 'ND8068-5 Russ' were observed with UreaSplit (3.10 and 3.86 kg ha^{-1}, respectively) followed by Grower's standard (2.50 and 2.63 kg ha^{-1}) while in 'Dakota Trailblazer' maximum N_2O-N loss occurred with Grower's standard (2.45 kg ha^{-1}) followed by SuperU (2.12 kg ha^{-1}) (Table 2.2). Across all cultivars, in 2015, SuperU significantly reduced N_2O emission compared to ESN and in 2016, averaged across cultivars there is a trend of lower N_2O emission from SuperU than ESN, although cumulative emissions were not statistically significant (Table 2.1.). This observation suggests that inhibition of urea hydrolysis and nitrification in SuperU treatment was more effective in reducing N_2O emission than the physical slow release mechanism in ESN where nitrification does not limit the substrate availability (NO_3^-) for denitrification (Maharajan et al., 2014).

Below root zone nitrate concentration

In 2015 the samples obtained from the lysimeters were extremely irregular. The amount of water collected each time under same treatment or two adjacent plots were also variable. So, maximum soil waster nitrate concentration from each plot in each month was recorded. We inferred that the slope, the variability in field hydrology and low water availability in coarse sandy loam soil created this irregularity in sample availability (Lord and Shepherd, 1993). Although ceramic cup lysimeters are used as the most common, cost-effective and universally used method for in situ collection of ambient soil water at different depths with minimal disturbance of the soil (Creasey and Dreiss, 1988; Lajtha et al., 1999; Weihermuller et al., 2007), high spatial and temporal variability may underestimate the solute concentration (Curley et al., 2011). Zotarelli et al. (2007) reported that, irrespective of irrigation and N treatments, NO_3-leaching measured by ceramic suction cup lysimeter was significantly lower compared to the measurement with drainage lysimeter or soil coring method. Our research plot did not have the infrastructure of drainage lysimeter and in season soil coring was also not feasible in the cropped field. So in 2016, we reduced the depth of lysimeter insertion from 0.9 to 0.6 m (Cambouris et al., 2008) as well as increased the time interval between two consecutive sampling (two weeks) to collect sufficient sample. However, the regularity in availability of samples did not improve in 2016. Other than that, in 2015, hilling up the rows two weeks after planting was difficult with the lysimeters already inserted in the plots, so in 2016, we installed the lysimeter after hilling.

In 2015 and 2016 growing season, the maximum below root zone NO_3^- concentration ranged from 0 to 53.77 and 0 to 83.05 mg NO_3^-N L^{-1} of water, respectively. Maharajan et al. (2014) also reported < 1 to 63 mg NO_3-N L^{-1} water at 1.2 m depth in a loamy sand soil. In 2015, most of the NO_3^- leaching occurred in July and reduced to negligible amount in August (Fig 2.5.). The maximum availability or mineralization of fertilizer N coupled with of maximum available water through rainfall and irrigation during the period resulted maximum leaching of NO_3^- below root zone (Maharajan et al., 2014; Wilson et al., 2010; Zvomuya et al., 2003). In 2016, NO_3^- concentration below root zone was considerably higher during August and September. Overall, the below root zone NO_3^- concentration was higher in 2016 compared to 2015 (Fig 2.5. and Fig 2.6.). We inferred that, firstly, due to lower depth of soil water extraction

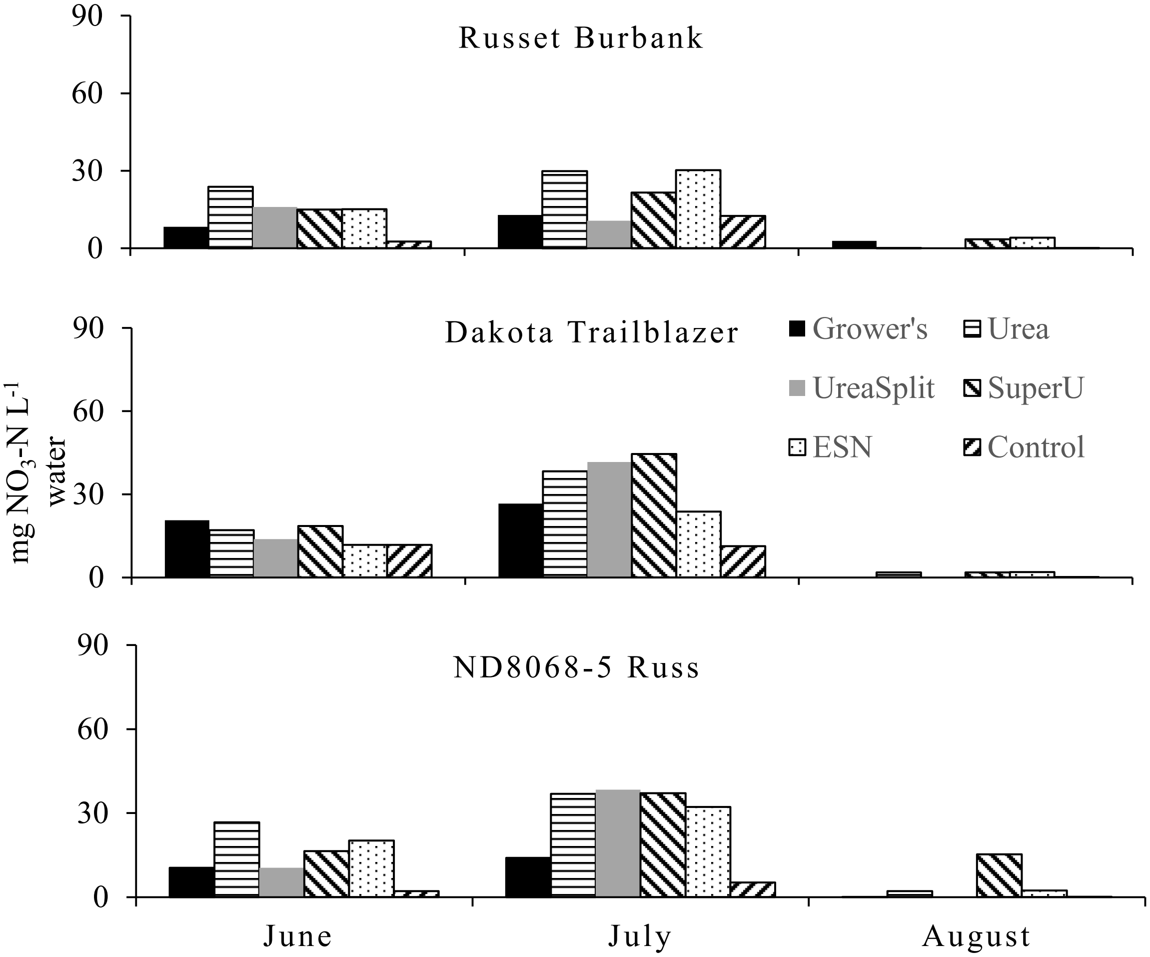

Fig 2.5. Soil water nitrate concentration (mg NO_3-N L^{-1}) below root zone (0.9 m) in 2015 growing season under three cultivars ('Russet Burbank', 'Dakota Trailblazer', 'ND8068-5 Russ') with different N treatments (Grower's standard, Urea, UreaSplit, SuperU, ESN and Control).

in 2016 growing season (0.6 m), the soil water NO_3^- concentration might have been higher in the months of August and September, while in 2015 the solute (NO_3^-) could not reach to the depth of 0.9 m. Secondly, a heavy flush of rain in early September might have increased the below root zone NO_3^- concentration in 2016 (Fig 1.1.). Wilson et al. (2010) also reported increased NO_3^- leaching with high rainfall fluxes in an irrigated potato production system. Nitrate leaching increases significantly with a single rainfall even of greater pulse than a few rainfall or irrigation events of smaller pulse (Yahdjian and Sala, 2010). Overall, the lower values of below root zone

NO_3-N concentration in 2015 than 2016 are also reflected in the lower residual N in soil data (Table 2.3.).

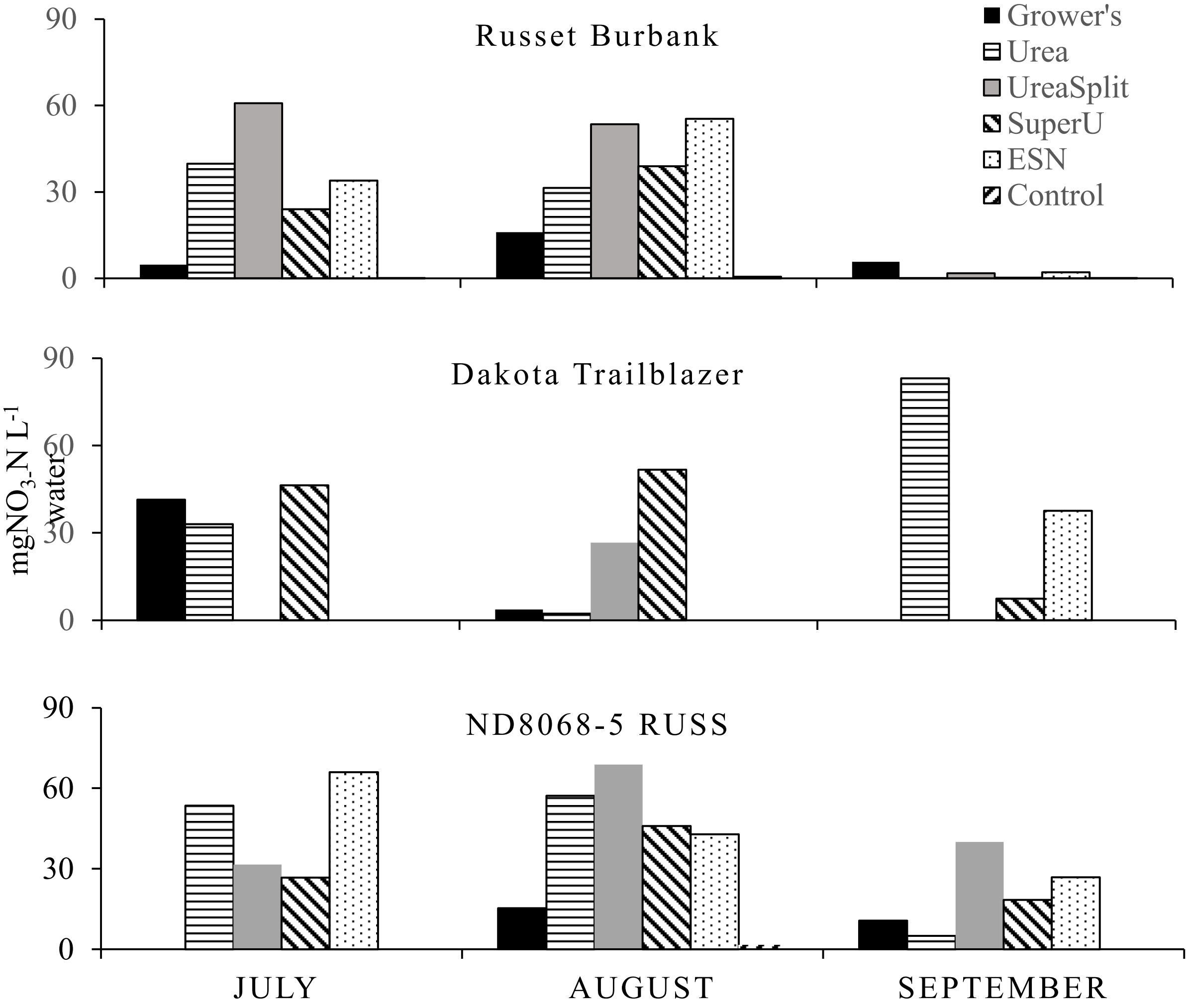

Fig 2.6. Soil water nitrate concentration (mg NO_3-N L^{-1}) below root zone (0.6 m) in 2016 growing season under three cultivars ('Russet Burbank', 'Dakota Trailblazer', 'ND8068-5 Russ') with different N treatments (Grower's standard, Urea, UreaSplit, SuperU, ESN and Control).

Residual soil nitrate (0-120 cm depth)

A Hydrus 1D simulation model run with all the experimental conditions and weather parameter in the experimental site showed that the NO_3^- leaching below 150 cm depth over the growing season is negligible (data not shown). So, the estimation of residual available NO_3^- after

Table 2.3 Effect of N treatments and cultivars on residual soil nitrate (0-120 cm) after harvest in two growing seasons (2015, 2016)

	Residual NO_3-N in soil (kg ha^{-1})	
N treatments	2015	2016
Grower's	43.3 (1.33)[ϕ]b[†]	59.6 (10.7)a
Urea	26.0 (2.58)c	37.2 (5.27)bc
UreaSplit	39.7 (3.94)b	52.6 (7.36)ab
SuperU	74.2 (1.74)a	66.2 (14.1)a
ESN	22.2 (1.53)cd	53.4 (6.85)ab
Control	14.7 (0.91)d	26.4 (2.60)c
Cultivar		
Russet Burbank	29.4 (3.79)b	34.6 (3.62)c
Dakota Trailblazer	41.2 (6.42)a	50.1 (3.66)b
ND 8068-5 Russ	39.4 (5.48)a	63.0 (9.34)a
	Analysis of Variance	
N treatment	***	***
Cultivar	***	***
N treatment X Cultivar	**	*

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[ϕ] Parenthesis include standard error

[†] Values followed by the same letter in each column are not significantly different

harvest through soil coring method can give an estimate of potential available NO_3^- loss over the growing season.

In both years 2015 and 2016, a significant N treatment × cultivar interaction effect on residual available NO_3^- in soil was observed (Table 2.3.). In 2015, in all cultivars SuperU and Grower's standard significantly increased the residual available NO_3^- in soil profile compared to control while ESN and Urea did not (Table 2.3.). In 2015 UreaSplit increased residual available NO_3^- significantly over control with 'Russet Burbank' and 'ND8068-5 Russ'. In 2016, with 'Dakota Trailblazer' cultivar, all N fertilizer addition similarly increased residual available NO_3^- in soil profile (Table 2.4.). For 'ND8068-5 Russ', Grower's standard and SuperU significantly increased residual available NO_3^- over control but other N fertilizer treatments did not (Table 2.4.). For 'Russet Burbank', only SuperU significantly increased residual available NO_3^- over control (Table 2.4.). Averaged across cultivars, all N fertilizer treatments except Urea

Table 2.4. Interaction effect of N treatments and cultivars on residual (0-120 cm) soil nitrate (kg NO_3-N ha^{-1}) after harvest in two growing seasons (2015, 2016)

	2015			2016		
N Treatments	Russet Burbank	Dakota Trailblazer	ND8068-5 Russ	Russet Burbank	Dakota Trailblazer	ND8068-5 Russ
Grower's	37.9 (2.31) [ϕ] b[†]	48.4 (10.4)b	43.5 (6.48)b	32.0 (7.51)ab	53.9 (4.42)a	93.0 (18.26)a
Urea	18.0 (4.47)c	34.7 (3.77)bc	25.2 (3.07)c	30.2 (6.25)ab	54.8 (4.84)a	26.4 (5.72)b
UreaSplit	40.8 (6.83)ab	30.4 (5.37)bc	47.8 (6.72)b	32.3 (8.21)ab	64.5 (9.23)a	61.1 (13.6)ab
SuperU	51.5 (3.01)a	90.9 (13.5)a	80.1 (4.85)a	49.3 (8.49)a	49.9 (6.42)a	99.5 (37.9)a
ESN	15.7 (2.64)c	24.8 (4.56)bc	26.2 (1.95)c	41.4 (14.1)ab	50.1 (11.12)a	68.6 (6.91)ab
Control	12.7 (1.57)c	18.1 (3.14)c	13.2 (2.04)c	22.6 (4.03)b	27.5 (3.55)b	29.2 (6.36)b

[ϕ] Parenthesis include standard error

[†] Values followed by the same letter in each column are not significantly different

increased residual available NO_3-N compared to control. Averaged across all N treatments, residual available NO_3^- under 'Russet Burbank' cultivar was significantly lower than the other two cultivars in both years (Table 2.3.). The residual available NO_3^- ranged from 12.7 to 90.9 kg ha^{-1} in 2015 and 22.6 to 99.5 kg N ha^{-1} in 2016. Several researchers (Errebhi et al., 1998; Gasser et al., 2002; Hill, 1986; Wilson et al., 2010; Zvomuya et al., 2003) reported NO_3-N loss ranging from 23.7 to 257 kg N ha^{-1} with soluble N fertilizer in irrigated potato system.

In both years (2015 and 2016) SuperU had the maximum residual available NO_3^- (74.2 and 66.2 kg N ha^{-1} respectively). This result is consistent with Gioacchini et al. (2002) who reported an increased NO_3^- leaching with urea amended with DCD and NBPT. The researchers suggested that the nitrification inhibitor (DCD) caused a priming effect by increasing NH_4^+ concentration in soil, which resulted a subsequent increase in the rate of soil organic matter mineralization. Besides that, we suspect that the slow release of NO_3^- and the increased release later in the growing season did not synchronize with the crop demand or uptake, which lead to leaching loss of unutilized NO_3^-. Reddy and Prasad (1975) also reported that unlike polymer coated urea, nitrification inhibitor can delay the mineralization more than 4 weeks after application, which may increase NO_3^- build up in later growing season.

In 2015, ESN significantly reduced residual available NO_3^- compared to unamended urea (UreaSplit), Grower's standard and SuperU (Table 2.3.). Similar to our observation, Wilson et al. (2010) reported a reduced NO_3^- leaching loss (23.4 kg N ha^{-1}) with an emergence application of ESN in irrigated potato production system. Several researchers (Errebhi et al., 1998; Prunty and Greenland, 1997) suggested that application of majority of the N fertilizer after emergence of potatoes helps reducing NO_3^- leaching. Urea treatment significantly reduced residual available NO_3^- compared to UreaSplit, Grower's standard and SuperU in both years (Table 2.3.). The increase in residual NO_3^- in profile after harvest with increased N rate suggests that with soybean as a previous crop 280 kg N ha^{-1} might be an excessive application of N fertilizer as no yield tuber yield benefit was also not found (Chapter 1).

Conclusions

The results from this experiment indicated that most of the NH_3 volatilization from unamended urea occur very early in the season and volatilization from UreaSplit treatment peaked after second split application at hilling. Ammonia volatilization from EEFs may increase in the mid-season because of slower mineralization, especially in determinant cultivars. In both years, UreaSplit treatment increased NH_3 volatilization tremendously. So, when applied at the same rate (280 kg N ha^{-1}), UreaSplit and Grower's standard significantly increased the cumulative NH_3 volatilization in both years. The 'Dakota Trailblazer' responses varied over the years, but in both years cumulative NH_3 volatilization with determinate 'ND8068-5 Russ' was lower compared to indeterminate cultivar 'Russet Burbank'. The rainfall after fertilizer application and irrigation application possibly helped reducing the NH_3 volatilization compared to previous reports.

Nitrous oxide emission with N fertilizer application attained the peak when available N concentration in soil was maximum coupled with maximum water availability through rainfall and irrigation. Vine type and ground cover significantly influenced N_2O emission, but the responses were different in two years and the conclusive explanations need more investigation. When applied at the same rate (280 kg N ha^{-1}) EEFs significantly reduced cumulative N_2O emission compared to urea. The inhibition of urea hydrolysis and nitrification in SuperU was more effective in reducing N_2O emission compared to the controlled release mechanism of ESN.

The below root zone NO_3^- concentration was maximum during the period of maximum availability or mineralization of fertilizer N coupled with maximum available water through rainfall and irrigation. Greater rainfall pulses increased the below root zone NO_3^- concentration, which suggests that even in irrigated potato production system rainfall intensity controls the NO_3^- leaching. Residual NO_3-N concentration up to 120 cm depth hugely increased with Grower's standard, UreaSplit and SuperU in both years. In 2015, ESN was successful in reducing residual NO_3-N concentration or NO_3^- leaching compared to other N treatments of same rate (280 kg N ha^{-1}), but in 2016 it could not reduce NO_3^- leaching. SuperU lead to maximum N leaching in both years, which suggests urease and nitrification inhibitor application would not be advisable for irrigated potato cultivation. Urea treatment reduced NO_3^- leaching in both years as the easily mineralize N was uptaken by the crop during the growing season. With ‘ND8068-5 Russ’, NO_3^- leaching were significantly higher than ‘Russet Burbank’ in both the years, which suggests a different N management practice and fertilizer rate should be developed for early maturing cultivars. Root depth and root morphology investigation for cultivar types in further research may help in understanding the differences in NO_3^- leaching with cultivars. The largest part of the N fertilizer loss occurred through NO_3^- leaching similar to the previous studies. However, a better infrastructure and instrumentation is needed to properly estimate in-season NO_3^- leaching in this potato growing region.

From the results discussed in chapter 1 and 2, it can be concluded that ESN can be a smart choice to achieve better yield consistently with reduced N losses. SuperU did not have any yield benefit over unamended urea and grower’s standard practice and increased NO_3^- leaching excessively, so it should not be recommended for irrigated potato cultivation. A different fertilizer N rate and management program is needed to be developed for early maturing determinate cultivars in order to reduce N losses. In this region, soybean is commonly cultivated in rotation with potato as a previous crop. However, considering the recent studies in Idaho and Canada, it is better to avoid soybean or any legume crop before potato cultivation as the residue degradation rate is extremely variable and thus estimation of legume crop credit before fertilization is not accurate. In case of planting delays due to rainfall, target yield may not be achieved, but lower rate of fertilizer N for presumed shorter growing period may be useful to reduce N losses.

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CHAPTER 3. PETIOLE NITRATE, TOTAL PETIOLE NITROGEN AND VEGETATION INDICES FOR ESTIMATING N STATUS AND YIELD PREDICTION

Abstract

In season N status assessment in potatoes is necessary to develop the best N management practices and yield prediction. In 2015 growing season, only petiole NO_3-N concentration during growing period were measured twice for N status assessment. The yield prediction power of the petiole NO_3^- concentration was found very poor as the yield responses of N fertilization were not very prominent. In 2016, along with petiole NO_3-N concentration, total N concentration in petiole and vegetation indices (VIs) calculated from crop reflectance data measured with ground-based active optical sensor. Although total N concentration analysis is very time consuming, it could best explain the marketable yield variability ($r = 0.72$) at 42 DAP. Petiole NO_3^- concentration did not differ significantly with cultivars, but total N concentration in petioles were significantly different with cultivars. Yield variability of 'Russet Burbank' were best explained by total N concentration in petiole. Vegetation indices (especially NDRE) can be a useful tool for very quick assessment of early season N status and yield prediction.

Introduction

Increasing interest in potato production over the world introduced the need for yield enhancement, crop protection and better post-harvest management systems (Al-Gaadi et al., 2016). Prediction of tuber yield prior to harvest can be very useful for market and post harvest decision making (Al-Gaadi et al., 2016**;** Bowen et al., 1999; Šťastná et al., 2010; Travosso et al., 1996). Prediction of crop yield is associated with agronomic variables such as plant density, vigour, maturity, which can be used as yield indicators (Soria-Ruíz and Fernández-Ordoñez, 2003, and Al-Gaadi et al., 2016). After the naturally sufficiently available carbon, hydrogen and oxygen; nitrogen (N) is the most essential but limiting nutrient element that takes vital part in controlling photosynthesis, regulating plant growth and building up protective resistance in plant (Hoffland et al., 2000; and Sinfield et al., 2010). Potato plant growth, yield and quality are highly dependent on the adequate supply of N from soil (Errebhi et al., 1998a) and more specifically, plant N uptake is closely related to a relaistic yield potential for the selected cultivar and land farmed (Lang et al., 1999). Proper N management in potatoes is necessary to maximize or maintain yield with minimum loss and environmental hazards. Decision making for N fertilization and yield prediction for potato production in irrigated sandy soil is still in need of an appropriate diagnostic test because of the high temporal and spatial variability in soil N availability and poor correlation between soil N and yield has been reported in recent studies (Belanger et al., 2001; Cambardella et al. 1996; and Redulla et al., 2002). Integrating soil and plant analyses for fertilization recommendation had been common (Dow and Roberts, 1982; and Neetson and Zwetsloot, 1989**)** as **s**oil tests are generally unreliable on coarse-textured soils because of potential NO_3^- leaching prior to crop establishment (Vitosh, 1986). In contrast, petiole NO_3-N analysis has been shown to be a reliable index of the current N status of potatoes and is a sensitive indicator of N uptake throughout the growing season (Roberts et al., 1989). Doll et al. (1971) suggested that petiole may be more responsive than other plant parts to represent soil N availability and plant N uptake. Petiole NO_3-N levels has been reported to show larger ranges than total N levels in leaf blades, however, the wider range of nutrient concentrations observed in petioles is also associated with greater temporal variability as well as across years and cultivars of same species (Christensen, 1969, 1984; Cook and Kishaba, 1956).

Measurement of spectral reflectance from crop canopy through remote sensing has rrecently been widely used as a tool to monitor crop condition and to make an in-season estimates of crop yield and quality (Al-Gaadi et al., 2016; Huang et al., 2013; Hoffman and Blomber, 2004; Panda et al., 2010; Sivarajan, 2011). Healthy vegetation has high reflectance in near infrared (NIR)wavelength and low reflectance in red wavelength bands and stressed vegetation shows the opposite trend (Sivarajan, 2011). Vegetation indices (VIs) calculated from the spectral reflectance at NIR and red wavelengths i.e. normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI) etc. have been used by many researchers to determine the N status of vegetation and yield prediction (Al-Gaadi et al., 2016; Bala and Islam, 2009; Gat et al., 2000; Groten, 1993; Liu and Kogan, 2002; Rasmussen, 1997).

Although yield prediction requires long term measurement of different site-specific variables, our objective was to evaluate the correlation of different cost effective N-status measurements i.e. petiole NO_3^-, total N concentration in petiole, VIs (from hand-held crop reflectance sensor data) with yield and N uptake. In 2015, only conventional petiole NO_3^- level was estimated as N-status of crop measurement; but in 2016 along with petiole NO_3^-, total N concentration in petiole and VIs from spectral reflectance were also measured.

Materials and methods

Site description and experimental design were already described in Chapter 1.

Sampling and analyses

Petiole nitrate

Eight to ten youngest fully expanded leaf i.e. fourth or fifth leaf from the top were randomly collected from each experimental unit for petiole samples. In 2015, petiole samples were collected at 35 and 56 DAP while in 2016 petiole samples were collected at 42 and 72 DAP. Leaves were stripped off from the petioles immediately after collecting and petioles were dried at 65ºC temperature for three days. Dried petioles were grinded in a Wiley mill plant sample grinder. Petiole NO_3^- sample (around 0.1 g) was extracted with 25 mL of 2% acetic acid solution for 15 mins (Prasad and Spiers, 1984). The NO_3^- concentration in the aliquot was then estimated with using Timberline TL2800 Ammonia Analyzer (Timberline Instruments, CO, USA).

Total N in petiole

In 2016, total N in petiole samples were determined following the procedure described by Nelson and Somner (1973). Ground petiole sample (0.2 g) was weighed in a cigarette paper, placed in a Folin-Wu digestion tube and 5 mL of salicylic acid H_2SO_4 mixture (5.0 g salicylic acid per 200 mL of H_2SO_4) was added and kept overnight. After that, 1.1 g of a salt-catalyst mixture (10: 1 K_2SO_4 and $CuSO_4.5\ H_2O$ mixture by weight) and 0.5 g $Na_2S_2O_3.\ 5\ H_2O$ were added. The tube was swirled and the mixture was digested in the aluminum heating block at 300ºC. A small glass was placed in the mouth of the tubes for refluxing of the digestion mixture. The sample was digested until at least 60 mins past clearing. The digest is diluted to 50 mL with distilled water after cooling. The NH_4^+ in the aliquot (10 mL) was then determined by capturing the NH_4^+ in a 4% boric acid-mixed indicator solution through an alkaline steam distillation using 10 N NaOH followed by a titration with 0.005 N HCl. A blank was run following the same procedure.

$$\%\ \text{N sample} = \frac{(S-B)*\text{Normality of titrant}*1.4007*\text{dilution factor of aliquot}}{\text{weight of plant sample}} \qquad \text{(Eq 3.1)}$$

where S= mL of acid consumed for sample titration, B= mL of acid consumed for blank titration.

Ground based active optical sensor reflection and vegetation index

In 2016, optical reflectance from canopy were recorded twice (30 and 44 DAP) during the vegetative growth stage using a RapidSCAN CS-45 Handheld Crop Sensor (Holland Scientific Inc., Lincoln, Nebraska, USA). The sensors measure height independent absolute reflectance using polychromatic modulated light source and three photodetector measurement channels: 670 (red), 730 (red edge) and 780 (near infrared or NIR) nm. One of the center two rows of each experimental unit were scanned from 0.5 m above the crop canopy at each sampling day by walking along the furrow. Any consistent sampling after 44 DAP was not possible as vine growth impeded walking in stable pace and thus the reflectance measurement. Normalized difference vegetation index (NDVI) and red edge NDVI (NDRE) were calculated using the following formula

$$\text{NDVI}=\frac{NIR\ reflectance-Red\ reflectance}{NIR\ reflectance+Red\ edge\ reflectance} \qquad \text{(Eq 3.2)}$$

$$\text{NDRE}=\frac{NIR\ reflectance-red\ edge\ reflectance}{NIR\ reflectance+red\ edge\ reflectance} \qquad \text{(Eq 3.3)}$$

Satistical analysis

Pearson product-moment correlation analyses were performed using the PROC CORR procedure in SAS 9.4, to find if there is any significant linear relationship ($P< 0.05$) between petiole NO_3-N/ total N concentration/ crop vegetation indices (VI) and total yield/ marketable yield/ N uptake exist. Petiole NO_3-N, total N concentrations in petiole and VIs were analyzed using analysis of variance (ANOVA) for factorial randomized complete block design (RCBD) model in R 3.2.0 to test the effects of N treatments and cultivars and their interaction effect. For VIs, as significant N treatment × cultivar interactions were found, regression analyses using PROC REG procedure in SAS 9.4 for each cultivar were performed.

Results and discussion

In 2015, only petiole NO_3-N was estimated to observe plant N status and as a yield predictor variable. In 2016, along with petiole NO_3-N, total N in petiole and VIs from ground based optical sensor reflection were also measured.

Petiole nitrate

In 2015, on 35 DAP petiole NO_3^- concentration was significantly correlated with total tuber yield, tuber N uptake and Total N uptake (Table 3.1.). On 56 DAP, petiole NO_3^- concentration was significantly correlated with vine N uptake, tuber N uptake and total N uptake, but not yield (Table 3.1.). In 2015, the low response of N treatments on tuber yield might be the reason for poor correlation between tuber yield and petiole NO_3^-. In 2016, on 42 DAP, petiole NO_3^- concentration was significantly correlated with marketable tuber yield, vine N uptake, tuber N uptake (Table 3.1.). On 72 DAP, petiole NO_3^- concentration was significantly correlated to total tuber yield, marketable yield, vine N uptake, tuber N uptake and total N uptake (Table 3.1).

Table 3.1. Pearson product moment correlation coefficient for predicting yield and N uptake from in-season petiole nitrate concentration

	2015		2016	
	35 DAP	56 DAP	42 DAP	72 DAP
Yield (Mg ha^{-1})	0.47*	0.33^{NS}	0.36^{NS}	0.53*
Marketable Yield (Mg ha^{-1})	0.35^{NS}	0.26^{NS}	0.66**	0.70**
Vine N uptake	0.42^{NS}	0.70***	0.70***	0.73***
Tuber N uptake	0.65**	0.48**	0.57**	0.71***
Total N uptake	0.62**	0.81***	0.76***	0.84***

*, **, ***Significant at $P < 0{:}05$, $P < 0{:}01$, and $P < 0{:}001$, respectively. NS is non-significant

In 2015, both N treatment and cultivar influenced the petiole NO_3^- concentration on 35 DAP and only N treatment influenced the petiole NO_3^- concentration on 56 DAP (Table 3.2). In 2016, only N treatments significantly influenced the petiole NO_3- concentration on both sampling days (Table 3.2.). Our observation over two years agree with Vitosh (1996) who also showed that sap NO_3^- did not vary with different potato cultivars.

Table 3.2. Effect of N treatments and cultivars on petiole NO_3^- concentration (mg kg^{-1}) in 2015 and 2016 growing season

	2015				2016			
	35 DAP		56 DAP		42 DAP		72 DAP	
Grower's	24367	(1406)[ϕ] ab[†]	16376	(2152)a	13120	(1288)b	8755	(2186)ab
Urea	22425	(1535)b	10992	(1457)b	12672	(1097)b	4478	(1384)bc
UreaSplit	25965	(938)a	12273	(1643)ab	20419	(1454)a	8738	(1680)ab
SuperU	24964	(1297)ab	15076	(1729)ab	21090	(1085)a	8025	(1413)ab
ESN	24502	(890)ab	13772	(1834)ab	19082	(1555)a	10495	(1542)a
Control	4347	(751)c	2276	(693)c	2353	(880)c	2598	(18885)c
Russet Burbank	23018	(1823)a	11057	(1412)	14203	(2012)	7087	(1173)
Dakota Trailblazer	21573	(2176)a	14103	(1660)	16113	(2024)	9098	(1314)
ND8068-5 Russ	18694	(1847)b	10222	(1527)	14051	(1824)	5360	(1382)
	Analysis of variance							
N treatment	***		***		***		*	
Cultivar	***		NS		NS		NS	
N treatment × cultivar	NS		NS		NS		NS	

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. NS is non-significant

[ϕ] Parenthesis include standard error

[†]Values followed by the same letter in each column are not significantly different

In 2015, on 35 DAP, lower rate of urea (225 kg N ha^{-1}) treatment had comparatively lower NO_3^- concentration compared to higher rate of urea (280 kg N ha^{-1}) (Table 3.2). On 56 DAP, in Grower's standard treatment, the split application of N with UAN at tuber initiation might have increased the NO_3-N concentration in petiole, although was not significantly higher than the other N treatments with same rate of N (Table 3.2). In 2016, at 42 DAP (before UAN spray), Grower's standard and Urea had significantly lower petiole NO_3-N concentration compared to the other N treatments; but at 72 DAP (after UAN spray), only Urea had lower petiole N concentration compared to the other N treatments. Similar to our observation, Ziadi et al. (2011) reported no difference in N status in potatoes for different N fertilizer source. In both seasons petiole NO_3^- concentration in second sampling days decreased from the first sampling days expectedly. Kelling et al. (2011); Love et al. (2005); Porter et al. (1993) also reported a gradual decrease in petiole NO_3^- concentration throughout the sampling period.

In 2015, at 35 DAP petiole NO_3^- concentration in all N fertilizer treatments exceeded 22000 mg N kg^{-1} dry weight (Table 3.2), which indicates N sufficiency in plants. Porter et al. (1993) and Wescott et al. (1991); Stark et al. (2004); Westermann et al. (1994), reported that the average petiole NO_3-N sufficiency range during the tuber initiation to early bulking stage ranged from 13000-16000 mg kg^{-1} dry weight. At 56 DAP, all other N fertilizer except for Urea could maintain the critical limit (Table 3.2). Porter et al. (1993) reported that samples collected earlier than 45 DAP were N deficient according to N testing criteria, but contrastingly in our study we observed NO_3-N sufficiency at 35 DAP. Similar to our observation, Errebhi et al. (1998b) showed that NO_3^- sufficiency range 15 DAE with the sap NO_3 testing electrodes were around 1500 mg L^{-1} which corresponds to about 15000-20000 mg kg^{-1} dry weight. Kelling et al. (2011) also reported petiole NO_3^- concentration of 17000-20000 mg kg^{-1} at 33 DAE with 252 kg N ha^{-1} fertilizer application. Assuming that the NO_3-N sufficiency in petiole at early vegetative stage could not predict the yield in 2015 and also as Westermann et al. (1994) showed that NO_3-N concentration around 61 DAP was better predictor of yield than earlier or later sampling; the petiole sampling dates in 2016 were delayed. The modification of sampling date 2016 showed stronger correlation of petiole NO_3-N with yield and N uptake.

Total N in petiole

In 2016, total N concentration in petiole was also estimated in spite of being more time consuming. Across all cultivars, total N concentration in petiole in both sampling days were significantly correlated with total yield, marketable yield, vine N uptake tuber N uptake and total N uptake (Table 3.3.). The Pearson correlation coefficient values indicated that, linear corrletion of total N concentration in petiole with marketable yield, and N uptake were stronger in 42 DAP compared to 72 DAP. Both N treatments and cultivar had significant effect on total N concentration in petiole in both sampling days (Table 3.4.).

Table 3.3. Pearson product moment correlation coefficient for predicting yield and N uptake from total N concentration in petiole in 2016 growing season

	Total N in petiole (mg kg^{-1})	
	42 DAP	72 DAP
Total yield (Mg ha^{-1})	0.58**	0.58**
Marketable Yield (Mg ha^{-1})	0.78***	0.71***
Vine N Uptake (kg ha^{-1})	0.72***	0.69***
Tuber N Uptake (kg ha^{-1})	0.67**	0.61**
Total N Uptake (kg ha^{-1})	0.79***	0.74***

*, **, ***Significant at $P < 0{:}05$, $P < 0{:}01$, and $P < 0{:}001$, respectively.

At 42 DAP total petiole N concentration in N-fertlizer treatments ranged from 40571 to 48138 mg kg^{-1} dry weight and at 72 DAP the range was 21182 to 27865 mg N kg^{-1} dry weight (Table 3.4). There are very few studies that reported total N concentration in petiole. In both sampling days 'Dakota Trailblazer' had and 'ND8068-5 Russ' had minimum concentration of total N in petiole (Table 3.4.). The total N concentration in 'ND8068-5 Russ' petiole were significantly lower than that of other two cultivars in both sampling days (Table 3.4.). As in both sampling days cultivars had significant effect on total N concentration in petiole, the regression analysis by cultivar showed that only 'Russet Burbank' petiole N concentration was significantly linearly related to total and marketable yield (Table 3.5.). Petiole N concentration in 'ND8068-5

Russ' was significantly linearly related to marketable yield at 42 DAP, but the coefficient of determination (R^2=0.25) is lower than that of 'Russet Burbank' (R^2= 0.44) (Table 3.5.). For 'Russet Burbank', the coefficient of determination was stronger in 42 DAP (R^2=0.75) compared to 72 DAP (R^2= 0.39) (Table 3.5).

Table 3.4. Effect of N treatments and cultivars on total N concentration (mg kg^{-1}) in petiole in 2016 growing season

	Total N concentration (mg kg^{-1})	
Treatment	42 DAP	72 DAP
Grower's	48138 (1940) ɸ a†	27865 (3085)a
Urea	40571 (2475)b	21182 (2605)bc
UreaSplit	47928 (2167)a	25988 (4584)ab
SuperU	45405 (3707)ab	25352 (3012)ab
ESN	47613 (1668)a	27454 (2728)ab
Control	28168 (3028)c	15560 (2056)c
Variety		
'Russet Burbank'	43408 (2532)b	24867 (2209)a
'Dakota Trailblazer'	48032 (1630)a	28771 (1901)a
'ND8068-5 Russ'	37470 (2458)c	18063 (2236)b
	Analyses of variance	
N treatments	***	**
Cultivars	***	***
N treatments × Cultivars	NS	NS

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. NS is non-significant

ɸ Parenthesis include standard error

†Values followed by the same letter in each column are not significantly different

Reis and Monnerat (2000) reported total N concentration in petiole at 48 DAE associated with maximum yield was 25.9 g kg^{-1}, which is lower than the values found in our study. Walworth and Munith (1993) reported total N concentration in petiole 3.50 to 7.00 % in early growth stage and 1.42 to 6.00 % which is consistent or higher than the values found in our study. Vitosh et al. (2012) reported about 50000 mg N kg^{-1} dry weight in potato petioles at tuber

Table 3.5. Regression analyses for the relationship between total N concentration in petiole and yield

Response variable (y)	Explanatory Variable (x)	Cultivar	R^2	P value	Linear Regression Equation
Total Yield	Total N in Petiole_42 DAP	Russet Burbank	0.75	<0.001	$y=0.0006x+26.8$
		Dakota Trailblazer	NS	0.214	_
		ND8068-5 Russ	NS	0.918	_
	Total N Petiole_72 DAP	Russet Burbank	0.39	0.007	$y=0.0004x+43.1$
		Dakota Trailblazer	NS	0.280	_
		ND8068-5 Russ	NS	0.735	_
Marketable Yield	Total N in Petiole_42 DAP	Russet Burbank	0.44	0.003	$y=0.0007x+5.83$
		Dakota Trailblazer	NS	0.219	_
		ND8068-5 Russ	0.25	0.032	$y=0.0002x+18.4$
	Total N Petiole_72 DAP	Russet Burbank	0.27	0.028	$y=0.0006x+20.3$
		Dakota Trailblazer	NS	0.221	_
		ND8068-5 Russ	NS	0.069	_

NS is non-significant at $P=0.05$

initiation. Contrasting to our observation Anderson et al. (1999) reported better correlation of petiole NO_3-N than total N in petiole with yield and marketable yield of tomatoes and mentioned that estimation of total N in petiole sap may not be the practical replacement for NO_3-N analysis. Although total nutrient analysis in plant tissue has been used as a standard technique to estimate plant nutrient status, many researcher's criticized it as time consuming and destructive (Munoz-Huerta et al., 2013) while petiole sap NO_3-N test has been established as a quick efficient method in assessing plant N status (Anderson et al., 1999). However, in our study total N in petiole was more effective in predicting yield than petiole NO_3-N. Till today, although petiole NO_3-N is being used as a reliable measure of plant N status, Sabbe and Zelinski (1990) found that petiole NO_3-N concentration is greatly affected by seasonal climatic changes and total N concentration in leaf blades may be a better predictor of crop N status. Cook (1966) stated that the greatest drawback of petiole nitrate analysis is the drop of concentration level rapidly after an irrigation or rainfall which requires 10 to 14 days to recover. So, using petiole NO_3-N concentration may not be the best choice for estimating plant N status in an irrigated system. Kliewer and Cook (1974) implied that petiole NO_3 differs narrowly between plants with low and high crop yields. Christensen (1969) showed a very wide year-to-year variations in petiole nitrate over a four-year period from 1964 to 1967, while total N levels were much more stable.

Ground based active optical sensor reflectance

In 2016, VIs (NDVI and NDRE) were also determined as a measure of plant N status as well as to predict yield and N uptake. In both sampling days, across all cultivars, NDVI were not significantly correlated with any (total yield, marketable yield, vine N uptake, tuber N uptake and total N uptake) response variable (data not shown). At 44 DAP, across all cultivars, NDRE was significantly positively correlated with total yield, marketable yield, tuber N uptake and total N uptake (Table 3. 6.)

Table 3.6. Pearson product moment correlation coefficient for predicting yield and N uptake from normalized difference vegetation index in 2016 growing season.

	NDRE	
	30 DAP	44 DAP
Total Yield	0.14 NS	0.60**
Marketable Yield	-0.13NS	0.46*
Vine N Uptake	-0.03NS	0.25NS
Tuber N Uptake	0.19NS	0.54**
Total N Uptake	0.11NS	0.49*

*, **, Significant at $P < 0.05$ and $P < 0.01$, respectively. NS is non-significant

The visual observation suggested that the cultivars themselves differ in canopy colors, which might affect the reflectance in visible light wavelength (red and red edge). Besides that, main effect of cultivars as well as the N treatment × cultivar interaction effects on NDVI and NDRE in both sampling days (Table 3.7.) also suggested that the different cultivars respond

Table 3.7. Analysis of variance for normalized difference vegetation index (NDVI) and red edge NDVI (NDRE)

	NDVI		NDRE	
	6-Jul	20-Jul	6-Jul	20-Jul
N treatments	**	**	**	**
Cultivars	***	***	***	**
Block	**	NS	NS	NS
N treatments × Cultivars	*	*	*	*

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. NS is non-significant

differently with respect to optical sensor reflectance. So, regression analyses between yields and VIs separately for each cultivar were performed. Minotti et al. (1994), Ziadi et al. (2011) also reported that potato cultivars differ significantly in terms of chlorophyll meter reading. Linear regression coefficients or coefficient of determination (R^2) between the predictor variable (NDVI/NDRE) and response variable (total/ marketable yield) has been reported in Table 3.6 when statistically significant. At 30 DAP, NDVI of ‘Russet Burbank’ and ‘Dakota Trailblazer’ significantly explained the total and marketable yield variability (Table 3.8.). At 30 DAP, NDRE of ‘Russet Burbank’ and ‘Dakota Trailblazer’ significantly explained marketable yield variability and only in case of ‘Dakota Trailblazer’, total yield variability was significantly explained by NDRE (Table 3.8.). At 44 DAP, NDVI of ‘Russet Burbank’ and ‘Dakota Trailblazer’ could significantly explain total yield variability and marketable yield variability in case of ‘Russet Burbank’ (Table 3.8.). At 44 DAP both total and marketable yield of ‘Russet Burbank’ could be significantly explained by NDRE and only marketable yield variability of ‘ND8068-5 Russ’ was significantly explained.

Bala and Islam (2009) reported regression coefficient (R^2) values of 0.42 and 0.66 in predicting yield from NDVI in 2006 at 48 and 64 DAP respectively; while the R^2 value was improved to 0.84 using two year (2005-2006) data with mean values of NDVI. They also showed high variability in R^2 values in predicting yield from NDVI throughout the growing season and

Table 3.8. Regression analyses for the relationship between vegetation indices and tuber yield

Response variable (y)	Explanatory Variable (x)	Cultivar	R^2	P value	Linear Regression Equation
Total Yield	NDVI_30DAP	Russet Burbank	0.23	0.009	y=37.9x+31.8
		Dakota Trailblazer	0.28	0.004	y=39.2 x+26.8
		ND8068-5 Russ	NS	0.148	_
	NDVI_44DAP	Russet Burbank	0.30	0.003	y=206.9x-125
		Dakota Trailblazer	0.35	<0.001	y=95.7x-34.6
		ND8068-5 Russ	NS	0.75	_
	NDRE_30DAP	Russet Burbank	NS	0.055	_
		Dakota Trailblazer	0.31	0.002	y=140x+19.5
		ND8068-5 Russ	NS	0.179	_
	NDRE_44DAP	Russet Burbank	0.28	0.004	y=182.4x-1.47
		Dakota Trailblazer	NS	0.096	_
		ND8068-5 Russ	NS	0.848	_
Marketable Yield	NDVI_30DAP	Russet Burbank	0.24	0.008	y=54.23x+4.09
		Dakota Trailblazer	0.22	0.011	y=49.1x+14.2
		ND8068-5 Russ	NS	0.959	_
	NDVI_44DAP	Russet Burbank	0.31	0.002	y=297.4x-221.5
		Dakota Trailblazer	NS	0.133	_
		ND8068-5 Russ	NS	0.059	_
	NDRE_30DAP	Russet Burbank	0.20	0.02	y=170.36x+1.63
		Dakota Trailblazer	0.24	0.008	y=171.6x+5.80
		ND8068-5 Russ	NS	0.78	
	NDRE_44DAP	Russet Burbank	0.33	0.001	y=278.8x- 49.1
		Dakota Trailblazer	NS	0.9	
		ND8068-5 Russ	0.29	0.003	y=147.0 x -15.8

NS is non-significant at P=0.05

maximum values were reported between 38 to 64 DAP. The very low R^2 values in predicting yield from NDVI or NDRE in our study might be due to single date measurements very early in the growing season (30 and 44 DAP). The main constraint in measuring optical reflectance with ground based optical sensor in potatoes is the vine growth that impedes consistent data collection. Although Jayanthi (2003) showed that long term integrated data of NDVI predicts yield the best, Sivarajan (2011) and Pathak (2005) validated single date NDVI based model. Jayanthi (2003) found that data collected 7-10 days prior to full vegetative cover is most effective in predicting yield, which supports our result where across all cultivars correlation between NDRE and yields were statistically significant at 44 DAP (Table 3.6). Similar to our observation, Al-Gaadi et al. (2016) reported R^2 values ranging from 0.12 to 0.48 in predicting yield from single date NDVI within 39 to 45 DAP. Al-Gaadi et al. (2016) used satellite images in calculating NDVI and they showed a great variation within the sources of imagery. Acquiring reflectance data from satellite images involves challenges with cloud interference, low resolution and cost of images (Wu et al., 2007), while acquiring data with handheld scanner is problematic after full vegetative growth. From the regression analyses (Table 3.8.) it can be inferred that the indeterminate cultivars ‘Russet Burbank’ and ‘Dakota Trailblazer’ respond better than the determinate cultivar ‘ND8068-5 Russ’ in terms of predicting yield from VIs. The reason for that might be the soil reflectance in the determinate cultivar with low vegetative growth. Sivarajan (2011), Al-Gaadi et al. (2016) reported better correlation of yield with soil adjusted vegetation index (SAVI) than NDVI. We, did not have data or sources to calculate soil correction factor and SAVI, which could have better predicted yield. The difference in growth patterns of different cultivars also influenced the yield prediction response. For ‘Russet Burbank’ both NDVI and NDRE had better response at 44 DAP compared to 30 DAP (Table 3.8). For ‘Dakota Trailblazer’, although NDVI had better response at 44 DAP, NDRE responded better at 30 DAP.

Further investigations are needed to be carried out to establish the effectiveness of VIs calculated with hand held crop reflectance sensor data before the full vegetative growth by increasing the number of sampling. Jayanthi (2003) showed that increasing the number of images acquired throughout the growing season, yield would be predicted with less variability. Except for the problem in data acquisition, collection of data before full vegetative cover is important because saturation might underestimate yield potential (Malnaou et al., 2006). When the canopy entirely covers the inter row space, yield potential is masked as the stunted, nutrient deficient crop may also produce enough canopy to cover the inter row space (Bu et al., 2016).

Conclusions

Total N content in petiole may be the better predictor of N status and yield than petiole NO_3 concentration. With limited number of data, VIs solely may not establish a strong model for yield prediction, but it has potential for cultivar specific forecast of yield early in the growing season. Although the hand held crop reflectance sensors limits data collection after full vegetative cover, it is easily operated quick and cheaper than data processed from satellite images and leaves scope for further investigation with increased number of sampling. Petiole nitrate ranges were similar for different cultivars mostly, but for total N concentration and VIs the yield prediction or estimation should be cultivar specific. Estimation of total N concentration in petioles may be a little more time consuming than petiole sap NO_3^- test and VI measurement, but it has a great promise in predicting yield depending on the time of sampling.

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APPENDIX. FIGURES

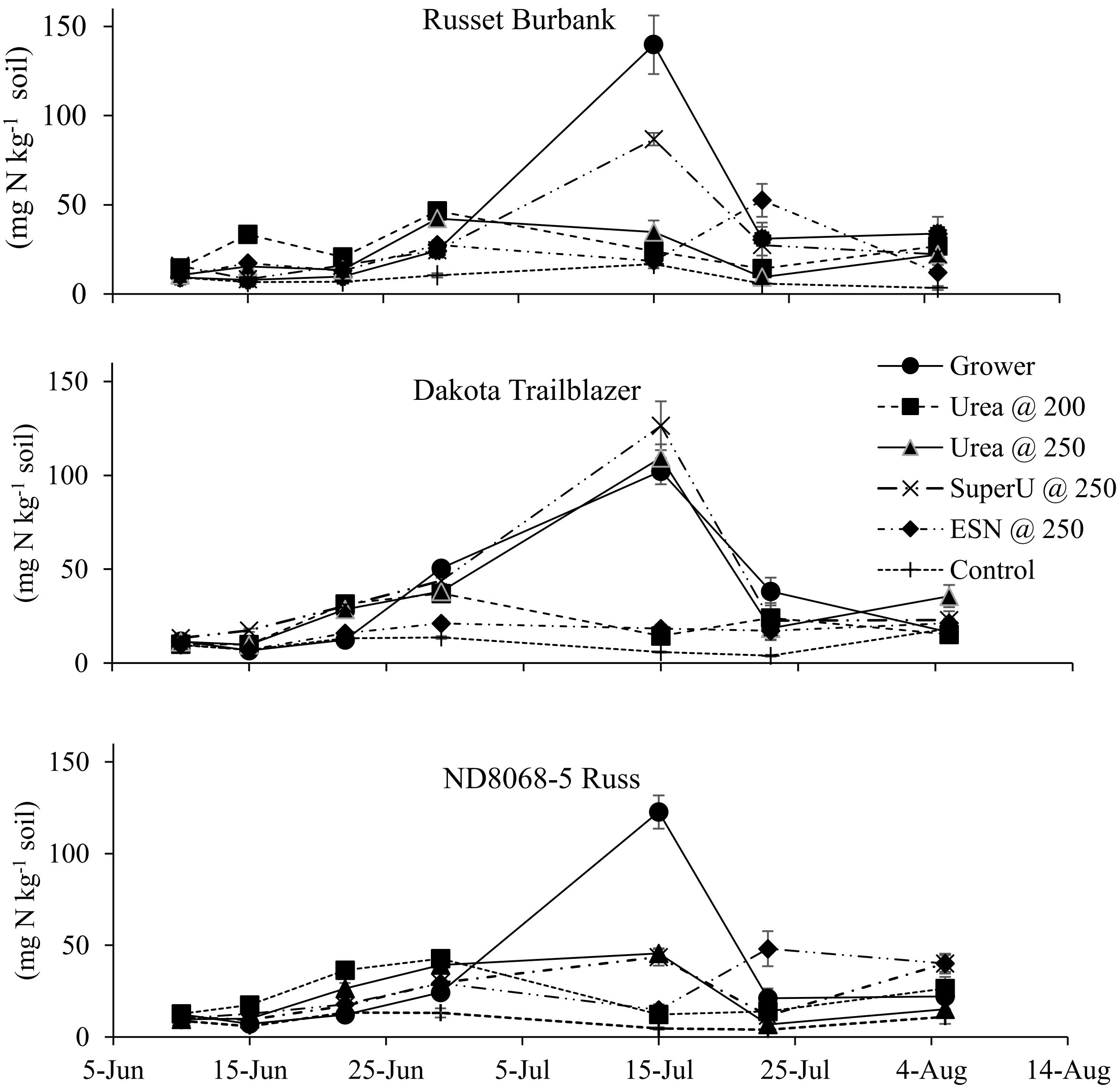

Fig A1. Soil N availability (mg kg^{-1} soil) in three potato cultivars (‘Russet Burbank’, ‘Dakota Trailblazer’, ‘ND8068-5 Russ’) throughout the growing season of 2015.

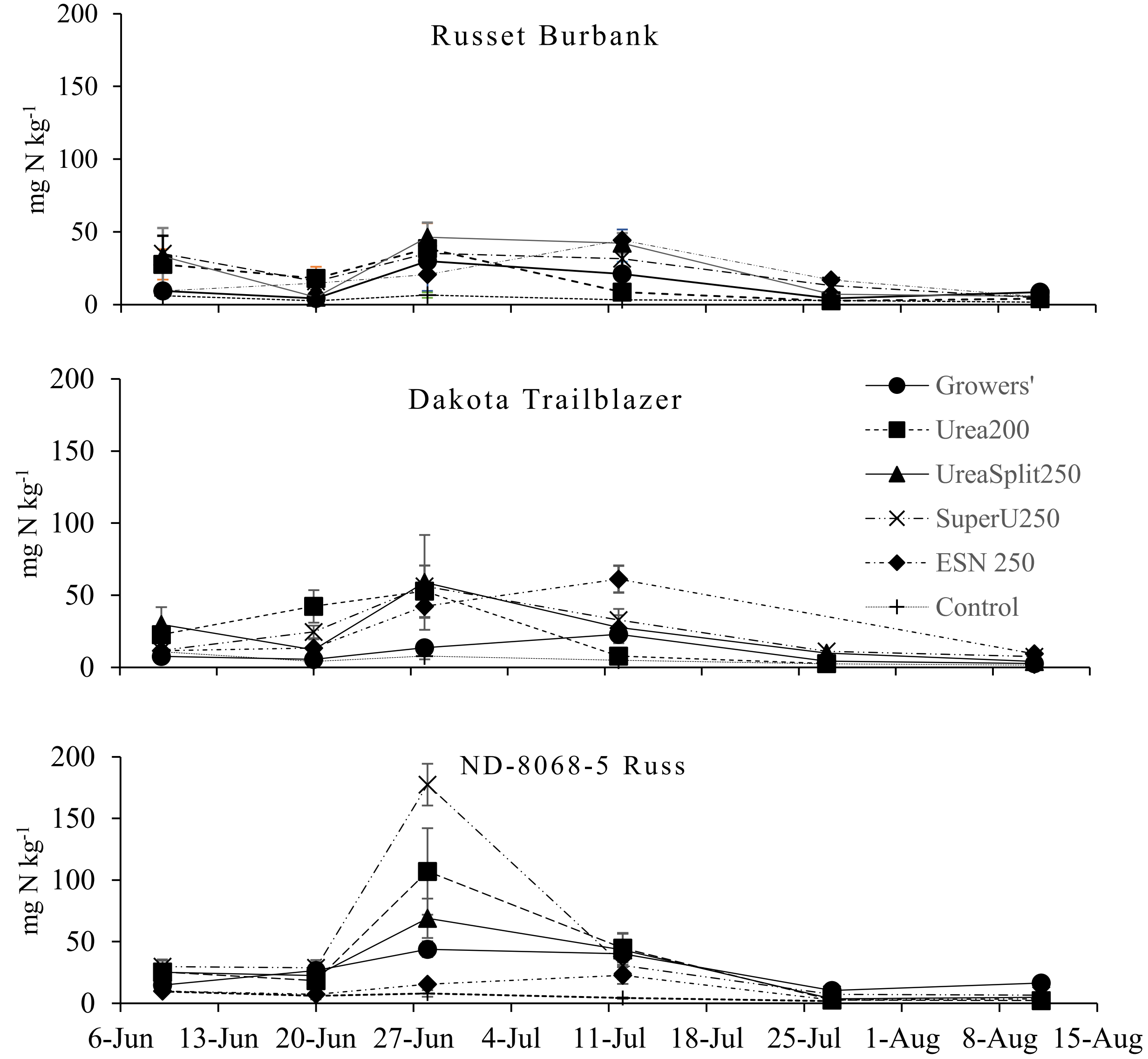

Fig A2. Soil N availability (mg kg^{-1} soil) in three potato cultivars (‘Russet Burbank’, ‘Dakota Trailblazer’, ‘ND8068-5 Russ’) throughout the growing season of 2016.