DEFINING IN-SEASON NITROGEN NEEDS FOR MAXIMUM ECONOMIC YIELDS AND QUALITY FOR ALTURAS AND PREMIER RUSSET

By

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To the Faculty of Washington State University:

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Abstract

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Proper nitrogen (N) management is a crucial component of potato cropping systems. Rapid adoption of two new cultivars, Alturas and Premier Russet, has necessitated the development of appropriate in-season N fertilizer recommendations tailored to each cultivar. A three year study was performed at the WSU Research Station in Othello, Washington to determine an in-season N rate that would maximize grower revenue and optimize field performance for each cultivar. Five in-season N rates were applied: 0, 25, 50, 100, and 150% of typical Russet Burbank fertilizer rates. Petiole and soil N values from each treatment were distinctly different from each other. Typically, higher N rates produced higher petiole and soil N values. Vine senescence at 141 days after planting (DAP) was hastened as in-season N rate decreased. As in-season N rates increased, total yield typically increased. Alturas total yield peaked at the 150% treatment (355 lbs in-season N/A) while Premier peaked at 125% (300 lbs in-season N/A). As N rate increased, specific gravity decreased significantly. In Alturas, revenue was optimized at 108% of the typical in-season N rate (259 lbs in-season N/A) for Russet Burbank, while Premier revenue was highest at 100% (240 lbs in-season N/A) of the standard rate. An additional component of the study was to establish the efficacy of a chlorophyll meter for *in situ* determination of current crop N status. SPAD readings were recorded in Premier once per week throughout the growing season and results regressed against corresponding petiole

NO_3-N concentrations as well as leaf and petiole total N (2008 data not included). The relationship between SPAD and petiole NO_3-N, leaf total N, and petiole total N were strong in 2007, but poor relationships were found in 2009. In general, SPAD correlated well with petiole NO_3-N concentrations of approximately 0.5 to 2.0%, but was not as responsive or precise to reflect treatment variations as was traditional petiole NO_3-N analysis. At petiole NO_3-N % above 2.0, the plant canopy was too green for SPAD to reliably predict crop N.

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INTRODUCTION

The potato (*Solanum tuberosum* L.) is the fourth most important food crop in the world after rice, wheat, and maize (Spooner and Bamberg 1994). Washington State is the second largest potato producing state in the United States accounting for more than 20% of all US potato production on 69,000 ha (USDA National Agricultural Statistics Service, 2008) Ideal combinations of temperature, abundant irrigation water, and rich alluvial soils in the arid region of the Columbia Basin allow growers to realize average annual yields of >600 CWT/A; the largest yields of any potato producing region in the world (Wang et al. 2007). In recent years, approximately 87% of Washington State potatoes have been processed into frozen products, such as french fries, hash browns, and dehydrated potato products (Washington State Potato Commission 2009; Wang et al. 2007). The potato processing industry in Washington is largely dependent on the high tuber yields and quality obtained by growers in the Columbia Basin.

Managing nutrient inputs properly, especially nitrogen (N) is essential for maximizing tuber quality and yield (Rowe 1993). Improper N management can significantly compromise yield and quality (Rowe 1993). Insufficient N can lead to reduced growth (Harris 1992), reduced light interception, limited yield (Chase et al. 1990; Laurer 1986; Munro et al. 1977; Santerre et al. 1986; White et al. 1974) delayed tuber set (Harris 1992), reduced dry matter content (Love et al. 2005; MacKerron and Davies 1986; McDole 1972; Painter and Augustin 1976; Westermann et al. 1994; Yungen et al.1958) and an increase in diseases such as early die, late blight, and Verticillium wilt (Davis et al. 1990; Rowe 1993). In contrast, excess N may reduce tuber N uptake efficiency, delay tuber initiation (Westermann and Kleinkopf 1985), and promote overgrowth of vines which can reduce the effectiveness of vine desiccants (Pavlista and Blumenthal 2000) and create a humid environment that promotes diseases associated with moisture such as aerial stem rot, Sclerotinia stem rot, pink rot, and other foliar and tuber diseases (Rowe 1993). Excess N may also affect storability (Long et al. 2004) and have adverse environmental effects such as groundwater run-off and leaching (Rowe 1993), which increases the risk of environmental pollution.

Because of the serious environmental impact caused by leaching, proper N management is crucial from more than just a crop production perspective, yet it is still common for producers to apply more N than needed for maximum yields. Kunkel et al. (1972) reported that excess N was often justified on potatoes because it would provide growers insurance against a loss of marketable tuber yield. Additionally, several studies examining N uptake by potato plants found that growers routinely applied N in excess of crop demand (Joern and Vitsoh 1995; Prunty and Greenland 1997; Tyler et al.1983). Studies on N requirements for maximum yield in potato and other crops, as well as the environmental fate of excess N, have been the focus of extensive research (Milburn et al. 1990).

In light of the importance of N management, there is considerable need in the potato industry for cultivar specific N recommendations that reduce excess N applications while returning maximum economic value to the grower. Standard industry fertilization practices for potato are generally driven by published regional fertilization guidelines. However, these guidelines are often based on the nutrient requirements of the well studied Russet Burbank cultivar (Kleinkopf and Westermann 1986; Lauer 1986; Roberts and Dow 1982; Roberts et al. 1982; Rykbost et al. 1993; Westermann and

Kleinkopf 1985; Westermann et al. 1988), which has demonstrated maximum yields with applied N rates from as little as 45 kg ha^{-1} following red clover (*Trifolium pratense* L.) to as much as 400 kg ha^{-1} (Lauer 1986; Porter and Sisson 1991*b*). Different potato cultivars have unique morphological, physiological and developmental characteristics that may differ from Russet Burbank in response to N fertilization (Arsenault et al. 2001) and as such may differ in their N requirements. Therefore, fertilizing cultivars other than Russet Burbank with typical Russet Burbank rates may not be the most effective strategy. In addition to being of limited value when a cultivar other than Russet Burbank is being produced, regional guidelines are rarely accompanied by a thorough economic analysis. Economics take into account the price/cost ratio of N fertilizer and potato value in a particular year and help quantify the true efficiency of a grower's fertilizer regime. Nitrogen affects a number of key processing characteristics in potato that directly relate to economic return. Processing contracts include economic penalties and incentives for processing parameters such as tuber size, internal and external quality, and specific gravity, all of which can be affected by N. (Knowles et al. 2009). Without examining the economics related with a particular N rate, a grower is not getting the whole picture. To further complicate the issue, N recommendations in potato are generally performed with the main goal of maximizing total yield. However maximum biological yield does not always equate to maximum economic yield (Pavek and Holden 2008) and there may be a large disparity between the two. Thus, a grower fertilizing a new cultivar in accordance with standard Russet Burbank fertilization practices may be compromising yield, quality, and net income.

One method that growers have adopted to improve their nitrogen use efficiency and compensate for some of the uncertainty involved in adopting a blanket N strategy is a fertilizing regime known as “dynamic optimization of nitrogen supply” (Vos and Struik 1992). Dynamic optimization, also known as “spoon-feeding”, refers to the practice of applying a reduced amount of N at pre-plant coupled with a series of small supplemental applications made throughout the growing season (in-season) based on actual crop need at each growth stage. Studies show that a spoon-fed crop results in lower NO_3-N leaching, higher N recovery by the crop and an improved marketable tuber yield (Errehbi 1998; Westermann et al. 1988; Russer et al. 1998; Waddel et al. 1999). A series of small in-season N applications through the irrigation system is a convenient and economical method of fertilizer delivery and is the most common method of in-season N application used by potato growers in the Columbia Basin.

Key to the success of this type of N management strategy is an accurate assessment of the current N status of the soil and plant to guide decisions on in-season N rates. Currently, N status is measured through periodic collection and analysis of soil and plant petioles throughout the growing season. Results from such analyses are then used to guide the grower’s fertilizer decisions as to when and how much fertilizer to apply based on regional N recommendations.

Petiole NO_3-N analysis as a nitrogen management tool in potato has been widely investigated and is considered to be the most effective means of monitoring current crop N status due to a strong correlation between petiole NO_3-N, N availability in the plant, and N uptake (Alva 2007; Bundy et al. 1986; Errebhi et al. 1998; Kleinkopf et al.1984; Macmurdo et al. 1988; Porter and Sisson 1991b; Roberts and Cheng 1988; Roberts et al.

1989; Vitosh and Silva 1994; Vitosh and Silva 1996; Waterer 1997; Westcott et al. 1991; Westcott et al. 1993; Williams and Meir 1990). Although traditional petiole sampling data can provide a relatively accurate determination of crop N status, it is time consuming and expensive to perform. The waiting time for results is often too slow to allow sufficient time to correct a potential N deficiency. More growers may adopt the dynamic optimization of N strategy if crop N status readings were immediate, precise, and affordable.

One instrument that may allow for these type of results in potatoes is the Minolta SPAD (Soil Plant Analytical Development) 502 Chlorophyll Meter (Minolta Corp, Ramsey, NJ.). The SPAD meter has many potential advantages over traditional crop N monitoring techniques (i.e., petiole and soil collection) because it is instant, requires no special skills to operate, and performs a function similar to, but more accurately than, that of a grower judging a crop via canopy greenness; the difference is that the SPAD meter performs the task “quantitatively as opposed to subjectively” (Vos and Bom 1993). While collection of petioles and soils for analysis can take from several hours to several days, SPAD readings from multiple plants can be averaged in less than one hour (Minotti et al. 1994).

SPAD use in potato was first investigated by Vos and Bom (1993) who worked with the cultivar Vebeca under different N rates and application times. They reported high correlations between leaf chlorophyll levels ($r = 0.97$), tissue N concentrations ($r = 0.97$) and SPAD readings; findings previously confirmed with other crops. Vos and Bom (1993) concluded that the SPAD meter could be a potentially useful tool for monitoring N status in a dynamically optimized system if critical SPAD thresholds were developed.

The thresholds would represent a range of SPAD values above which there is no crop yield response to additional N applications but below which a yield response could be expected. Vos and Bom suggested that the practicality of the SPAD meter to monitor crop N status would be limited unless further research was conducted to address how factors other than N rate could affect SPAD readings (e.g. cultivar effects, location, nutritional limitations other than N, drought and diseases). Minotti et al. (1994) investigated varietal effects of potatoes on SPAD readings under varying levels of N from insufficiency to excess. Using regression analysis for N rate on tuber yield and SPAD values, they estimated SPAD critical threshold values (lowest amount of N giving the highest yield) of approximately 49 to 56 SPAD units at 29 to 37 DAP (days after planting) for cultivars 'Katahdin', 'Allegheny', 'Castille', and 'Superior', but stressed that SPAD is significantly affected by cultivar and that SPAD thresholds should be developed for each cultivar independently. This thought was echoed by Schepers et al. (1992) working with maize and Gianquinto (2007) working with potatoes. All the authors agreed that SPAD critical thresholds are impossible to establish unless a well fertilized (non N-limiting) reference crop strip is established to standardize the SPAD readings across locations, climates, and cultivars.

The recent release of two new cultivars from the Tri-State Breeding Program and the USDA/ARS, Alturas and Premier Russet (Premier), has necessitated the development of appropriate in-season N fertilizer recommendations tailored to each cultivar. The reported research examines in-season N rates that are associated with maximum economic return and tuber quality for these two cultivars as well as an investigation into the efficacy of a chlorophyll meter as a nitrogen management tool relative to traditional petiole testing with the following specific objectives: 1) assess a new research method for N application that closely mimics commercial fertigation and allows for a large number of treatments, 2) develop a cultivar-specific understanding of N response as it relates to yield, quality, and economics of these cultivars, 3) define specific petiole and soil critical concentrations for each cultivar for maximum economic returns, 5) test the efficacy of a SPAD chlorophyll meter in determining crop N status in situ as compared to traditional petiole NO_3-N analysis, and 6) develop SPAD threshold values that relate to maximum economic returns. In addition, we sought to understand the effects of in-season N on whole plant morphology and physiology in an effort to improve our ability to make management recommendations for these and other cultivars.

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CHAPTER ONE

DEFINING IN-SEASON NITROGEN NEEDS FOR MAXIMUM ECONOMIC YIELDS AND QUALITY FOR ALTURAS AND PREMIER RUSSET POTATOES

ABSTRACT

Proper nitrogen (N) management is a crucial component of potato (*Solanum tuberosum* L.) cropping systems and is generally one of the costliest inputs. Rapid adoption of two new cultivars, Alturas and Premier Russet, has necessitated the development of cultivar specific in-season N fertilizer recommendations. A three-year study was performed at the WSU Research Station in Othello, Washington to determine an in-season N rate that would maximize grower revenue and optimize field performance for each cultivar. Five in-season N rates (0, 25, 50, 100 and 150% of typical Russet Burbank rates) were applied to each cultivar in a method simulating N application via overhead irrigation (fertigation). Plant growth and development as well as petiole and soil N concentrations were monitored throughout the season. A mock processing contract was used to determine economic value. Typically, petiole and soil N values from each treatment were distinctly different correlated with N rate; higher N rate produced higher petiole NO_3-N and soil total N values. The effect of in-season N rate became increasingly visible late in the season as the canopies of the no/low N rate treatments began to senesce earlier than those receiving the higher rates. As in-season N rates increased, total yield typically increased. Alturas total yield peaked at the 150% treatment (345 lbs in-season N/acre) while Premier peaked at 125% (287 lbs in-season N/acre) of the typical Russet Burbank rate. As N rate increased, specific gravity decreased significantly. In Alturas, revenue was optimized at 108% of the standard in-season N rate (248 lbs in-season N/acre) for Russet Burbank, while Premier revenue was highest at 100% (240 lbs in-season N/acre) of the typical rate. Based on this research, we recommend Columbia Basin growers maximize profits by maintaining petiole NO_3-N levels between 23,000-26,000 ppm at 60 DAP, 17,000-20,000 ppm at 90 DAP, and <10,000 ppm at 120 DAP for both cultivars.

INTRODUCTION

The potato (*Solanum tuberosum*) is the fourth most important food crop in the world after rice, wheat, and maize (Spooner and Bamberg 1994). Washington State is the second largest potato producing state in the United States accounting for more than 20% of all US potato production on 69,000-ha (USDA National Agricultural Statistics Service, Washington 2008). Ideal combinations of temperature, abundant irrigation water, and rich alluvial soils in the arid region of the Columbia Basin allow growers to realize average annual yields of >600 CWT/A; the largest yields of any potato producing region in the world (Wang et al 2007). In recent years, approximately 87% of Washington State potatoes have been processed into frozen products, such as french fries, hash browns, and dehydrated potato products (Washington State Potato Commission 2009; Wang et al. 2007). The potato processing industry in Washington State is largely dependent on the high tuber yields and quality obtained by growers in the Columbia Basin.

Managing nutrient inputs properly, especially nitrogen (N) is essential for maximizing tuber quality and yield (Rowe 1993). Improper N management can significantly compromise yield and quality (Rowe 1993). Insufficient N can lead to reduced growth (Harris 1992), reduced light interception, limited yield (Chase et al. 1990; Laurer 1986; Munro et al.1977; Santerre et al.1986; White et al. 1974) delayed tuber set (Harris 1992), reduced dry matter content (Love et al. 2005; MacKerron and Davies 1986; McDole 1972; Painter and Augustin 1976; Westermann et al. 1994; Yungen et al. 1958) and an increase in diseases such as early die, late blight, and Verticillium wilt (Davis et al. 1990; Rowe 1993). In contrast, excess N may reduce tuber N uptake efficiency, delay tuber initiation (Westermann and Kleinkopf 1985), and promote overgrowth of vines which can reduce the effectiveness of vine desiccants (Pavlista and

Blumenthal 2000) and create a humid environment that promotes diseases associated with moisture such as aerial stem rot, Sclerotinia stem rot, pink rot, and other foliar and tuber diseases (Rowe 1993). Excess N may also affect storability (Long et al. 2004) and have adverse environmental effects such as groundwater run-off and leaching (Rowe 1993) which increases the risk of environmental pollution.

In the Washington counties of Adams, Franklin and Grant, approximately 20% of all drinking-water wells have nitrate concentrations (NO_3-N) exceeding the US Environmental Protection Agency's maximum contaminant level of 10 mg L^{-1}, the source of which is believed to be from local crop and livestock production (USGS Water Resources of WA 2000). Because of the serious environmental impact caused by leaching, proper N management is criticalfrom more than just a crop production perspective, yet it is still common for growers to apply more nitrogen than needed. Kunkel et al. (1972) reported that excess N was often justified on potatoes because it would provide growers insurance against a loss of marketable tuber yield. Additionally, several studies characterizing N uptake by potato plants found that growers routinely applied N in excess of crop demand (Joern and Vitsoh 1995; Prunty and Greenland 1997; Tyler et al.1983). Studies on N requirements for maximum yield in potato and other crops as well as the environmental fate of excess N have been the focus of extensive research (Milburn et al. 1990).

Synchronization between N availability in the soil and N uptake by potato roots has been proposed as a means to maximize yield and reduce leaching. With proper timing and quantities of fertilizer applications, N availability can be controlled without reducing yield (Bouldin & Selleck 1977; Errebhi et al.1998; Stark et al. 1993; Watkins et al. 1998). Split N fertilizer applications (in-season) as opposed to a single pre-plant application are recommended as a method to improve tuber yield, quality, and N uptake efficiency. Studies show that reduced N rates applied at planting, coupled with timely, multiple, and small in-season applications applied via irrigation water (fertigation) and corresponding with crop needs, result in lower NO_3-N leaching, higher N recovery by the crop, and improved marketable tuber yield (Errehbi 1998; Ojala et al. 1990; Russer et al. 1998; Stark et al. 1993; Waddel et al. 1999 Westermann et al. 1988; Watkins et al. 1998). This N management strategy is commonly called "spoon feeding" and is a convenient and economical method of fertilizer delivery as well as the most common method of in-season N application used by potato growers in the Columbia Basin.

Extensive literature exists pertaining to N management for potato. However, there are gaps in this research. Much of the existing research deals with N relations in the well studied and commercially important Russet Burbank cultivar and as such, most Columbia Basin fertilizer recommendations are based on the N needs of this one cultivar (Kleinkopf and Westermann 1986; Lauer 1986; Roberts and Dow 1982; Roberts et al. 1982; Rykbost et al. 1993; Westermann and Kleinkopf 1985; Westermann et al. 1988). However, different potato cultivars have unique morphological, physiological and developmental characteristics that may differ from Russet Burbank in response to N fertilization (Arsenault et al. 2001). Longer season cultivars tend to require higher N rates for maximum yield, but this is not always the case (Arsenault et al. 2001; Lewis and Love 1994). Maximum potato yields for Russet Burbank have resulted with applied N rates from as little as 45 kg ha^{-1} following red clover (*Trifolium pratense L.*) to as much as 400 kg ha^{-1} (Lauer 1986; Porter and Sisson 1991a). In addition, establishing optimum in-season N rates and application times for any potato cultivar is no easy task due to the intricacies and complexities of the potato growth cycle and the interactions present among N delivery method, N source, application timing, weather, soil, seedpiece spacing, pathogen pressures, and irrigation, among other factors. Therefore, making N recommendations for other cultivars based on research for Russet Burbank may be of limited value. Another difficulty in developing N recommendations is the inability to conduct small plot research trials with a large number of replicated fertilizer treatments while utilizing standard farm irrigation systems as the fertilizer carrier.

Another gap in the literature is the fact that many studies look at N rate strategies for obtaining maximum total tuber yield and don't examine the real-world economics or tuber quality aspects involved in reaching these yields. Maximum biological yield does not always equal maximum economic yield (Pavek and Holden 2008). Economics take into account the price-cost ratio of N fertilizer and potato value in a particular year. Too often, additional N applications are made in an effort to maximize tuber yields. In many cases, the additional expenses of these N applications may not be offset by the gain in marketable tubers. Essentially, the higher yields become too expensive to achieve. In addition, N affects a number of key processing characteristics in potato that directly relate to economic return (Knowles et al 2009). Previous studies that focus only on yield are doing a disservice to the industry. Processing contracts include economic penalties and incentives for processing parameters such as tuber size, internal and external quality, and specific gravity, all of which can be affected by N.

Because N management is so vital to a potato cropping system, a framework needs to be developed for important new commercial cultivars that allows growers to maximize profits with high quality tuber yields while potentially reducing environmental impacts associated with excess N. Additionally, growers are more apt to accept research results when treatments are applied in a manner that closely mimics application methods similar to theirs.

The recent release of two new cultivars from the Tri-State Breeding Program and the USDA/ARS, Alturas and Premier Russet (Premier), has necessitated the development of appropriate in-season N fertilizer recommendations tailored to each cultivar. The reported research examines in-season N rates and their association with maximum economic return and tuber quality for these two cultivars. The purpose of this research was to 1) assess a new research method for N application that closely mimics commercial fertigation and allows for a large number of treatments, 2) develop a cultivar-specific understanding of N response as it relates to yield, quality, and economics of these cultivars, 3) define specific petiole and soil critical concentrations for each cultivar needed to obtain maximum economic yields, and 4) understand the effects of in-season N on whole plant morphology and physiology in an effort to improve our ability to make management recommendations for these and other cultivars.

MATERIALS AND METHODS

Plant Material

Field studies to compare the response of Alturas and Premier Russet (Premier) to five in-season N rates were conducted at the Washington State University Research and Extension Unit near Othello, WA (46º 47.277’ N. Lat., 119 º 2.680’W. Long.) during 2007-09. Each year, certified seed tubers of Alturas and Premier were hand cut into 43- to 85-g seed pieces, suberized at 50 ºF at 95% relative humidity for 14 days, and planted on 5 April, 2007, 17 April, 2008, and 23 April, 2009.

Field Plot Design and Maintenance

Alturas and Premier were each planted in separate trials and arranged in a randomized complete block design with four replications in a Shano Silt Loam [classified as Andic Mollic Camborthid (Lenfesty 1967] with a custom built two-row assist feed planter and grown under regional standard practices, with the exception of in-season N fertilization. Seed pieces were planted 20-cm deep and 25-cm apart within each row. Each row was 86-cm from center to center and plots were five rows wide by 7.62-m long. Data were collected on the second and fourth rows of each plot. One plant of a purple-skinned variety, 'All Blue', guarded the beginning and the end of each row and plot to separate plots and provide end plants with competition during growth.

Plots were treated with five in-season N rates: 0%, 25%, 50%, 100%, and 150%. Treatments are expressed as a percentage of the typical Columbia Basin post-emergent (in-season) N rates for the Russet Burbank cultivar. The "typical" Russet Burbank rates were essentially a compilation of local grower and researcher practices and suggestions by Lang et al. (1999). All treatments received the same pre-plant N during a given year with rates determined by soil analysis. Pre-plant, in-season and total season N rates and associated in-season N expense are shown in Tables 1 through 4.

In-season N (urea-ammonium-nitrate (UAN) 32-0-0) was applied once or twice weekly beginning when plants were 10-12 inches tall, approximately 50 days after planting (DAP), and continued until 100 DAP. To mimic commercial applications of water-applied N (fertigation), in-season N was applied via a custom fertigation simulator (tractor pulled flood-nozzle sprayer; Fig. 1) which delivered precise quantities of N to each plot using 4-mm of water as a carrier. Plots were irrigated with solid-set irrigation and soil moisture was maintained between 65%-85% of field capacity using tensiometers and neutron probes (monitored by Professional Ag Services, Pasco WA). Herbicides, insecticides, and fungicides were applied as needed, according to standard Columbia Basin practices. Based on soil and petiole analyses, in-season phosphorus (liquid ammonium polyphosphate 10-34-0) was also applied as needed in accordance with current Columbia Basin phosphorus recommendations (Lang et al. 1999). Any N added to the trial via the 10-34-0 applications was accounted for and is reflected in Tables 1 through 3.

Tissue and Soil Sample Collection

Between 60- and 120-DAP, the fourth leaf from the top of the plant was collected from ten random plants per plot weekly, during the morning, and used for petiole analysis as per Lang et al. (1999). Petioles from plots of the same treatment (a total of 40) were combined each week resulting in one composite analysis per treatment. Petioles were either dried via a drying oven or refrigerated prior to delivery to the testing facility. Petioles were analyzed for % NO_3-N with a Skalar Sanflow 4 channel segmented flow analyzer (Skalar Analytical, Netherlands). Petiole P, K, and S was analyzed with a Perkin Elmer Optima 300 (PerkinElmer, Waltham, MA) radial induced argon plasma emission spectrophotometer.

Soil samples were collected every other week at 30-cm depths using an open side tubular auger with a 1.9- cm diameter (AMS Sampling Equipment, Idaho Falls, ID). Three random samples from each depth were taken from each plot and a composite sample was made by combining all samples of the same treatment together. Soil samples were bagged and held at 8ºC until delivery to the testing facility.

Hand Dig Data Collection

In order to assess in-season plant development, hand harvests were initiated at 70 DAP and performed approximately every eighteen days in 2007 and every fourteen days in 2008-09 until vine kill. At each harvest, four plants were hand harvested from the center row and the first, outer-most plant discarded due to lack of intra-row competition. Data on stem number, tuber number, fresh vine and tuber weights were collected. A total of seven hand-harvests were performed each year. Harvest index for both cultivars was calculated on each harvest date using the following formula: (fresh tuber weight)/(fresh vine weight + fresh tuber weight)*100. Vine senescence was visually rated and a "percent dead" value assigned to each plot in each treatment. Vine senescence values represent the average "percent of vine death" of four replications of each treatment.

Post Harvest Measurements

Vines were removed from all treatments using a flail type mower at 172 days after planting **(**DAP) in 2007, 159 DAP in 2008, and 166 DAP in 2009. Plots were harvested 186 DAP in 2007, 172 DAP in 2008, and 167 DAP in 2009 with a one-row mechanical plot harvester. Each tuber was washed, weighed, and counted using a two-lane electric sizer **(**Lectro-Tek Industries, Wenatchee WA**).** Total tuber yield was partitioned into US No. 1, US No. 2, and cull categories. Total yield included the combined weights of all categories. U.S. No. 1 yield was equal to the sum of all categories except cull and undersize (<113 g) tubers. Marketable yield included total US No.1 and US No.2 tubers greater than 113 g. The undersize category was composed of tubers <113 g. Ten, 227- to 397 g tubers from each replicate were evaluated for black spot bruise, stem end discoloration, shatter bruise, brown center, hollow heart, and internal brown spot defects. Length and width of five, 227- to 397 g tubers from each plot were measured and length to width ratio was calculated. Tubers weighing between 113 to 340 g were used for weight-in-water/weight-in-air specific gravity determination (Gould, 1999). Tubers 227- to 340-g from the 0%, 50%, and 150% treatments were stored at 44°F and french fried at 375°F at 21, 53, 131, 191, and 228 days after harvest in 2007-2008. In 2008-2009, tubers were fried at 11, 39, 102, 162, and 227 days after harvest. Postharvest fry evaluations for the 2009-10 growing season are still under investigation.

Statistical Analysis

All data were analyzed using ANOVA and the means separated using Fishers's Protected Least Significant Difference Test at the 0.05 level of probability. Interactions among the main factors were partitioned and discussed accordingly. Unless relevant to the discussion, the main effects of year were excluded from the final data set. A polynomial regression analysis was used to determine the effects of in-season N on the growth and development of both cultivars. Quadratic and cubic regression models were used where appropriate because they provided the best fit of the data.

Economic Value

Gross income less N expense was determined for both cultivars using four-year regional average process-market values for the 2004 through 2008 market periods (National Agricultural Statistics Service, 2004-2008) and based on the following contract parameters:

1. Base price of $6.66/CWT (U.S. No. 1 and 2) grade tubers.

2. Premiums were added to the base price for total yields composed of 56% to 85% 6 oz and larger market grade tubers. Premiums of \$0.05/CWT were applied for 56% > 6 oz and increased \$0.05/CWT for each percentage point increase above 56% up to a maximum of \$0.55/CWT at 66% > 6oz (e.g. 56% > 6 oz = \$0.05/CWT, 57% > 6 oz = \$0.10/CWT, 58% > 6 oz = \$0.15/CWT, and so on). Between 66% and 75% > 6 oz the premium was \$0.55/CWT. For each percentage point increase above 75% > 6 oz the premiums declined by \$0.05/CWT down to a low of \$0.00/CWT for 86% > 6 oz. No premiums were applied to the base price for total yields with more than 86% > 6 oz market grade tubers. Penalties were subtracted from the base price for total yields with less than 55% > 6 oz tubers. The penalties were \$0.05/CWT for each percentage point decline below 55% > 6 oz and increased to \$0.45/CWT at 46% > 6 oz. Below 46% > 6 oz, penalties were \$1.00/CWT with no rejection minimum. Tuber specific gravity premiums for average values above and penalties for values below 1.076. Premium per CWT was \$0.10 at 1.077, \$0.20 at 1.078, \$0.30 at 1.079, \$0.40 at 1.080, \$0.50 at 1.081, \$0.60 at 1.082 with a maximum of \$0.70 for gravities up to 1.088. Penalties for gravities of 1.075 were \$0.50/CWT. Gravities below 1.075 were assessed a penalty of \$1.00/CWT with no minimum rejection.
3. Undersized market grade potatoes less than 113 g (undersize and process culls) were valued at \$3.00/CWT.
4. No premiums or penalties were applied for tuber fry color, sugar content, bruise, or internal defects.
5. Nitrogen costs were set at \$0.44 lb.

RESULTS

The spring of 2008 was much cooler than the normal 5 and 10 year temperature averages (Holden and Pavek, 2008), resulting in lower cumulative degree days during the period of plant emergence from 0 to 44 DAP (data not shown). Consequently, plants emerged later in 2008 than in 2007 or 2009. However this had no effect on final plant emergence (data not shown).

Petiole and Soil Nitrogen Trends

Treatment differences were evident and distinct in the petiole NO_3-N analyses for both cultivars, especially as each season progressed (Figs. 2 and 3). As expected, increasing N rates typically led to increased N concentration in the plant tissue (Figs. 2 and 3) and the soil (Figs. 4 and 5) throughout the growing season. The season long trends demonstrated, for the most part, that soil petiole analyses were sensitive enough to detect fairly minor differences in N application rates. Petiole differences were evident within ten days of the first in-season application across all years for both cultivars (Figs.2 and 3). As N applications began for both cultivars, petiole values typically climbed and eventually peaked between 70 and 80 DAP. Following the peak, petioles declined steadily as the season progressed (Figs. 2 and 3). For both cultivars, treatment differences in soil N were not as defined or obvious as with the petioles (Figs. 4 and 5). Often, the soil N levels appeared to reflect the rates being applied. Occasionally, however, the soil values from the treatments intertwined and trends were not clear. During mid to late season, the highest N rate could typically be resolved from the other treatments, with soil values far in excess of the other treatments (Figs. 4 and 5).

Vine Weights, Senescence and Harvest Index

The effects of N became somewhat apparent within 10 days after the first in-season N application. The two highest N treatments of both cultivars typically started to develop the heaviest overall canopy weights, which continued throughout most of the season (Figs. 6 and 7). Vine weight differences between the lowest three N rates, and occasionally all N rates, were not always apparent. For the most part, however, the 0% treatments of both cultivars produced the lowest vine weights (Figs. 6 and 7). As the season progressed, fresh vine weights of Premier typically peaked close to 100 DAP while Alturas vine weights appeared to have peaked 20 to 40 days later. This perhaps reflects a major growth difference between the cultivars and, with further research, may have implications for improving N application timing. Although the vine weights did not always appear to correlate with the in-season N treatments, the differences between the lowest and highest treatments were typically quite pronounced and indicated that much of the additional N available to the plants in the high N treatments was directed toward vine production in both cultivars (Figs. 6 and 7). Beyond 100- to 120-DAP, vine weights across most treatments of both cultivars began to decline due to the onset of natural vine senescence, suggesting a changing source/sink relationship between the vines and tubers. In general, Alturas vines appeared heavier on average than Premier and persisted later into the season. (Figs. 6 and 7)

In-season N rate substantially affected the harvest index for both cultivars across years. By the time foliar weight had peaked during the season, those plants receiving lower N rates had partitioned more fresh weight to tubers than plants receiving higher amounts of N (Figs. 8 and 9). In essence, plants receiving less N favored tuber production and plants receiving virtually unlimited N favored vine production as a percentage of whole-plant fresh weight at this point in the growing season.

When vine senescence was regressed against N rate, highly significant non-linear trends were revealed. For both cultivars, vine senescence at 140 DAP increased as N rate declined. This trend was significant for Premier all three years, but was only significant for Alturas during 2007 and 2008 (Fig. 10). Lush growth was seen across all Alturas treatments for most of the year during 2009. As a result, the trend that existed in the previous years was not seen, and treatments were not different at 140 DAP (data not shown). Compared with the previous years, the lack of differences among the 2009 Alturas treatments was likely an effect of growing season. Though not measured, vine senescence differences appeared to be more evident as the 2009 season progressed beyond 140 DAP.

Tuber Quality and Specific Gravity

In-season N rate did not significantly affect blackspot bruise, stem end discoloration, shatter bruise, hollow heart, internal brown spot, length to width ratio or brown center (data not shown). Overall, incidences of these tuber defects were very low with the exception of shatter bruise in Premier. Though treatments were not statistically different, Premier appeared to be genetically susceptible to shatter bruise averaging 70%, 77%, and 88% in 2007, 2008, and 2009, respectively, across all treatments.

Tuber specific gravity was highly correlated with N rate for both cultivars across all years (Fig. 11), with the exception of Premier in 2009 (data not shown). Specific gravity increased as in-season N rate decreased. Because there were highly significant trends during the previous years for both cultivars, it is plausible that climate and/or field variability during 2009 complicated the otherwise typical specific gravity x N rate trend seen in Premier (data not shown). Relative to the mock processing contract parameters, the specific gravity values for all treatments of both cultivars were well within the range where the maximum incentives could be achieved (Fig. 11).

Stem Number, Tuber Number, and Average Tuber Weight

Stem and tuber number per plant were not significantly different across treatments and years for either cultivar (data not shown). Stem number averages across three years were 2.5 stems per plant for Premier and 3.04 stems per plant for Alturas. Alturas averaged 10.3 tubers per plant across all treatment levels and years while Premier averaged 7.8 tubers per plant. Premier average tuber weight across all years increased as more in-season N was applied (Fig. 12). The average increase in tuber weight for each 25% increase in the in-season N treatment was 0.4 oz. The difference in tuber size between the 150% treatment and the 0% difference was 1.8 oz (Fig. 12). There was no significant trend when Alturas average tuber size was regressed against N rate, however, treatment differences existed. Alturas tubers receiving no in-season N were among the lightest, averaging 5.8 oz per tuber and were significantly different from tubers of the 100% (P = 0.0476) and 50% (P = 0.0033) treatments; tubers from those treatments weighed 6.22 oz and 6.4 oz on average, respectively (data not shown). Tubers from the 25% and 150% treatments were not significantly different from the other treatments and weighed an average of 6.18 oz each (data not shown).

Total Tuber Yield and Size Distribution

In-season N levels had a significant and substantial affect on total tuber yields in both cultivars in all years of the study. As in-season N rates increased, total yield of both cultivars increased in a highly significant non-linear trend (Fig. 13). Alturas maximum yield occurred when the highest rate of N was applied (approximately 355 lbs in-season N/A). Premier total yield peaked at 123% (approximately 295 lbs in-season N, Fig. 13). The difference in total yield between the 0% and 100% treatment of Premier was approximately 100 CWT/A. Based on the decline in total yield beyond 123%, it appears as though excess N did not contribute to a corresponding yield response in Premier. Total yields in both cultivars were substantially lower in 2008 than in 2007 or 2009 (data not shown).

In-season N level influenced tuber size distribution for both cultivars across all years. Significant correlations were obtained when market yields of > 4 oz and > 6 oz tubers were regressed against in-season N (Figs. 14and 15). The trends and responses to applied in-season N were similar for both cultivars, differing only in the amount of in-season N required to reach maximum yields in the size categories examined.

For Alturas, maximum yields of marketable tubers > 4 oz occurred at 120% of the typical Russet Burbank in-season rate (approximately 288 lbs in-season N/A, Fig. 14) while maximum yields of marketable tubers > 6 oz peaked, at 160% of the typical in-season N rates (384 lbs in-season N/A, Fig. 15). > 12 oz tubers peaked at 120% of the typical russet Burbank in-season rate (approximately 288 lbs N/A; Fig 16). In Premier, yield of tubers > 4 oz reached a maximum at 117% of the current in-season N recommendations (280 lbs in-season N/A, Fig. 14) and 108% (259 lbs in-season N/A, Fig. 15) in the > 6 oz category. Maximum yield of >12 oz tubers occurred at 117% of typical Russet Burbank in-season rates (Fig 16). When total yield was partitioned into four tuber size categories, 0-4 oz, 4-8 oz, 8-12 oz, and >12 oz, it became evident that in-season N had little to no effect on total yield tuber size distribution (Figs. 17 and 18).

Alturas tuber size distribution remained unaffected (Fig. 17), despite the effects N rate had on yield (Fig. 13). Only yields of the smaller Premier tubers (<8 oz) were affected by N rate (Fig 18. In essence, more small tubers were produced as N rate declined. 10% of Premier total yield fell into the 0-4 oz category when no in-season N was applied while only 7.6% of the 100% treatment's yield was undersized (Fig. 18). Likewise, 42% of the 0% treatment's yield was 4-8 oz tubers while 31% of the 100% treatment's yield was 4-8 oz tubers (Fig. 18).

Economics

With the exception of Premier in 2007, adjusted gross processing income reached a maximum at in-season N rates at, or slightly above, the 100% rate (Fig. 19). Too much N (150%) was typically detrimental to the grower's bottom line (Fig. 19). In Alturas, revenue was optimized at 108% of the typical in-season N rate (259 lbs in-season N/A) and Premier revenue was optimized at in-season N rates of 100% (240 lbs in-season N/A). During 2007-09 in Alturas and 2008-09 in Premier, the marginal revenue gains from in-season N declined as the total amount of N increased beyond the maximum. Beyond the optimal rates of 108% for Alturas and 100% for Premier, additional in-season N only served to reduce revenue, despite any marginal gains in yield. Adjusted gross income was maximized at the various rates for both cultivars due to a mix of optimizing incentives within the processing contract, producing relatively high market yields, and minimizing N expense per unit of production. Importantly, the economic analyses for both cultivars demonstrated that maximum biological yield was typically not synonymous with maximum economic yield.

Nitrogen response patterns were established for both cultivars by dividing the total yield (tons/A) associated with the N rate that provided maximum economic returns (423 lbs total season N for Alturas and 392 lbs total season N for Premier) by the pounds of N required to reach that yield. Both cultivars required 11 pounds of total season N/A to produce one ton of fresh tuber weight.

Postharvest Fry Color Analysis

The effect of in-season N rate on fry color out of 44ºF storage was cultivar dependent. For both cultivars across all in-season N rates, fry color was generally darker in 2008 than in 2009 (Figs. 20 and 21). For Alturas, tubers in both years and across all in-season N rates typically produced acceptable fry color (USDA 1 or better) after being stored at 44ºF until mid-April. Tubers from the 150% in-season N treatment produced lighter fries (USDA 0) than the 0% in-season N tubers in both years. In 2007, after 228 days in storage, tubers from the highest N treatment (150%) retained uniform fry color (<9 reflectance units difference between stem and bud end) while tubers from the 0% treatment developed non-acceptable uniform fry color (stem to bud fry color difference ≥ 9 reflectance units; Fig. 20). In 2008, tubers from both the 0% and the 100% treatments produced acceptable fry color throughout the 228-day storage season, although the difference in stem to bud end fry color was greater for the 0% N crop. Not surprisingly, Premier, a cultivar noted for resistance to low temperature sweetening (Novy et al. 2008) retained processing quality for the duration of the 228-day storage season in both years of the study. However, as with Alturas, tubers from the 150% N treatment tended to produce lighter colored fries, on average, than tubers produced with 0% in season-N.

DISCUSSION

Current Columbia Basin nutrient guidelines recommend optimum petiole NO_3-N values for Russet Burbank of 1.5 to 2.6%, 1.2 to 2.0% and 0.6 to 1.0% during tuber initiation (45-60 DAP), tuber bulking (60 DAP), and tuber maturation (120 DAP), respectively (Lang et al. 1999). The petiole values from the 100% treatment of both cultivars were typically within these recommended Russet Burbank ranges, while the 150% treatment values were significantly higher for much of the season. Similar to the 100 and 150% treatment, the reduced N treatments (0%, 25%, and 50%) produced petiole NO_3-N levels that appeared to be largely dose-dependent. According to Pavek and Holden (2008), petiole NO_3-N concentrations for Alturas and Premier typically exceed those of Russet Burbank early to mid season but track closer to Russet Burbank mid to late season. They also found that Alturas petiole levels tend to be similar or slightly above Russet Burbank's near the end of the season while Premier's petiole NO_3-N values are typically lower.

Tested and proven previously by Pavek and Holden (2008), the fertigation simulator appeared to be an extremely effective method for testing the five water-applied fertilizer treatments, as evidenced by the distinct petiole and soil trends among treatments (Figs 2-5). The unique design allowed precise and accurate applications of in-season N and, similar to commercial potato production, utilized water as the fertilizer carrier. Recommendations from research using the fertigation simulator are more likely to be adopted by growers since the in-season fertilizer delivery method closely mimics their own farm operations. In addition, there is the potential to utilize the fertigation simulator for further research into water-applied pesticides, fungicides, and miticides in a variety of field crops outside of potatoes.

Despite the fact that many growers in the Columbia Basin have reported profits on both Alturas and Premier with reduced in-season N rates (as much as half of what it is normally applied to Russet Burbank), our research demonstrates that these growers may be compromising their bottom line with the lower in-season rates. Both Alturas and Premier responded somewhat uniquely yet appeared to share a common trend relative to adjusted gross returns. Except for Premier in 2007, the adjusted gross returns for both cultivars followed the classic "law of diminishing returns" across all years; adjusted gross returns increased steadily as in-season N rates increased, eventually reaching a maximum (Fig. 19). Beyond this maximum, the marginal increase in yield was offset by a disproportional increase in N expense, resulting in a decline of adjusted gross returns. For Alturas, maximum economic yield was found at 108% of the typical in-season N rate for Russet Burbank (approximately 258-280 lbs/A in-season N, 405-410 lbs/A total season N, including residual and pre-plant). Currently published N recommendations for Alturas range from 105 to 145 lbs of N/A (Novy et al. 2003) to 220 to 260 lbs N/A (Atkinson, et al. 2003). The recommendations in both of these studies are based on total season N rates required to reach maximum total and US #1 yields with no economic analyses performed. In addition, these studies were performed in southern Idaho which typically has a shorter growing season with lower yield potential than the Columbia Basin. Therefore, N recommendations from these studies should be expected to be markedly lower than studies performed in the Columbia Basin. However, according to our results, if growers fertilized this cultivar at either of the Idaho-established rates in the Columbia Basin, yield and economic potential could be compromised.

For Premier in 2008-09, maximum economic yield was achieved with 100% of the typical in-season Russet Burbank rate (approximately 240 lbs/A in-season N, 390 lbs/A total season N). The only published Columbia Basin-specific N recommendation for this cultivar advises total season N of 263 to 304 lbs/A (Novy et al. 2008) which is 86-127 lbs lower N per acre than the highest grossing rates from this study. Again, growing this cultivar according to the published rate could have limited the yield and economical potential.

This study demonstrated the importance of developing site and cultivar specific N recommendations for new potato releases. Newer potato cultivars are being adopted quickly because of improved characteristics such as earliness, yield, quality, and storability, and increased resistance to insects, pathogens and other environmental stresses (Atkinson, et al 2003). However, little information is available on the nutrient requirements of these newer cultivars and growers are faced with more decisions all the time as new cultivars are released from breeding programs**.** For potato growers growing a new cultivar for the first time, maximum economic return, as opposed to maximum yield, should be the most important consideration in determining optimum fertilizer rates (Love et al. 2005). An understanding of a cultivar's nitrogen response pattern (lbs of N required to produce each unit of yield) and how it relates to economics is an important contributor to maximum economic return and should also be evaluated when considering growing a new cultivar. Cultivars can vary significantly in the amount of N required per unit of final yield and N costs related to production will vary as well. For example, a study by Pavek and Holden (2008, unpublished) showed that Alturas was 26% more efficient in nitrogen use (yield per pound of N required) than Russet Burbank while Premier was 13% more efficient.

Prior to the initiation of this study, it was common knowledge within the industry that many Alturas growers were applying 50% of the N typically (full season) used to produce Russet Burbank. It is now apparent that these growers may have been losing more than $250/A of potential profits due to insufficient N. This equates to a loss of over $31,000 per average size center pivot (125 acres). Following the Columbia Basin guidelines for Premier (Novy et al. 2008), growers could have lost as much as \$390/A in 2007 and \$57/A in 2008-09 compared with the economically optimum rates determined in this study. The resulting loss in grower adjusted gross income could have been as high as \$48,750 per pivot during 2007 and \$7,125 in 2008-09. Data from these experiments confirm the well known but often forgotten concept that maximum biological yield is not always the same as maximum economic yield. Indeed, maximum total yields for Alturas and Premier were obtained with 150% and 125% of the typical Russet Burbank in-season N rate, respectively. For both cultivars, however, *revenue* was generally optimized at a rate closer to 100% of typical for Russet Burbank. In addition to revenue loss from the costs associated with higher N rates, some reduction in economic return came from a shift in tuber size profile. Contract incentives were reduced on yields from the higher N rates because there were fewer tubers within the desirable size range (6-12 oz). This is of special concern to producers who enter into processing contracts with deductions for oversize tubers. Alturas total yield from the 100% treatment was 756 CWT/A across years and total yield from the 150% treatment was 781 CWT/A, a difference of 25 cwt. Although the 150% treatment had higher total yields, the fertilizer-cost-adjusted base price/CWT after contract incentives/decentives was higher at the 100% treatment (\$7.50/cwt at 150% vs \$7.56/CWT at the 100% treatment), an increase of \$0.06/CWT; N cost per acre was \$54/A higher for 150% treatment than for the 100% treatment. To produce potatoes at the 150% rate, it cost more but returned less than at the 100% treatment. A closer look at the economics reveals that the proportion of 6 oz and greater tubers was higher at the 100% treatment than the 150% treatment (32% vs 29%) and the proportion of culls and tubers < 4 oz were less at the 100% treatment than the 150% (12% vs 14%). Though these differences appear minute, the extra \$0.06/CWT multiplied by a yield of 750 CWT/A translates into an extra $5,625 in processing contract incentives per 125 acre pivot.

Economics for Premier were quite similar to those of Alturas, with the exception that the 100% treatment in Premier had higher total yields than the 150% treatment (719 CWT/A vs 714 CWT/A, respectively). Similar to Alturas, the percentage of undersize tubers was less at the 100% treatment (7.56%) than the 150% treatment (7.92%) and the percentage of > 6 oz tubers was higher at the 100% treatment (79%) than the 150% treatment (77%). This combination led to a contract-adjusted base price of $7.59/CWT at the 100% and $7.58 for the 150% treatment. For a standard sized pivot, the extra $0.01 incentive resulted in an $875 gain (per 125 acre pivot), illustrating again that a fractional shift in tuber size distribution can affect the growers bottom line. These data suggests that the appropriate amount of in-season N management is essential for producing tuber size profiles of maximum economic value.

It is widely reported in the literature that excess N can delay crop maturity. The findings in this experiment confirm those conclusions. Recent work by the N.R. Knowles lab at Washington State University on the effects of N on physiological maturity of tubers has demonstrated that higher in-season N can delay the onset of tuber physiological maturity. Tuber physiological maturity is defined as the window at the end of the growing season where tubers have reached maximum specific gravity, with minimum concentrations of sucrose and reducing sugars (Knowles et al. 2009). Tuber maturity affects the postharvest behavior and quality of processing potatoes which in turn affects the grower's bottom line. For many cultivars, tubers will maintain processing quality the longest during storage if harvested at physiological maturity (Knowles et al. 2009). Physiological maturity is gauged through key indices of crop maturity including harvest index (tuber weight as a proportion of total plant weight calculated at maximum foliar weight), vine persistence, and total vine biomass, as well as specific gravity. In this study, in-season N had a substantial impact on each of these important maturation criteria. In general, as in-season N increased, harvest indices decreased (Figs. 8 and 9) and vines persisted longer into the growing season (Figs. 10 and 11); plants receiving the highest N rate produced the most foliar biomass. These trends characterize the effects of N on source-sink relationships; plants grown with unlimited N (150%) partitioned more fresh weight to vines than to tubers, up to the point of maximum foliar growth. High N delayed plant senescence and the attainment of physiological maturity. These data support the well known fact that excess N can delay tuber maturity and lead to excessive vine growth at the expense of tubers (Harris 1992). However, excess vine growth, at least in these two cultivars, wasn't necessarily detrimental as the highest yields were found at the highest in-season N rates, as were the heaviest vines. These data also illustrate that N management can be a valuable tool for tailoring crop maturity to maximize processing incentives and profits.

Specific gravity is an important quality criterion for processing potatoes. It is used as an estimate of the solids or dry matter content of tubers - the higher the dry matter content the lower the water content and the higher the specific gravity. Consumers, fast food retailers, and processors alike have recognized that the ideal french fry is light in color, not too oily, and crisp on the outside and fluffy or mealy on the inside. High specific gravity potatoes are needed to produce such a product. The desired range of specific gravity desired by processors of frozen potato processors is 1.076 to 1.095, which is reflected by contract incentives for market grade tubers within these ranges. Moreover, penalties are assessed for potato lots with gravities above or below the desired range. Increasing N resulted in depressed specific gravities in both cultivars in a highly significant non-linear trend (with the exception of Premier in 2009; Fig. 11). This trend was expected as physiologically younger tubers, such as those seen at the 100% and 150% N rates typically display lower gravities (Knowles et al. 2009). Although specific gravity decreased as N increased, the gravity values for both Alturas and Premier remained within the acceptable range for processing at all in-season N levels. This demonstrates that even at multiple levels of in-season N (0% and 150%), these cultivars will likely be eligible for specific gravity incentives. Overall, Premier tubers produce specific gravity values that appeared to surpass those of Alturas (Fig. 11). This came as no surprise, however, because Premier is noted for having higher specific gravity than most standard processing cultivars (Novy et al. 2008).

The effects of N on the physiological maturity of tubers also became evident during out-of-storage fry color analysis. Data from the Knowles lab at Washington State University shows that for both cultivars in both years, the physiologically younger tubers (150% in-season N) produced lighter fries (USDA 0) than the older tubers grown with 0% in-season N. Tubers grown with high N (150%) also produced smaller differences between stem and bud end reducing sugars when compared against the 0% treatment (Figs. 20 and 21). This is indicative of physiologically younger tubers and typically translates into better quality for processing out of storage (Knowles at al. 2009) as evidenced by Alturas retaining uniform fry color at 44ºF through 228 days of storage at the highest in-season N rate (physiologically younger tubers), in both years of the study, while the low N rate (physiologically older tubers) had higher concentration of reducing sugars in the stem end and developed unacceptable non-uniform fry color by 131 days in storage in 2007 (Fig. 20). Attainment of physiological maturity was also delayed in Premier grown with 150% N; however, this cultivar maintained processing quality throughout the entire 228-day storage period in both years and never developed non-uniform fry color (Fig. 21). This was expected, however, because of Premier’s cold sweetening resistance.

As illustrated by these trends, in-season N has definite implications for the attainment of physiological maturity which in turn has implications for processing quality out of storage, which can affect grower revenue (Knowles et al. 2009).

In-season N management can influence tuber production and processing quality and should be tailored by growers to maximize their profits. This research highlights the importance of understanding the effects of N on whole plant morphology and illustrates that maximum yield should not be the only consideration when growing new cultivars. Too often N recommendations are directed towards obtaining the maximum biological yield and not the maximum economic yield. Of much more interest to a producer should be an understanding of the relationships between N management, input costs, yield, tuber quality, and profitability. In addition to effects on yield, in-season N management can affect specific gravity, average tuber size, fry color out of storage, and key crop maturity indices such as harvest index, vine persistence, and total foliar biomass; all of which may impact tuber quality and grower revenue.

In order for Columbia Basin growers to minimize risk and maximize returns when producing Alturas and Premier, we recommend petiole and soil N concentrations be maintained within the ranges found in Tables 5 and 6. These values were established following a detailed review of data from all years for both cultivars with the goal of finding ranges that were relatively low-risk, yet profitable. Due to all the different elements involved in crop production, it is difficult to recommend a specific N fertilizer regime that will work for all growers across all situations and seasons. Soil type, organic matter content, previous crop residues, weather and other factors all affect N availability; producers may find they can apply less N than levels found in this study and still produce profitable yields. However, coarse textured soils, prevalent in many parts of the Columbia Basin, may require slightly higher rates of N if leaching is prevalent.

In addition, as input costs and potato prices changes the amount of in-season N required to maximize profits may change.

By utilizing the recommended petiole NO_3-N and soil N ranges, growers can adjust their inputs as needed for each situation, thereby maintaining plant growth and health that is necessary to produce a profitable crop. It is essential for growers to keep all other nutrients at appropriate levels, according to Columbia Basin Russet Burbank recommendations (Lang et al. 1999). Moreover, if plant health is compromised by improper irrigation, disease, insects, mites, or other pests, the recommended petiole and soil values herein may not be appropriate. We feel that these recommendations provide a solid foundation for growers to make informed decisions regarding N management within their own, unique operation. Although it may be possible to make a profit with in-season N rates and petiole and soil values lower or higher than those found in this study, our intent was to identify N management that would lead to the maximum economic yields for these cultivars. As with any research and crops, these recommendations may be modified in the future as the management of these two cultivars becomes better understood.

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Fig. 1. Chemigation simulation unit applying in-season fertilizer treatments on the Othello Research station.

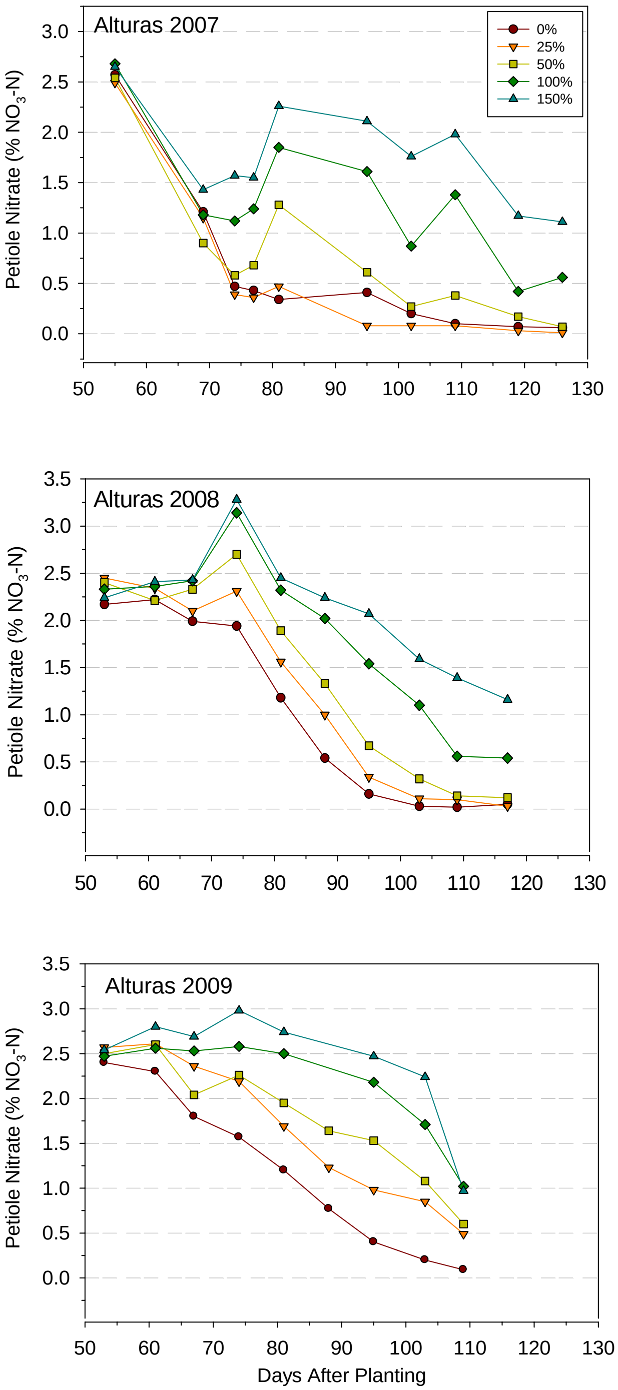


Fig. 2. Alturas petiole NO_3-N concentration across five different in-season N treatments during 2007-09.

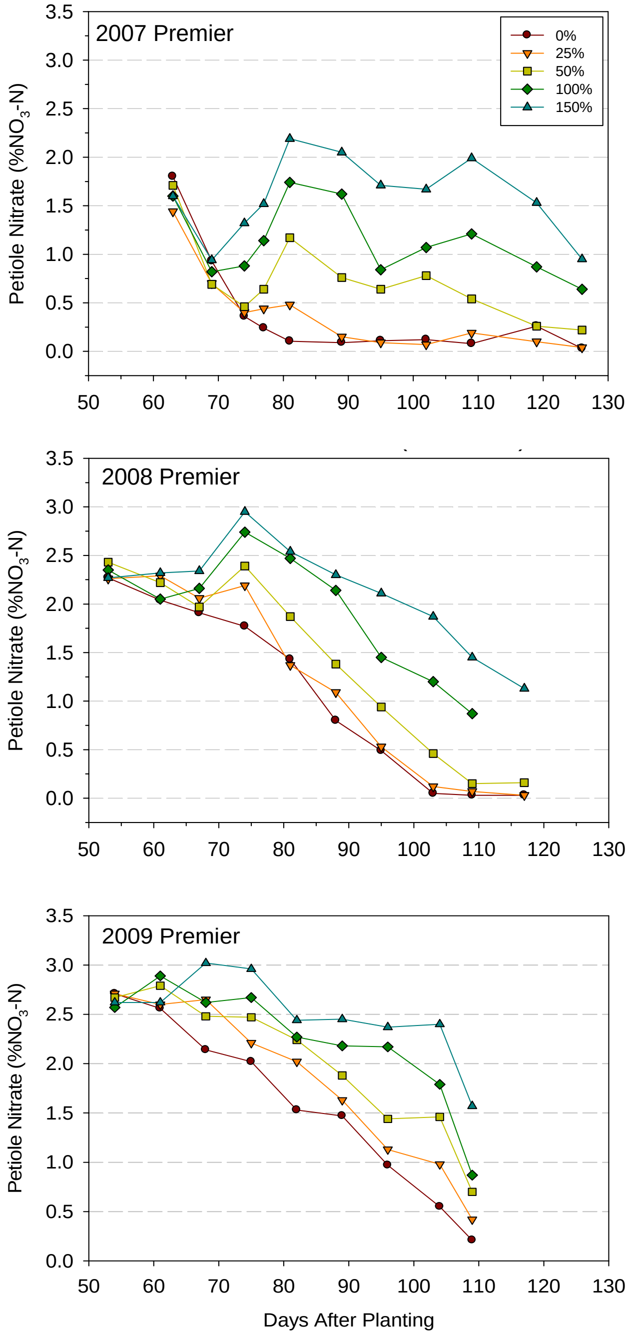


Fig. 3. Premier petiole NO_3-N concentration across five different in-season N treatments during 2007-09.

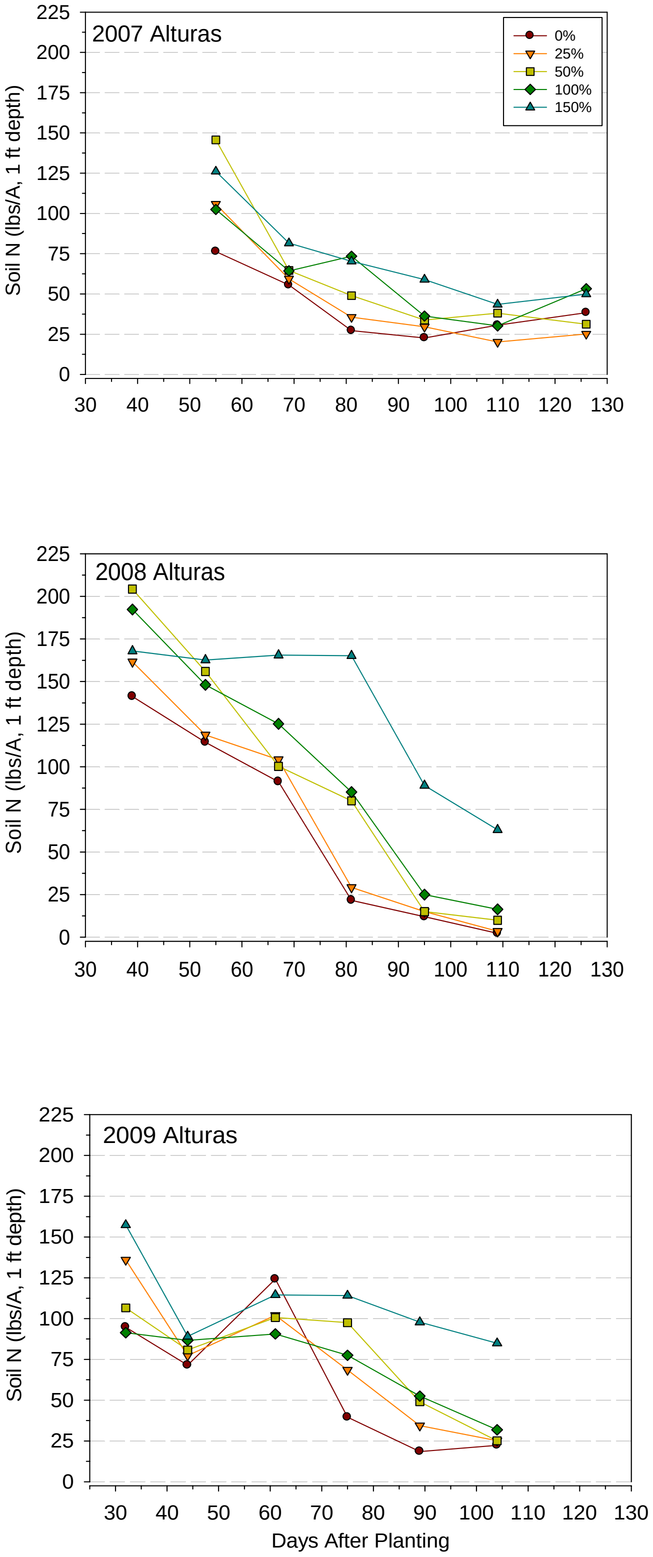


Fig. 4. Alturas soil total N (NO_3-N + NH_4) levels across five different in-season N treatments during 2007-09.

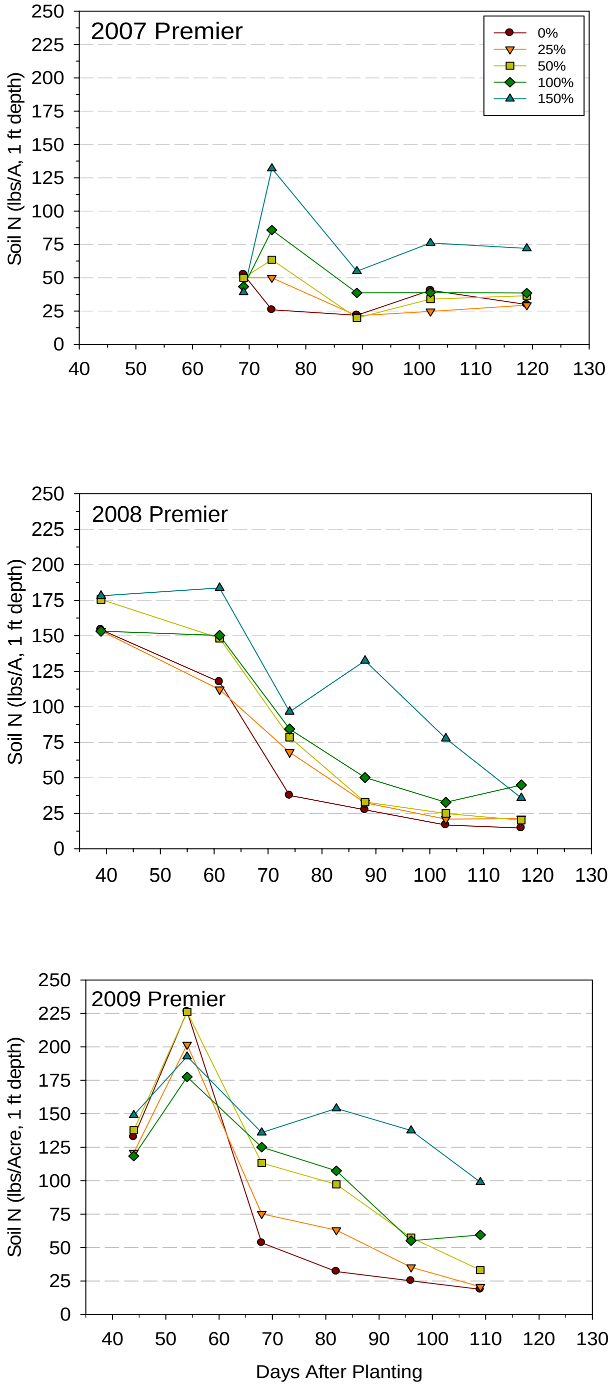


Fig. 5. Premier soil total N ($NO_3 + NH_4$) levels across five different in-season N treatments during 2007-09.

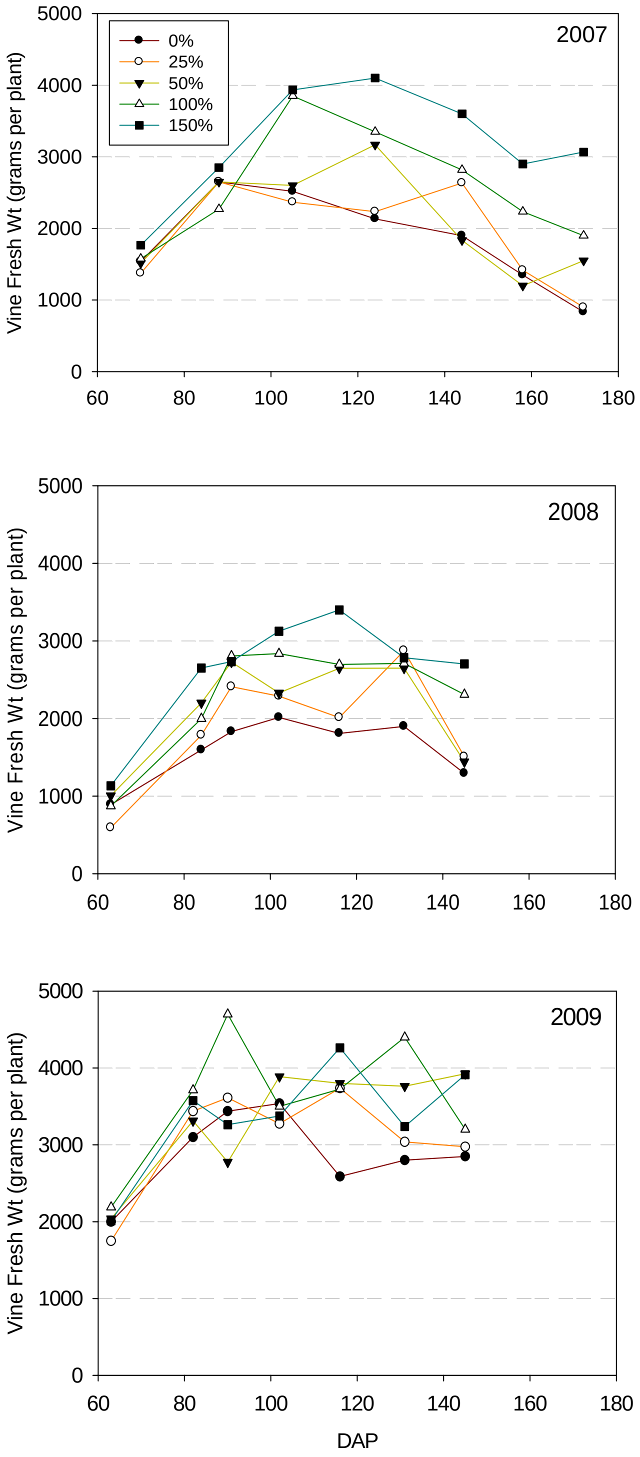


Fig. 6. Alturas fresh vine weights across the growing season for five in-season N rates during 2007-09.

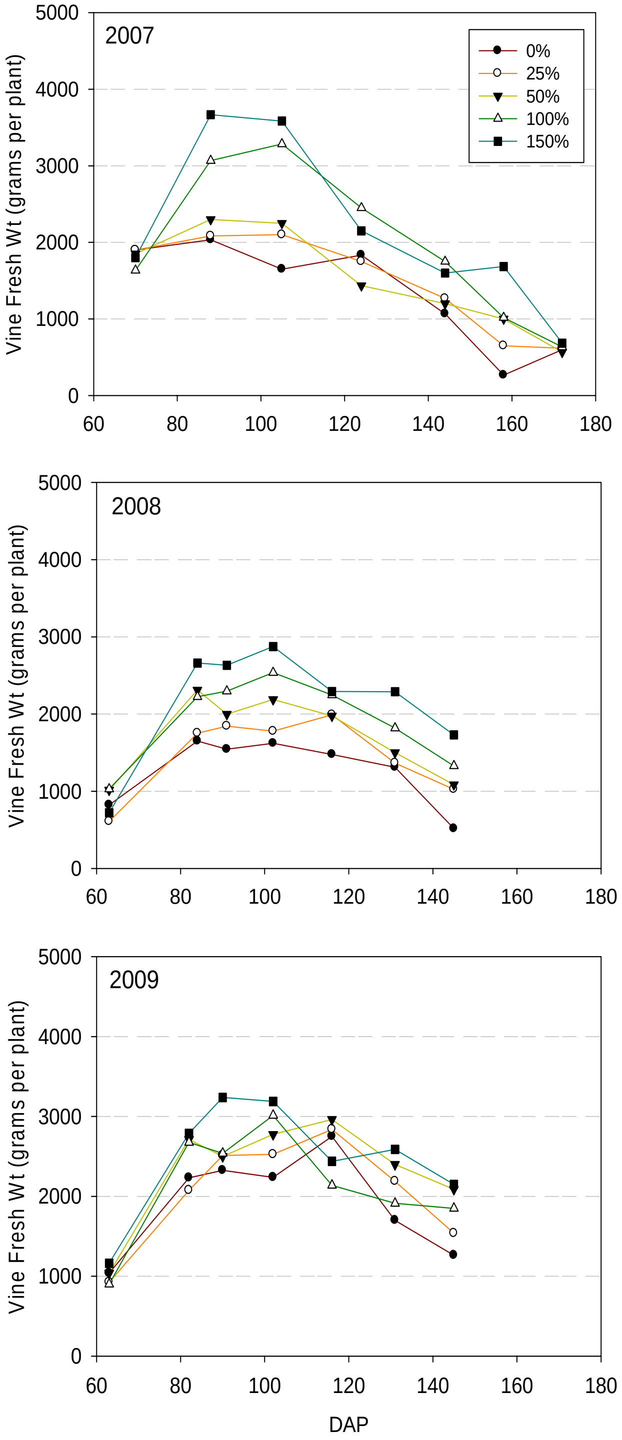


Fig. 7. Premier fresh vine weights across the growing season for five in-season N rates during 2007-09.

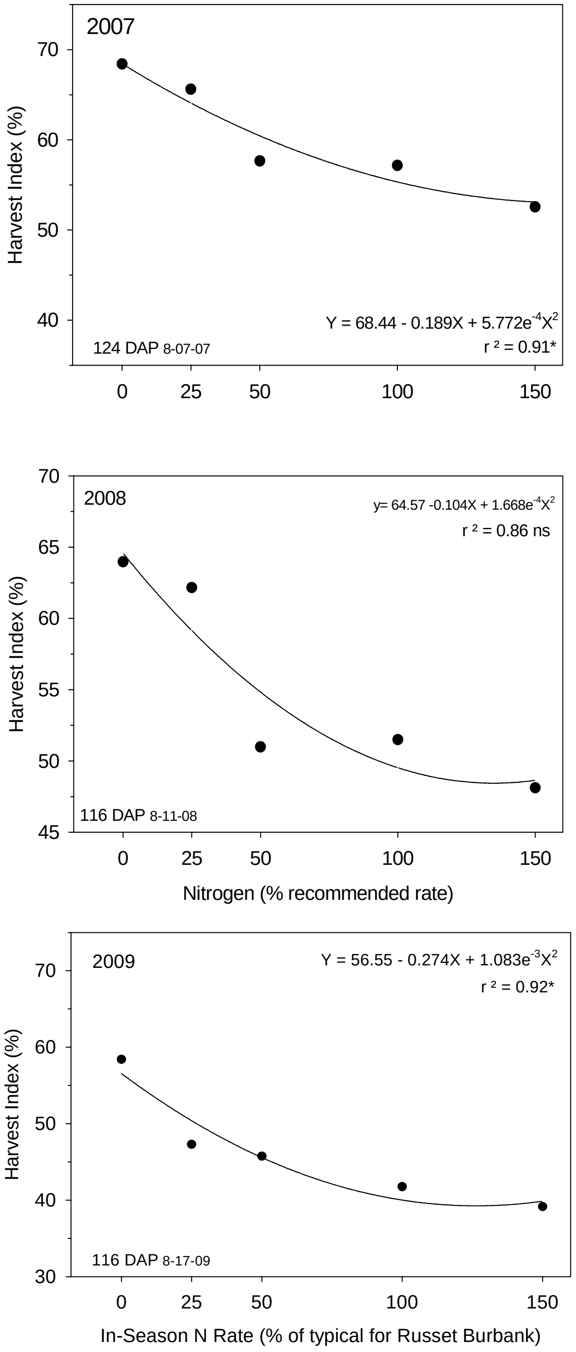


Fig. 8. Alturas harvest index at 124 DAP (2007) and 116 DAP (2008 and 09).
*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

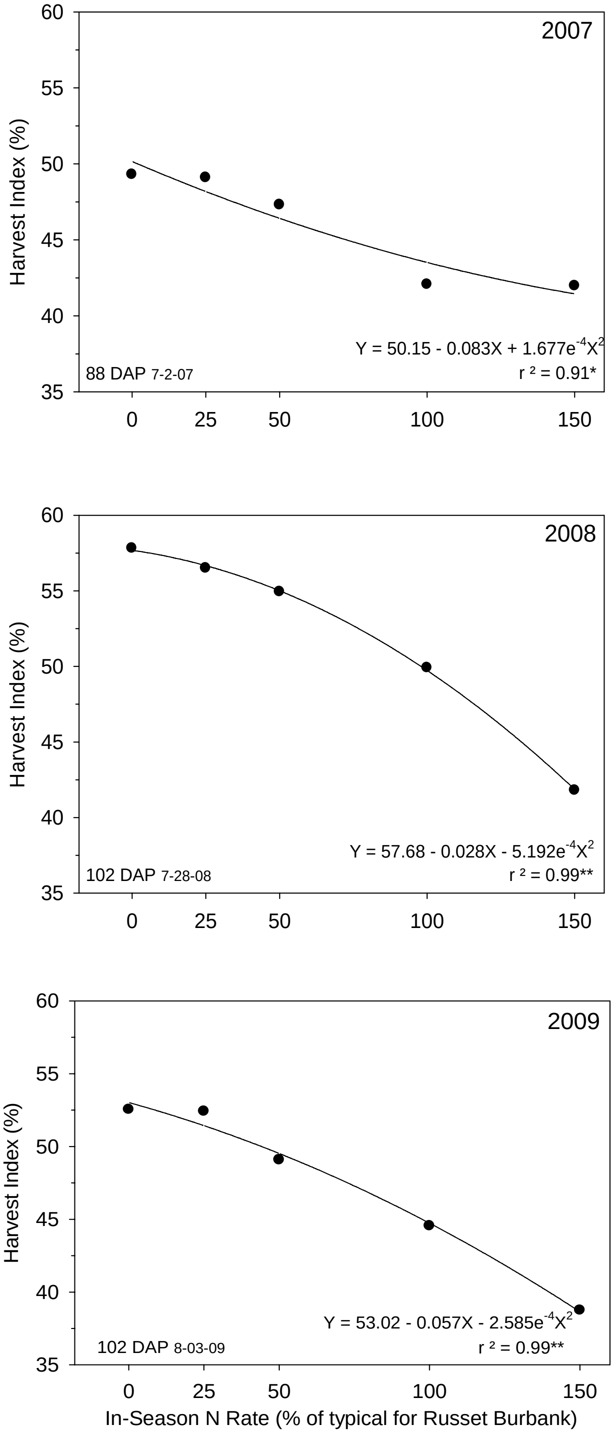


Fig. 9. Premier harvest index (calculated as tuber weight/tuber weight + above ground-fresh plant weight x 100) at 124 DAP (2007) and 116 DAP (2008-09).

*, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

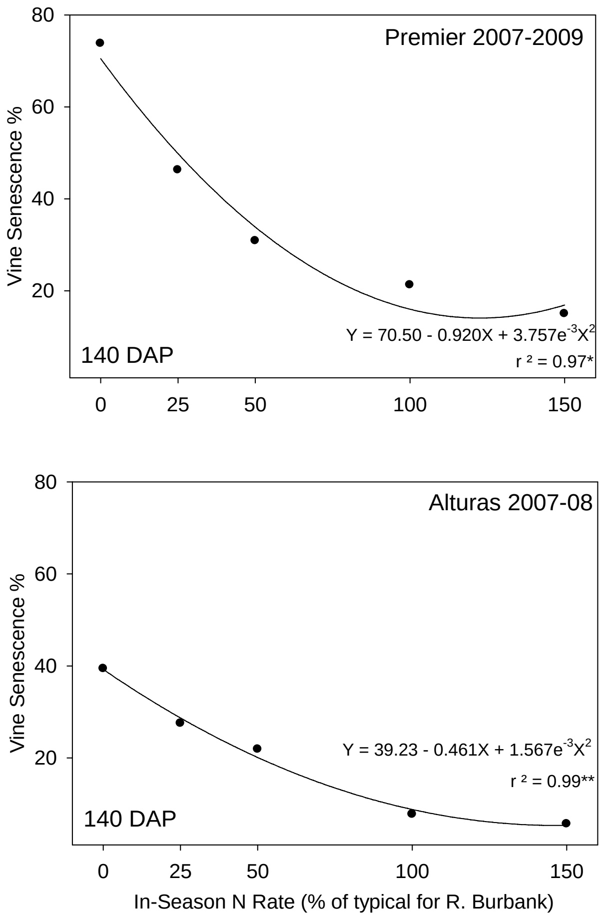


Fig. 10. Premier vine senescence (2007-2009) and Alturas vine senescence (2007-08) as a function of in-season N rate. Vines were visually rated at approximately 140 DAP. Trends in Alturas vine senescence was non-significant in 2009 and are not shown.

*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

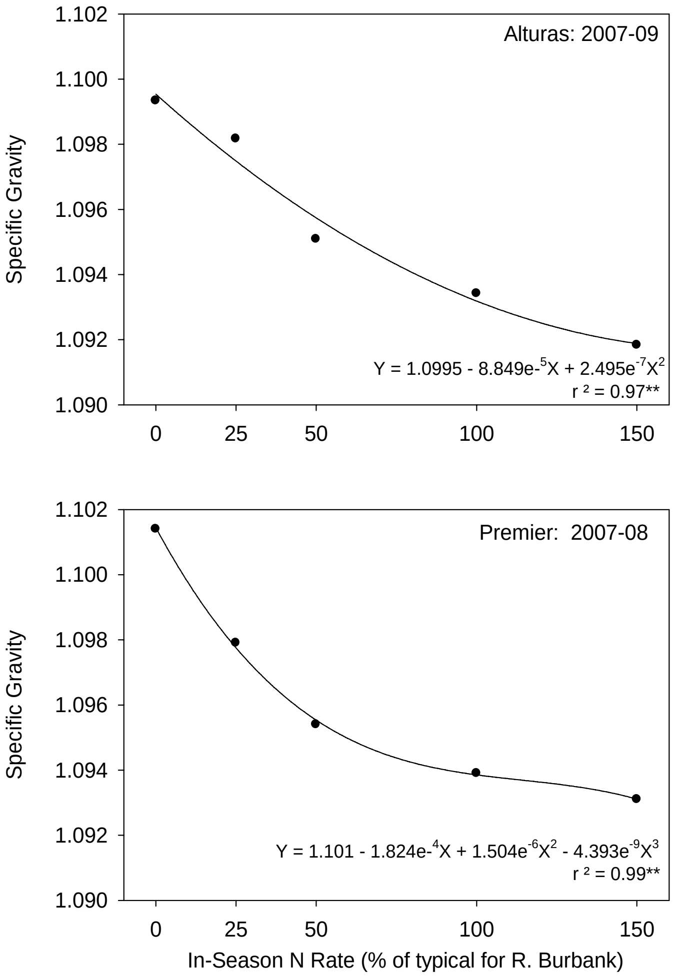


Fig. 11. Specific gravity for Alturas (2007-09) and Premier (2007-08) across five in-season N rates. No differences were observed in Premier in 2009 therefore data is not shown.
*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

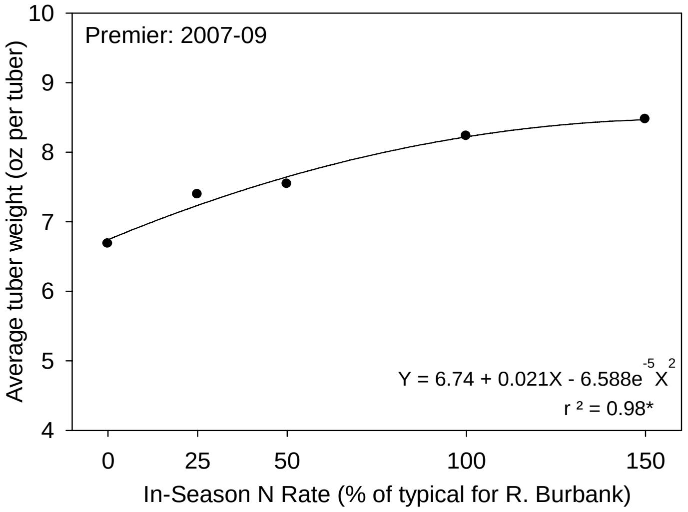


Fig. 12. Premier average tuber weight at harvest for combined years 2007-09.Tuber weight was not significant for Alturas (data not shown).

*, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

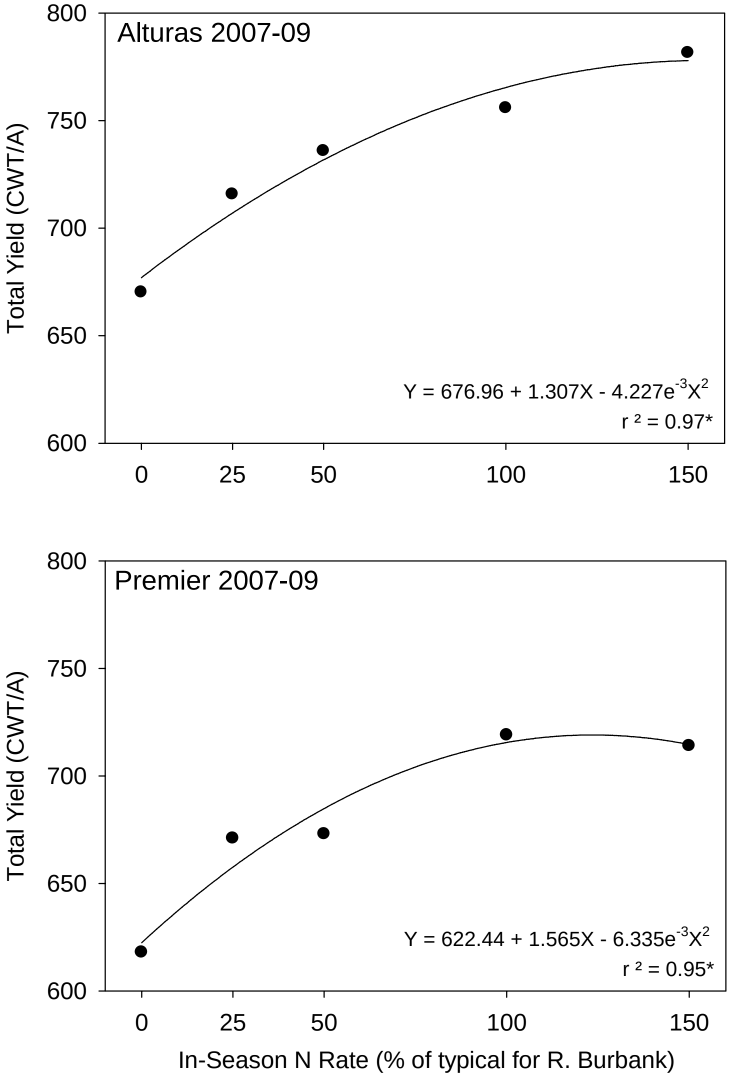


Fig. 13. Alturas and Premier total yield across five in-season N rates during 2007-009. *, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

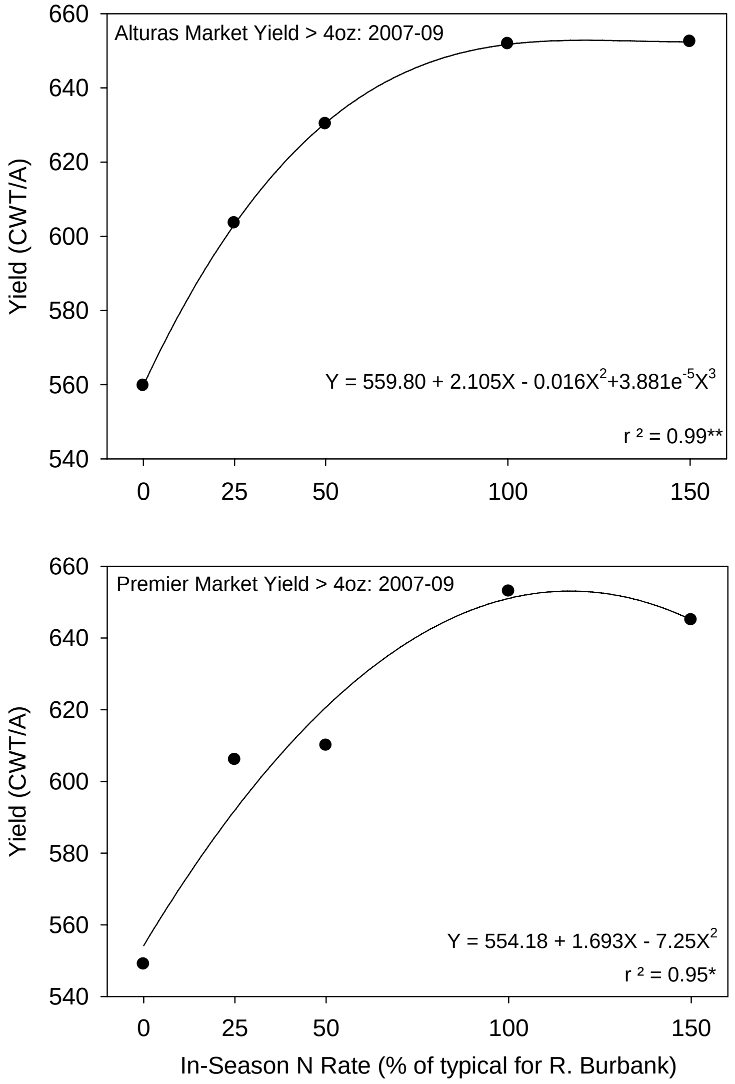


Fig. 14. Alturas and Premier market yield >4 oz across five in-season N rates during 2007-09. *, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

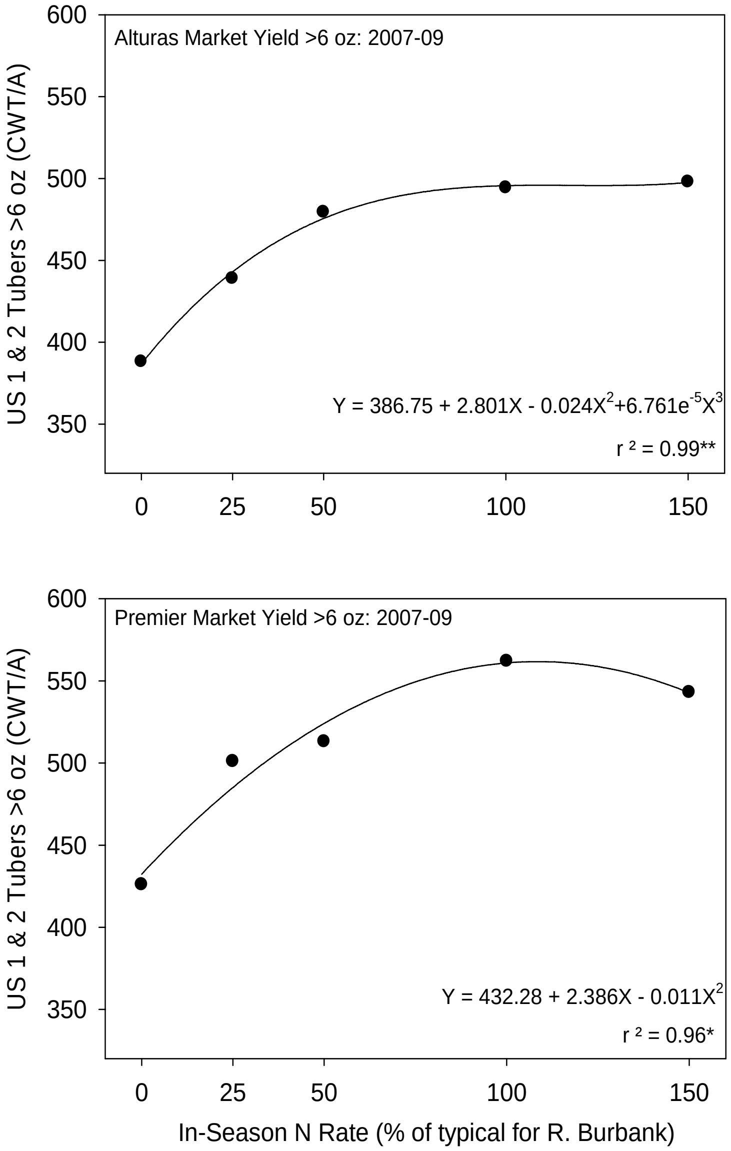


Fig. 15. Alturas and Premier market yield >6 oz across five in-season N rates during 2007-09. *, *, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

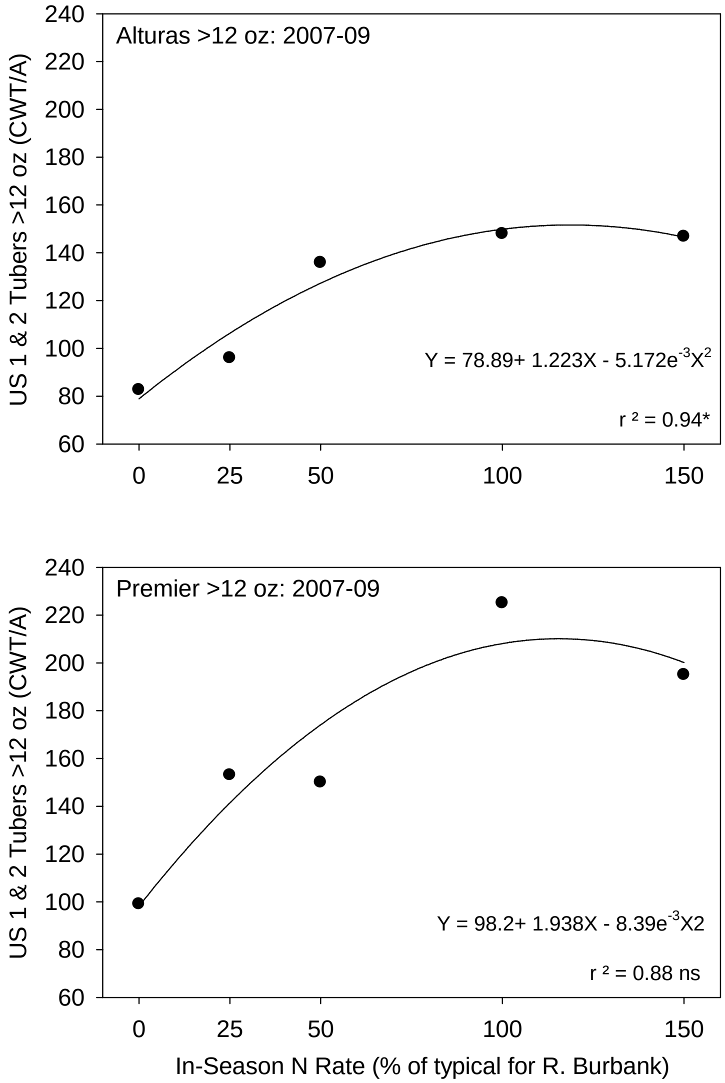


Fig. 16. Yield of > 12 oz tubers for Premier and Alturas across 5 in-season N rates during 2007-09.

*, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

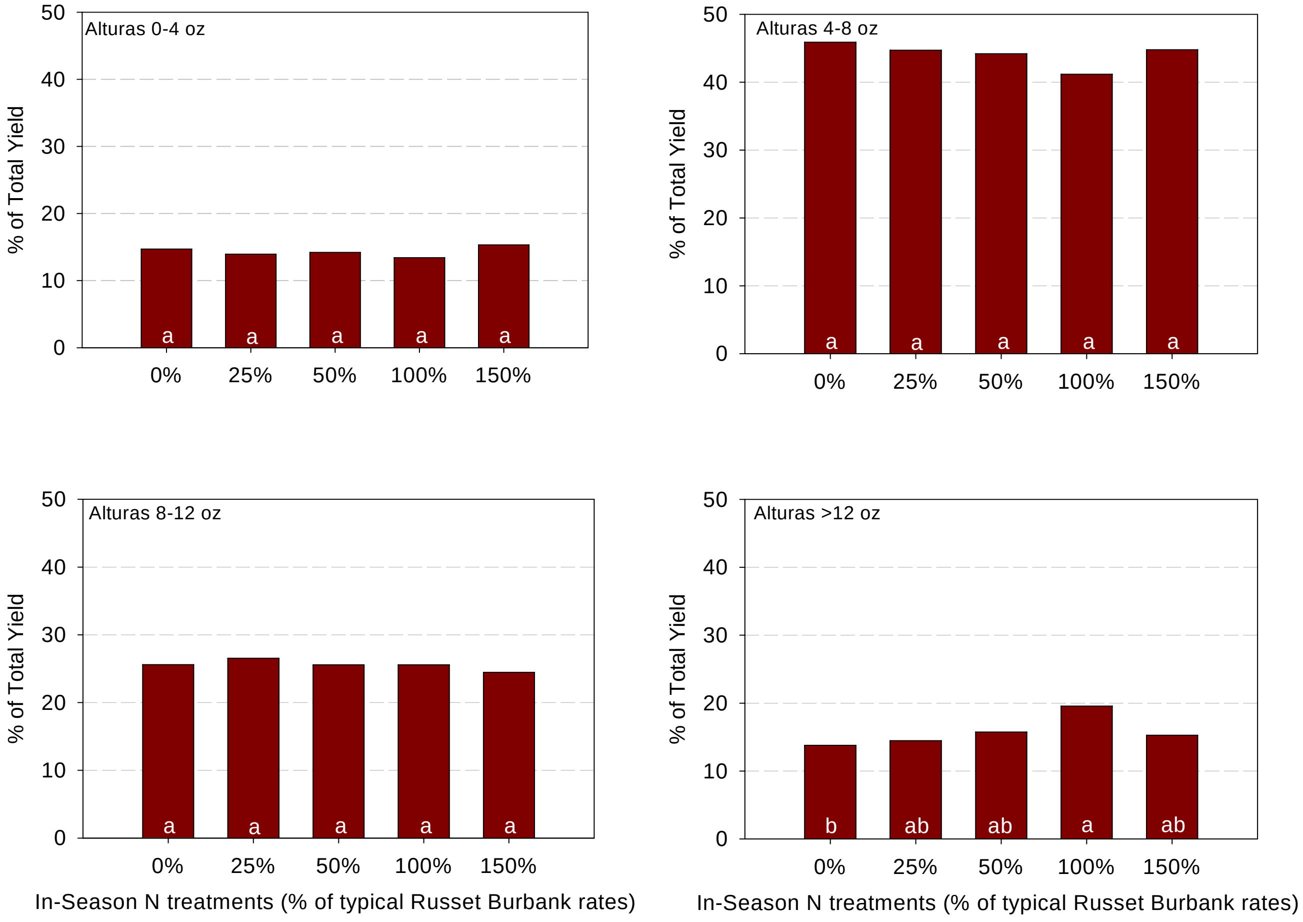


Fig. 17. Alturas total yield by size category across 5 in-season N rates during 2007-2009. Means in the columns with the same letter are not statistically different by Fisher's Protected LSD Test at the 0.05 level of significance.

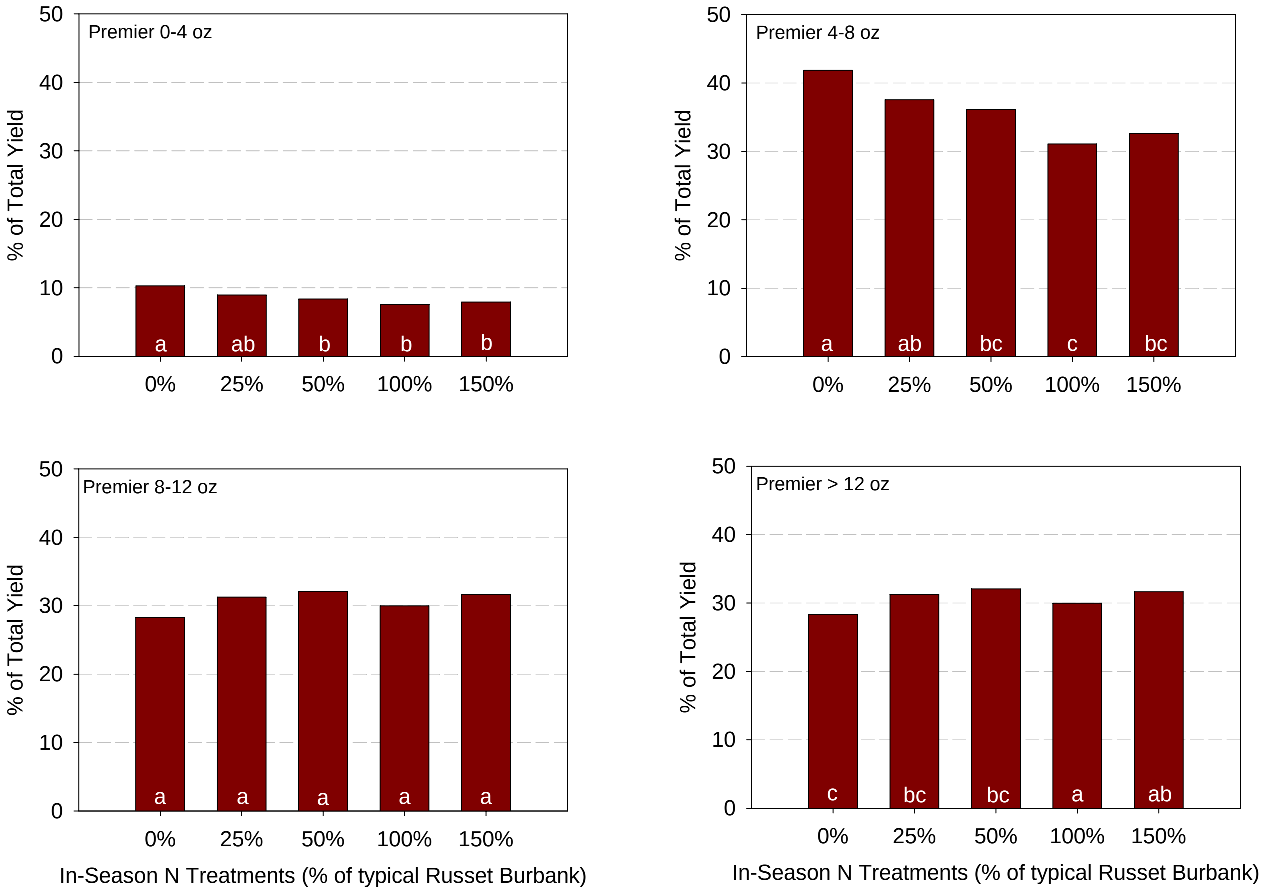
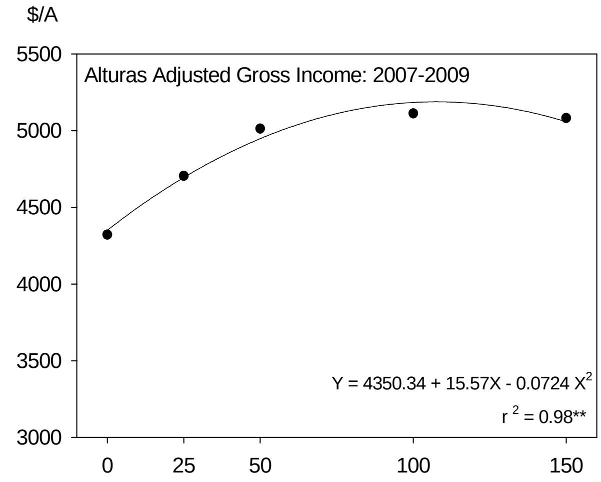


Fig. 18. Premier total yield by size category across 5 in-season N rates during 2007-09. Means in the columns with the same letter are not statistically different by Fisher's Protected LSD Test at the 0.05 level of significance.



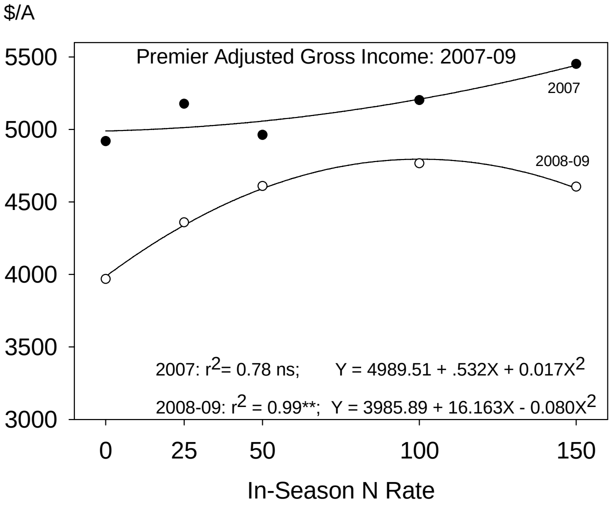


Fig. 19. Nitrogen-cost adjusted gross income for Alturas and Premier during 2007-09. The economic evaluation was based on a mock processing contract modeled after contracts currently in use in the Columbia Basin of Washington and Oregon with the cost of N set at $0.44/lb. *, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

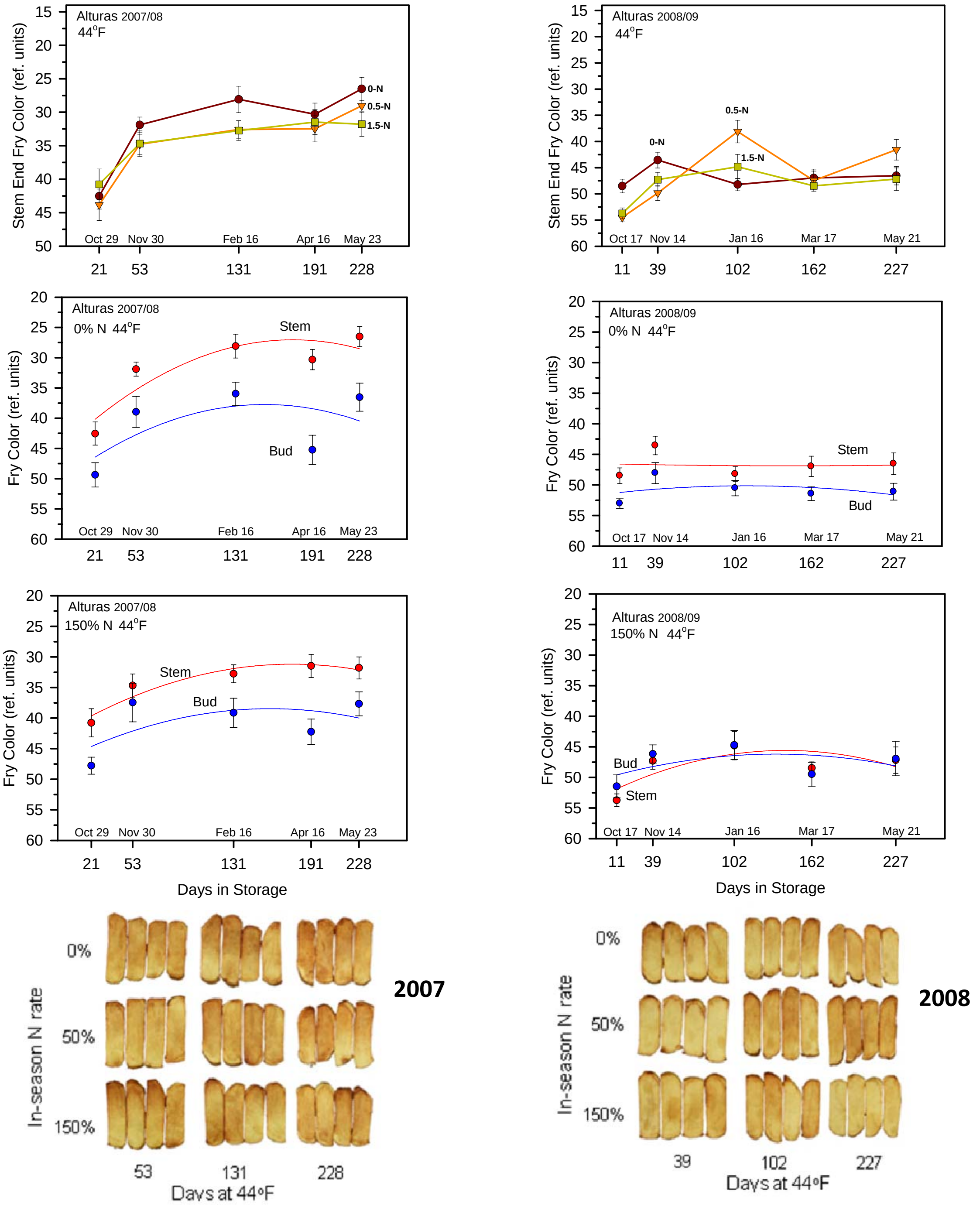


Fig. 20. Changes in fry color (photovolt reflectance) during storage of Alturas tubers at 44°F for the 2007-09 growing season as affected by in-season N rate. The crop was grown with five different in-season N treatments. Fry data was collected on the 0, 50, and 150% treatments. Low reflectance values indicate darker fries. Photovolt readings >31= USDA 0; 25-30= USDA 1; 20-24 = USDA 2; 15-19= USDA 3; <14= USDA 4. Differences in photovolt reflectance units of <9 between the stem and bud end reflectance values are considered to be acceptable, while differences of ≥9 reflect constitute unacceptable, non-uniform fry color.

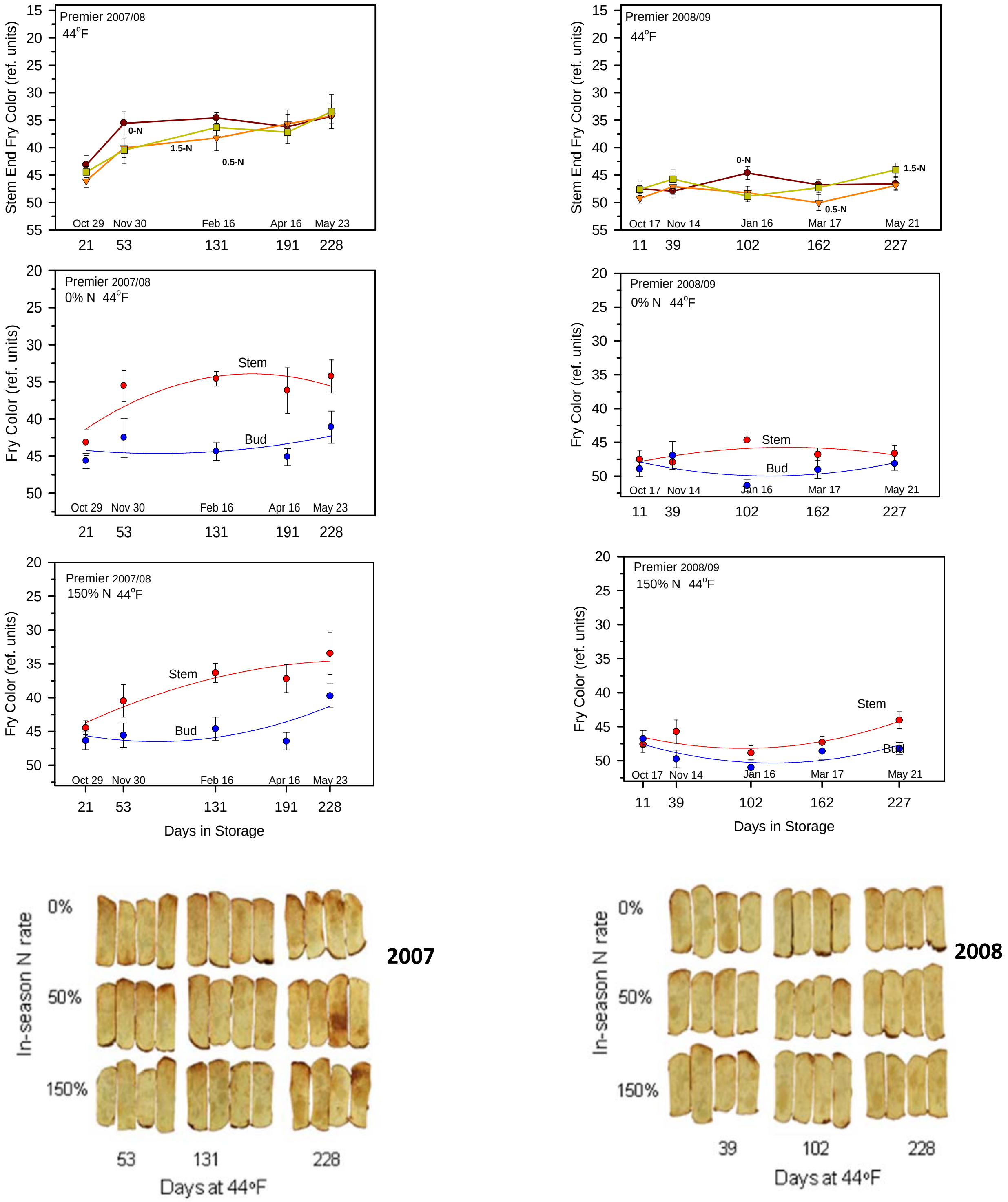


Fig. 21. Changes in fry color (photovolt reflectance) during storage of Premier tubers at 44°F for the 2007-09 growing season as affected by 5 different in-season N rate. Fry data was collected on the 0, 50, and 150% treatments. Low reflectance values indicate darker fries. Photovolt readings >31= USDA 0; 25-30= USDA 1; 20-24 = USDA 2; 15-19= USDA 3; <14= USDA 4. Differences in photovolt reflectance units of <9 between the stem and bud end reflectance values are considered to be acceptable, while differences of ≥9 reflect constitute unacceptable, non-uniform fry color.

Table 1. Preplant, in-season, and total season nitrogen for 2007 and associated in-season N expense for five rates of in-season N applied to Premier and Alturas

Treatment As a % of Standard RB Rate	Applied Pre-plant N + Soil Residual[a]	Measured At-Emergence Soil N[b]	Applied In-Season N	Applied In-Season N Via Phos Applications	Total Applied In-season N	Total N Applied in 2007	In-season N Fert Expense ($0.44/lb)
%	----------	----------	----------	lbs/A	----------	----------	$/A
0	125	127	0	30	30	155	0
25	125	127	58	30	88	213	23
50	125	127	115	30	145	270	46
100	125	127	230	30	260	385	92
150	125	127	345	30	375	500	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (75 lbs/A) plus soil N (NO_3-N 8 lbs/A, NH_4 42 lbs/A) = 125 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 100 lbs/A, NH_4 27 lbs/A).

Table 2. Preplant, in-season, and total season nitrogen for 2008 and associated in-season N expense for five rates of in-season N applied to Premier and Alturas

Treatment As a % of Standard RB Rate	Applied Pre-plant N + Soil Residual[a]	Measured At-Emergence Soil N[b]	Applied In-Season N	Applied In-Season N Via Phos Applications	Total Applied In-season N	Total N Applied in 2008	In-season N Fert Expense ($0.44/lb)
%	----------	----------	----------	lbs/A	----------	----------	$/A
0	152	168	0	9	9	161	0
25	152	168	58	9	67	219	23
50	152	168	115	9	124	276	46
100	152	168	230	9	239	391	92
150	152	168	345	9	354	506	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (80 lbs/A) plus soil N (NO_3-N 24 lbs/A, NH_4 48 lbs/A) = 152 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 159 lbs/A, NH_4 9 lbs/A).

Table 3. Preplant, in-season, and total season nitrogen for 2009 and associated in-season N expense for five rates of in-season N applied to Premier and Alturas

Treatment As a % of Standard RB Rate	Applied Pre-plant N + Soil Residual[a]	Measured At-Emergence Soil N[b]	Applied In-Season N	Applied In-Season N Via Phos Applications	Total Applied In-season N	Total N Applied in 2009	In-season N Fert Expense ($0.44/lb)
%	--lbs/A--						$/A
0	152	171	0	10	10	162	0
25	152	171	58	10	68	220	23
50	152	171	115	10	125	277	46
100	152	171	230	10	240	392	92
150	152	171	345	10	355	507	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (90 lbs/A) plus soil N (NO_3^- 30 lbs/A, NH_4^+ 32 lbs/A) = 152 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 163 lbs/A, NH_4 8 lbs/A).

Table 4. Rate scheme for five in-season N rates for 2007-2009

Treatment as a % of RB standard	Number of Applications*			
	Two	Four	Two	Two
%	----------------------------N lbs/A----------------------------			
0	0	0	0	0
25	5	7.5	6	3
50	10	15	13	5
100	20	30	25	10
150	30	45	38	15

***Applications started approximately 10 days after >90% emergence**

Table 5. Recommended petiole values at 60-, 90-, and 120-days after planting (DAP) for Alturas and Premier Russet.

Variety	End Tuber Initiation Mid June 60 DAP	Mid Bulking Early July 90 DAP	Late Bulking Late July 120 DAP
	(ppm NO3)	ppm (NO3)	(ppm NO3)
Alturas	23-26,000	17-20,000	<8,000
Premier	23-26,000	17-20,000	<10,000

Table 6. Recommended total soil N values (N03-N + NH4) at 60-, 90-, and 120-days after planting (DAP) for Alturas and Premier Russet in the top 12”.

Variety	End Tuber Initiation Mid June 60 DAP	Mid Bulking Early July 90 DAP	Late Bulking Late July 120 DAP
	(lbs/A)	ppm (NO3)	(ppm NO3)
Alturas	90-150	50	<50
Premier	90-150	50	<50

CHAPTER 2

USE OF THE CHLOROPHYLL METER AS A NITROGEN MANAGEMENT TOOL FOR PRODUCTION OF THE POTATO CULTIVAR PREMIER RUSSET

ABSTRACT

One of the most important aspects of profitable potato production is a sound nitrogen (N) management program. Implementation of a proper N management program is contingent upon an accurate assessment of the current N status of the soil and plant. Currently, N status in potatoes is measured through analysis of soil and petioles throughout the growing season. However these tests are time consuming, relatively expensive and often slow, depending on time of year. A three year study was performed at the WSU Research Station in Othello, Washington to investigate the efficacy of a SPAD (Soil Plant Analytical Development) meter, in determining current crop N status, relative to traditional petiole NO_3-N analysis in the cultivar Premier. SPAD readings for five different in-season N rates during 2007 and 2009 were recorded throughout the growing season and compared to traditional petiole analysis (No data available for 2008).

Petiole NO_3-N analysis appeared to differentiate N treatments better than SPAD especially early in the season. SPAD readings correlated better with petiole NO_3-N levels during the middle of the growing season; early and late readings were less conclusive. Relationships between SPAD readings and the concentrations of total N in the dry matter of the leaf laminae and the petiole were high during 2007 (r^2= 0.78 and 0.76, $P \leq 0.001$, respectively) but insignificant in 2009. In general, the range of SPAD readings was lower when leaf and petiole N concentrations were high (above approximately 5.0-5.5 %). Changes in petiole NO_3-N from 0 to 0.5% caused no detectible changes in leaf color as measured by SPAD in 2007 (2009 data not significant). As NO_3-N increased from approximately 0.5 to 2.0%, leaf SPAD values increased linearly, reflecting significant changes in leaf greenness and a stronger correlation existed between SPAD and petiole NO_3-N. At NO_3-N levels higher than 2.0%, considerable variation

was seen among SPAD readings as the plant canopy became too green to resolve differences in chlorophyll. There appears to be a limit at which SPAD can be used to predict differences in petiole NO_3-N. At petiole NO_3-N concentrations above 2.0 or below 0.5 ppm, SPAD appeared to be an unreliable indicator of crop N status.

INTRODUCTION

Nutrient management, especially nitrogen (N) management, is a critical component of potato cropping systems. Good fertilization and N management practices are essential for maximizing tuber quality and producing the most profitable yield. Excess and deficit N levels can compromise yield, quality and economic return (Rowe 1993). Insufficient N can lead to reduced growth, delayed tuber set (Harris 1992), reduced light interception, limited yield (Chase et al. 1990; Laurer 1986; Munro et al.1977; Santerre et al.1986; White et al. 1974) reduced dry matter content (Love et al. 2005; MacKerron and Davies 1986; McDole 1972; Painter and Augustin 1976; Westermann et al. 1994; Yungen et al. 1958) and an increase in diseases such as early die, late blight, and Verticillium wilt (Davis et al. 1990; Rowe 1993). In contrast, excess N may reduce tuber N uptake efficiency, delay tuber initiation (Westermann and Kleinkopf 1985), and promote overgrowth of vines which can reduce the effectiveness of vine desiccants (Pavlista and Blumenthal 2000) and create a humid environment that promotes diseases associated with moisture such as aerial stem rot, Sclerotinia stalk rot, pink rot, and other foliar and tuber diseases (Rowe 1993). Excess N may also affect storability (Long et al. 2004) and have adverse environmental effects such as run-off and ground water leaching (Rowe 1993). In Adams, Franklin, and Grant Counties of Washington, approximately 20% of all drinking-water wells have nitrate concentrations (NO_3-N) exceeding the US Environmental Protection Agency's maximum contaminant level of 10 mg L^{-1}; the source of which is believed to be from local crop and livestock production (USGS Water Resources of WA 2000). Therefore, proper N management is just as crucial to our environment's health as it is to the grower's bottom line.

In recent years, a technique coined "dynamic optimization of nitrogen supply" by Vos & Struik (1992) has gained favor among growers as a strategy to improve plant N use efficiency and limit leaching and volatilization losses of applied N. Dynamic optimization, also known as "spoon-feeding", refers to the practice of applying a reduced amount of N at pre-plant coupled with a series of small supplemental applications made throughout the growing season based on actual crop need at each growth stage. Studies show that a spoon-fed crop results in lower NO_3-N leaching, higher N recovery by the crop and an improved marketable tuber yield (Errehbi 1998; Russer et al. 1998; Waddel et al. 1999; Westermann et al. 1988).

Key to the success of this type of N management strategy is an accurate assessment of the current N status of the soil and plant to guide decisions on in-season N rates. Currently, N status is measured through periodic collection and analysis of soil and plant petioles throughout the growing season. Results from such analyses are then used to guide the grower's fertilizer decisions as to when and how much fertilizer to apply based on regional N recommendations.

Petiole NO_3-N analysis as a N management tool in potato has been widely investigated and is considered to be the most effective means of monitoring current crop N status due to a strong correlation between petiole NO_3-N, N availability in the plant, and N uptake (Alva 2007; Bundy et al. 1986; Errebhi et al. 1998; Gardener and Jones 1975; Kleinkopf et al.1984; Macmurdo et al. 1998; Porter and Sisson 1991a; Roberts and Cheng 1988; Roberts et al. 1989; Vitosh and Silva 1994; Vitosh and Silva 1996; Waterer 1997; Westcott et al. 1991; Westcott et al. 1993; Williams and Meir 1990).

Soil tests alone are generally a poor indicator of season-long plant available N because variations in soil type and environmental conditions make accurate predictions of soil N contributions difficult (Minotti et al. 1994). Likewise, petiole NO_3-N analysis alone is of limited value in predicting crop available N since it provides information on current crop N status only, with no indication of future contributions (or lack thereof) of N sources already present in the soil. However, when soil and petiole analyses are used in combination with previous crop N use patterns, the results can provide a relatively accurate snapshot of current crop N status as well as an expectation of crop N uptake and contributions from soil and organic matter (Gardener and Jones 1975; Dean 1993; Westermann 1993).

Although traditional petiole and soil sampling data can provide a relatively accurate determination of crop N status, they are time consuming and expensive to perform. Turnaround time for results may be too slow to allow sufficient time to correct a potential N deficiency. Growers may better utilize the dynamic optimization of N strategy if crop N status readings were immediate, precise, and affordable. One instrument that may allow for these type of results in potatoes is the Minolta SPAD (Soil Plant Analytical Development) 502 Chlorophyll Meter (Minolta Corp, Ramsey, NJ.)

The SPAD meter is a small, lightweight, portable, hand-held chlorophyll meter that provides instant, non-destructive readings of plant chlorophyll levels (Yadava 1986). High correlation between chlorophyll meter readings and actual plant chlorophyll levels has been established in the literature for many crops, including potato (Vos and Bom 1993). The SPAD meter capitalizes on that relationship by measuring the transmittance of red (650 nm) and infrared (940 nm) radiation through the leaf (Uddling et al. 2007) and calculating a SPAD value that "should correlate to the chlorophyll in the sample leaf" (Minolta 1989). The SPAD meter has many potential advantages over traditional crop N monitoring techniques (i.e., petiole and soil collection) because it is instantaneous, requires no special skills, and performs a function similar to, but more accurately than a grower subjectively judging a crop via visual canopy greenness; the difference is that the SPAD performs the task “quantitatively as opposed to subjectively” (Vos and Bom 1993). While collection of petioles and soils for analysis can take from several hours to several days, SPAD readings from multiple plants can be averaged in less than one hour (Minotti et al. 1994).

Use of the SPAD meter as a N management tool has been extensively investigated. SPAD studies have been performed on virtually every major agronomic crop including rice (Balasubramanian et al. 2000; Singh et al. 2002;), maize, (Piekielek and Fox 1992; Peikielek et al.1995; Schepers et al.1992;), and wheat (Barraclough 2001; Follett et al. 1992; Singh et al. 2002; Uddling et al. 2007; Vouillot et al. 1998). A common thread among these studies is a significant linear relationship between SPAD readings, actual leaf chlorophyll levels, and tissue N concentrations. These results indicate a potential usefulness of the SPAD meter as a N management tool in a wide variety of crops, including potatoes.

SPAD use in potato was first investigated by Vos and Bom (1993) who worked with the cultivar ‘Vebeca’ under different N rates and application times. They reported high correlations between leaf chlorophyll levels (r = 0.97), tissue N concentrations (r= 0.97) and SPAD readings; findings previously confirmed with other crops. Vos and Bom (1993) concluded that the SPAD meter could be a potentially useful tool for monitoring N status in a dynamically optimized system if critical SPAD thresholds were developed. The thresholds would represent a range of SPAD values above which there is no crop yield response to additional N applications but below which a yield response could be expected. Vos and Bom suggested that the practicality of the

SPAD meter to monitor crop N status would be limited unless further research was conducted to address how factors other than N rate could affect SPAD readings (e.g. cultivar effects, location, nutritional limitations other than N, drought and diseases). In 1994, Minotti et al. investigated varietal effects of potatoes on SPAD readings under varying levels of N from insufficiency to excess. Using regression analysis based on N rate on yield and SPAD readings, they estimated SPAD critical threshold values (lowest amount of N giving the highest yield) of approximately 49 to 56 SPAD units at 29 to 37 DAP (days after planting) for cultivars ‘Katahdin’, ‘Allegheny’, ‘Castille’, and ‘Superior’, but stressed that SPAD is significantly affected by cultivar and that SPAD thresholds should be developed for each cultivar. This thought was echoed by Schepers et al. (1992) working with maize and Gianquinto (2007) working with potatoes. All the authors agreed that SPAD critical thresholds are impossible to establish unless a well fertilized (non N-limiting) reference crop strip is established to standardize the SPAD readings across locations, climates, and cultivars.

The objectives of this study were to investigate the feasibility of the SPAD chlorophyll meter as a N management tool in the newly released potato cultivar Premier Russet and to develop SPAD threshold values for this cultivar that relate to maximum economic yields.

MATERIALS AND METHODS

Plant Material

Field studies to compare the response of Premier Russet (Premier) to five in-season N rates were conducted at the Washington State University Research and Extension Unit near Othello, WA (46º 47.277’ N. Lat., 119 º 2.680’W. Long.) during the 2007-09 growing seasons. Each year, certified seed tubers of Premier were hand cut into 43- to 85-g seed pieces, suberized at 50ºC at 95% relative humidity for 14 days, and planted on 5 April, 2007, 17 April, 2008, and 23 April, 2009.

<u>Field Plot Design and Maintenance</u>

Premier was planted and arranged in a randomized complete block design with four replications in a Shano Silt Loam [classified as Andic Mollic Camborthid (Lenfesty 1967) with a custom built two-row assist feed planter and grown under regional-standard practices, with the exception of in-season N fertilization. Seed pieces were planted 20-cm deep and 25-cm apart within each row. Each row was 86-cm from center to center and treatment plots were five rows wide by 7.62-m long. Data were collected on the second and fourth rows of each plot. One plant of a purple-skinned variety, 'All Blue', guarded the beginning and end of each row within the plot to separate plots and provide end plants competition during growth.

Plots were treated with five in-season N rates: 0%, 25%, 50%, 100%, and 150% of the typical Columbia Basin post-emergent (in-season) N rate for the Russet Burbank cultivar (300-350 lbs total season N) as per Lang et al. (1999). All treatments received the same pre-plant N during a given year with rates determined by soil analysis. Pre-plant, in-season and total season N rates and associated in-season N expenses are shown in Tables 1 through 4.

In-season N (UAN 32-0-0) was applied once or twice weekly, beginning when plants were 10-12 inches tall, approximately 50 days after planting (DAP), and continued until 100 DAP. In an effort to mimic commercial applications of water-applied N (fertigation), in-season N was applied via a custom fertigation simulator (tractor pulled flood-nozzle sprayer) which delivered precise quantities of N to each plot using 4-mm of water as a carrier. Plots were irrigated with solid-set irrigation and soil moisture was maintained between 65%-85% of field capacity using tensiometers and neutron probes (monitored by Professional Ag Services, Pasco WA). Herbicides, insecticides, and fungicides were applied as needed, according to standard Columbia Basin practices. Based on soil and petiole analyses, in-season phosphorus (10-34-0) was also applied as needed in accordance with current Columbia Basin phosphorus recommendations (Lang et al. 1999). Any N added to the trial via the 10-34-0 applications was accounted for and is reflected in Tables 1 through 3.

Tissue and Soil Sample Collection

Between 60 and 120 DAP, the fourth leaf from the top of the plant was collected from ten random plants per plot weekly, during the morning, and used for petiole analysis as per Lang et al. (1999). Petioles from plots of the same treatment (a total of 40) were combined each week, resulting in one composite analysis per treatment. Petioles were either dried via a drying oven or refrigerated prior to delivery to the testing facility. Petioles were analyzed for NO_3-N with a Skalar Sanflow 4 channel segmented flow analyzer (Skalar Analytical, Netherlands). Petiole P, K, and S was analyzed with a Perkin Elmer Optima 300 (PerkinElmer, Waltham, MA) radial induced argon plasma emission spectrophotometer.

Soil samples were collected every other week at a 30-cm depth using an open side tubular auger with a 1.9- cm diameter (AMS Sampling Equipment, Idaho Falls, ID). Three random samples were taken from each plot and a composite sample made by combining all samples of the same treatment. Soil samples were bagged and held at 8ºC until delivery to the testing facility.

Field Chlorophyll Measurements

Field chlorophyll measurements were made with a Minolta SPAD 502 Meter. Ten plants from each N treatment were randomly selected within the first replication. The fourth leaf down from the apex of the plant was collected and a SPAD reading taken immediately from the terminal leaflet for a total of ten readings per treatment on each collection date. The readings were then averaged. For consistency, measurements were always made in the center of the left side of the terminal leaflet. Readings were initiated at 77 DAP in 2007 and performed approximately every seven days until 137 DAP. In 2008, readings were initiated at 53 DAP and performed approximately every seven days until 119 DAP. In 2009, readings were initiated at 63 DAP and performed approximately every seven days until 105 DAP. Terminal leaflets were separated from the petioles and both were then stored at -29°C until laboratory analysis. In preparation for analysis, petioles and terminal leaflets were lyophilized and ground through a 35 mesh screen in a Wiley-Mill (Thomas Scientific, Swedesboro, NJ) and analyzed for total N content with a TruSpec CN (Carbon Nitrogen) Analyzer model 630-100-100 (Leco Industries, St. Joseph, MI). Regression analyses for SPAD values on DAP, % leaf total N, petiole total N, and petiole NO_3-N were conducted to define the relationships between leaf color and petiole NO_3-N concentrations associated with the in-season N rates that returned maximum economic yields.

RESULTS AND DISCUSSION

This study was performed during the years of 2007 through 2009. However, due to complications in the field, data for the 2008 growing season were discarded and are therefore not shown. SPAD readings were highly correlated with the laboratory measurements of petiole nitrate-N concentration (NO_3-N) in 2007 ($r^2 = 0.70$, $P \leq 0.01$) and 2009 ($r^2 = 0.47$, $P \leq 0.01$; Fig. 1). A stronger correlation was seen in 2007, however, when both years were combined, the correlation became even stronger ($r^2=76$, $P \leq 0.001$; Fig. 1).

Nitrogen regimes affected SPAD values and petiole NO_3-N concentrations in 2007; however, petiole NO_3-N analysis appeared to resolve treatments among N treatments and discern early season trends sooner than SPAD (Figs. 2, 3, and 4). The initial in-season N treatment in 2007 was 63 DAP. Petiole and soil data from this date confirmed that soil and plant N were at the same level among all treatments. Petiole NO_3-N and soil analyses clearly differentiated among treatments prior to 77 DAP, or 14 days after the initial N treatment (DAT) and a clear separation among treatments was evident throughout the course of the season. In contrast, SPAD did not resolve differences until approximately 81 DAP, or 19 DAT (Figs. 2 and 3). These findings are similar to results by Vos and Bom (1993), who investigated SPAD response to N rate and timing. They reported a delay of 20 days between emergence and the ability of the SPAD meter to detect differences in pre-season N treatments. Wu et al. (2007) reported that a severe N deficiency was not reflected in SPAD values until approximately 30 days after emergence (DAE) while petiole NO_3-N analysis revealed the deficiency within 14 days. Although petiole NO_3-N from the higher N-rate treatments clearly differed from those of the non-fertilized (0%) and low (25%) treatments by 88 DAP in 2007, a clear separation in SPAD among the three highest rates of N occurred at 105 DAP (Figs. 2 and 3). Clear separation among treatments was not evident at any point in 2009 with SPAD (Figs. 1 and 4). These results suggest that SPAD measurements taken earlier in the season may not accurately detect N deficiencies in plants that have received moderate levels of fertilizer, but may be used to identify situations of extreme N deficiency. These data also suggest that SPAD chlorophyll measurements are not as sensitive to changes in plant N status as petiole NO_3-N concentrations, indicating that changes in chlorophyll concentrations lag behind changes in petiole NO_3-N concentration. These results agree with those of Gerendas and Pieper (2001), Gianquinto et al (2004), and Uddling (2007).

Highly significant non-linear trends were obtained when SPAD was regressed against N treatments for five of the seven measurement dates in 2007 (Fig. 3). Regression analysis showed no significant changes in SPAD at77 DAP and 137 DAP in 2007. SPAD readings correlated better with petiole NO_3-N levels in the middle of the growing season than at the beginning or end of the growing season (Fig. 3), confirming similar results by Vos and Bom (1993) and Gianquinto et al. (2004). These results suggest that early in-season N levels were more than sufficient and thus younger plants (ie.77 DAP) were relatively insensitive to the different N rates. However, as the season progressed and N was slowly depleted, SPAD was able to progressively differentiate differences in chlorophyll concentrations caused by the N rates as demonstrated by highly significant correlation coefficients during the middle of the season (Fig. 3). By 137 DAP, plants grown with 0-50% in-season N were becoming depleted of N and senescing, causing a yellowing of the leaves (data not shown), as indicated by the low SPAD values (Fig. 3). Petiole NO_3-N values began to decline earlier than SPAD values (Fig. 2) and the decline was more pronounced among the petiole analysis than it was for SPAD (Fig. 3). This may suggest that once senescence starts, reduction of NO_3-N to the leaves occurs more rapidly than chlorophyll degradation.

SPAD values correlated significantly ($P \leq 0.001$) with changes in leaves (Fig. 5) and petioles (Fig. 6) in 2007. In 2009, the correlation between SPAD and leaf N was relatively low ($r^2 = 0.45$, $P \leq 0.01$; Fig 5) was relatively low ($r^2=0.45$**) compared with the correlation between SPAD and petiole total N ($r^2=0.70$, $P \leq 0.001$); Fig. 6). Higher coefficients of determination were obtained between SPAD and petiole and leaf total N when data from both years was combined (r^2= 0.78, P and 0.82, $P \leq 0.01$, respectively; Figs. 5 and 6). In general, there was very little change in SPAD readings when leaf and petiole N concentrations were high (above approximately 5.0-5.5%), a trend that was particularly evident in 2009 when leaf total N was much higher than in 2007. This likely indicates that the SPAD meter does not respond to luxury N consumption and is consistent with the results of Gerendas and Pieper (2001), Gianquinto (2004), and Uddling (2007).

Utilizing data obtained from the regression analysis of Premier against adjusted gross income (2007-09) from the in-season N rate study described in chapter 1 of this thesis, we estimated SPAD threshold values associated with the in-season N rate that returned maximum economic yield for Premier. These values ranged from approximately 44 to 47 SPAD units for the month of July and into August (118-126 DAP) and declined to approximately 31 SPAD units by the end of August (137 DAP; Table 5.) An attempt was made to establish SPAD threshold values in the month of June at 77 DAP but petiole NO_3-N correlated poorly with SPAD early in the season and correlation could not be established. In addition, we utilized a normalization procedure first outlined by Schepers et al. (1992) and later adapted by Minotti et al. (1992), that allowed us to compare SPAD readings from the optimum N rate for Premier (100% treatment) with a well fertilized reference strip (150% treatment). The procedure was used in an attempt to establish a threshold of SPAD values throughout the season which would indicate sufficient N fertilization. Values from the reference strip were compared to values at the optimum N rate on the same DAP, providing an estimate of the range between the optimum rate and the high fertilizer rate (Table 6). In general, we conclude that Premier had adequate amounts of N when the SPAD units were within 2 to 3 units of the reference measurement with the exception of the last measurement (137 DAP). The high differential found at this date most likely reflects greener vines later in the season as a result of the higher N rates for the reference plot and does not reflect realistic Columbia Basin fertilizer rates for this cultivar.

In general, changes in NO_3-N from 0 to 0.5% caused no change in leaf color as measured by SPAD in 2007, suggesting that SPAD cannot resolve NO_3-N status at this low range of nitrate. These results are in agreement with Vos and Bom (1993) who showed that SPAD was unable to resolve differences in leaf color when NO_3-N concentrations in the petiole sap were below 1000 mg/l^{-3}. As NO_3-N increased from approximately 0.5 to 2.0%, leaf SPAD increased linearly reflecting significant changes in leaf greenness and better correlation was found between SPAD and petiole NO_3-N concentration. At petiole NO_3-N levels higher than 2.0%, considerable variation was seen among SPAD readings. There appears to be a limit at which SPAD can be used reliably to detect differences in petiole NO_3-N. After this limit is reached, the plant canopy becomes too green for SPAD to discern differences in petiole NO_3-N based on leaf color.

In 2009, growing conditions on the Othello Research Station in the Columbia Basin were not conducive for SPAD studies. Higher than normal levels of soil N across all treatments for the duration of the growing season were responsible for elevated levels of petiole NO_3-N and total N in the plant leaf tissue in relation to the 2007 growing season. In many cases, petiole NO_3-N concentrations during 2009 were triple those found at similar DAP in 2007. At these high levels of petiole NO_3-N, chlorophyll production is at a maximum and no further differentiation in canopy color due to limited N availability is possible. This led to a smaller range of SPAD values in 2009 compared to 2007 and a comparatively weaker correlation between SPAD values and petiole NO_3-N ($r^2 = 0.47$, $P \leq 0.01$; Fig 1) than was seen in 2007 ($r^2 = 0.78$, $P \leq 0.01$; Fig.1). In addition, there were no significant correlations found between SPAD and in-season N treatments at any DAP examined in 2009 (Fig. 4). SPAD values had a maximum range of only 7 units in 2009 (43-54 SPAD units) while there was a range of 29 units in 2007 (23-52 SPAD units; Fig. 2). Though treatment differences in SPAD were not clearly evident in 2009 (Figs. 2 and 4), petiole NO_3-N for the same year showed clear separation among treatments with higher values found for higher rates of N (Fig. 1). This data suggests that SPAD is of limited value for estimation of petiole NO_3-N levels during similar production years where soil N is more than adequate and petiole NO_3-N is above approximately 2.0%. These results are in accordance with those of Denuit et al. (2002) who reported that SPAD was unsuitable as a potential indicator of N deficiency in potato when high N reference strips were used for calibration. These results also confirm the validity of petiole testing as a reliable tool for potato production, relative to nutrient analysis.

The ability of SPAD to detect differences in leaf color due to N varied with growth stage and growing season. The results from this study as well as those of Vos and Bom (1993), Minotti et al. (1994) and Gianquinto et al. (2004) suggest that SPAD is not as responsive to changes in N levels as traditional petiole NO_3-N assessment and that there is a potential delay of 20 -30 days before SPAD can clearly reflect plant N status. This is an important consideration for a grower trying to identify a potential N deficit soon after emergence or determine if a supplemental application is needed late in the season. At concentrations of petiole NO_3-N above approximately 2.0%, the plant canopy is too green for SPAD to discern subtle differences in NO_3-N, limiting the usefulness of the SPAD meter to reliably identify situations of excess N, as was seen in 2009. However, at NO_3-N of approximately 0.5 to 2.0, we conclude that SPAD is a viable indicator of crop NO_3-N -status for Premier and could readily detect a potential N deficiency within this range. This range would allow for applications of supplemental fertilizer as needed. We suggest

SPAD threshold values of approximately 43 to 48 for the month of July, with declining SPAD values throughout August.

It should be noted that factors other than N have been shown to effect SPAD readings such as previous crop residues, growing season, and location, which makes it difficult to establish SPAD threshold values that are widely adaptable. Values may change from season to season in response to any one of these variables. Therefore, in order to maximize the reliability of SPAD for a particular operation, it would be wise for a producer to establish a well fertilized reference strip for each cultivar for calibration of the SPAD unit as per the procedure outlined above in order to generate a calibration curve unique to one's own operation, thus minimizing variability.

Overall we feel that the SPAD meter does indeed have an application for Premier in the Columbia Basin, depending on growing season, but should be recognized as another tool that may complement, but not replace, other aspects of sound N management, such as traditional petiole NO_3-N analysis.

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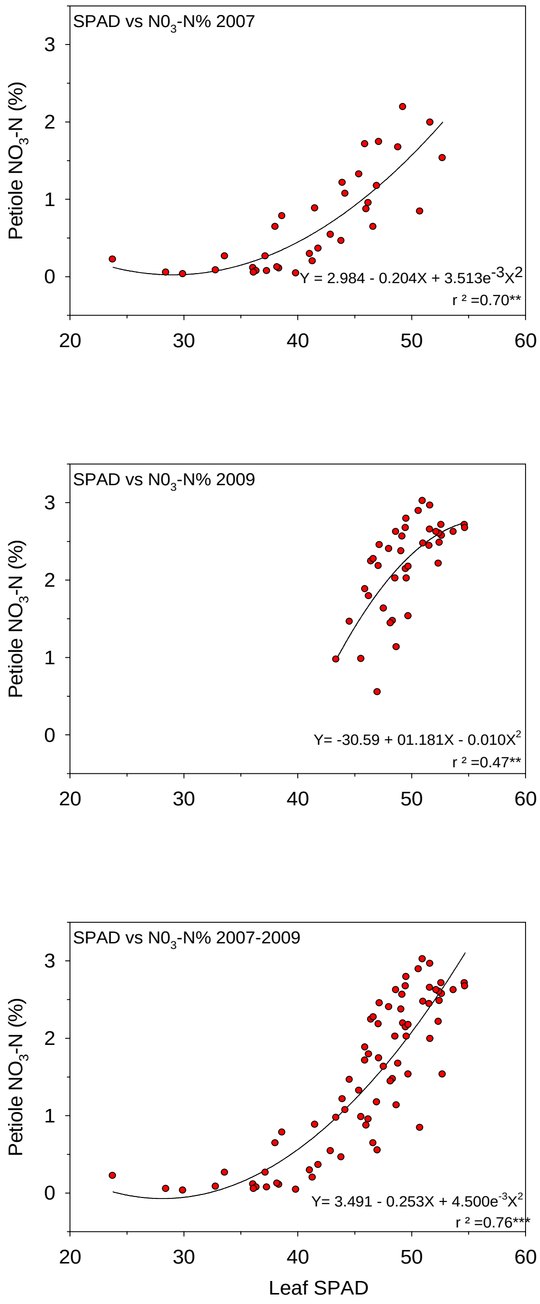

Fig. 1. Relationship between leaf SPAD readings and actual petiole NO_3-N % during 2007 and 2009 (No data available for 2008).

*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

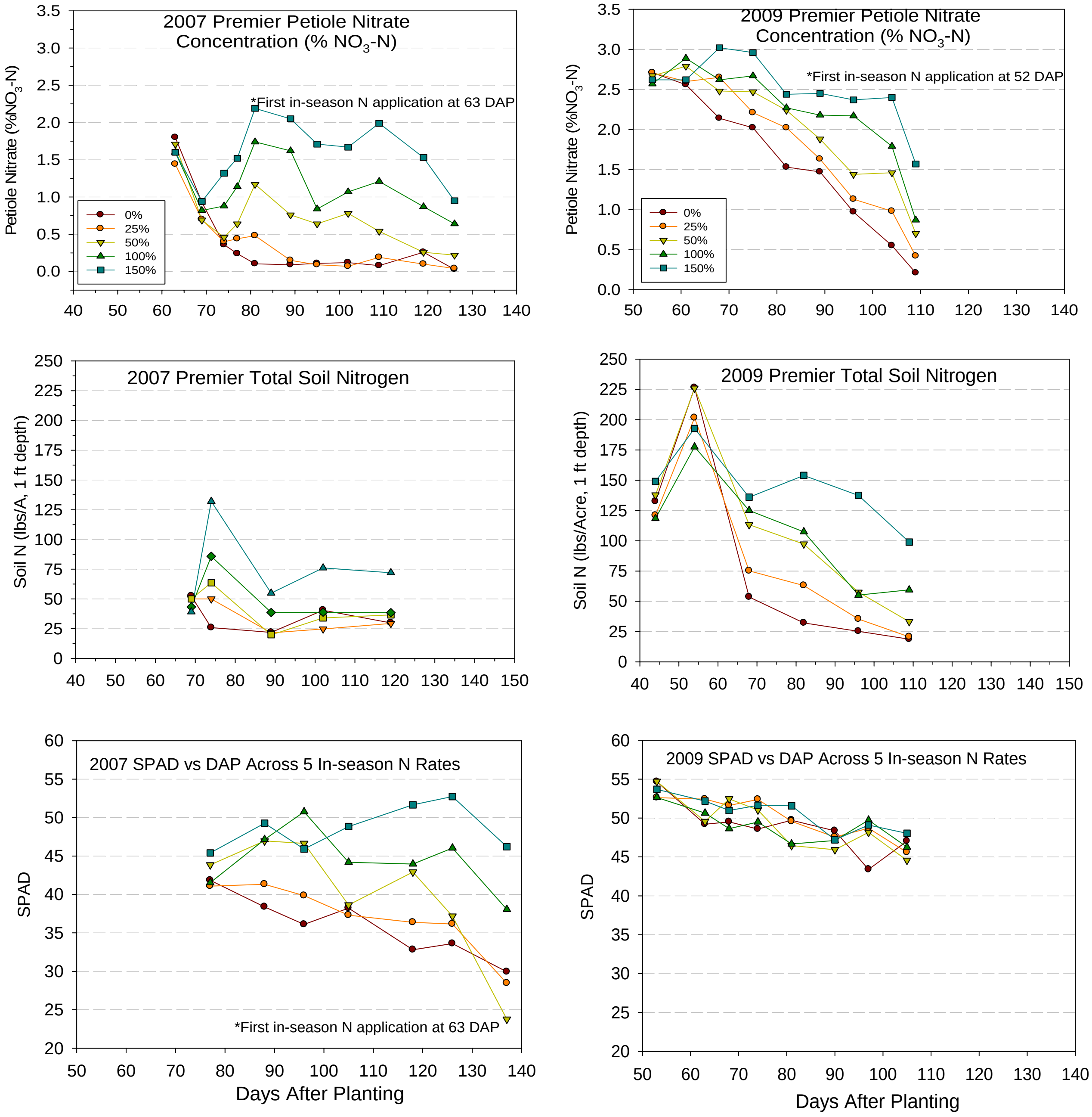

Fig. 2. Petiole NO_3-N, total soil N, and SPAD values for Premier in 2007 and 2009.

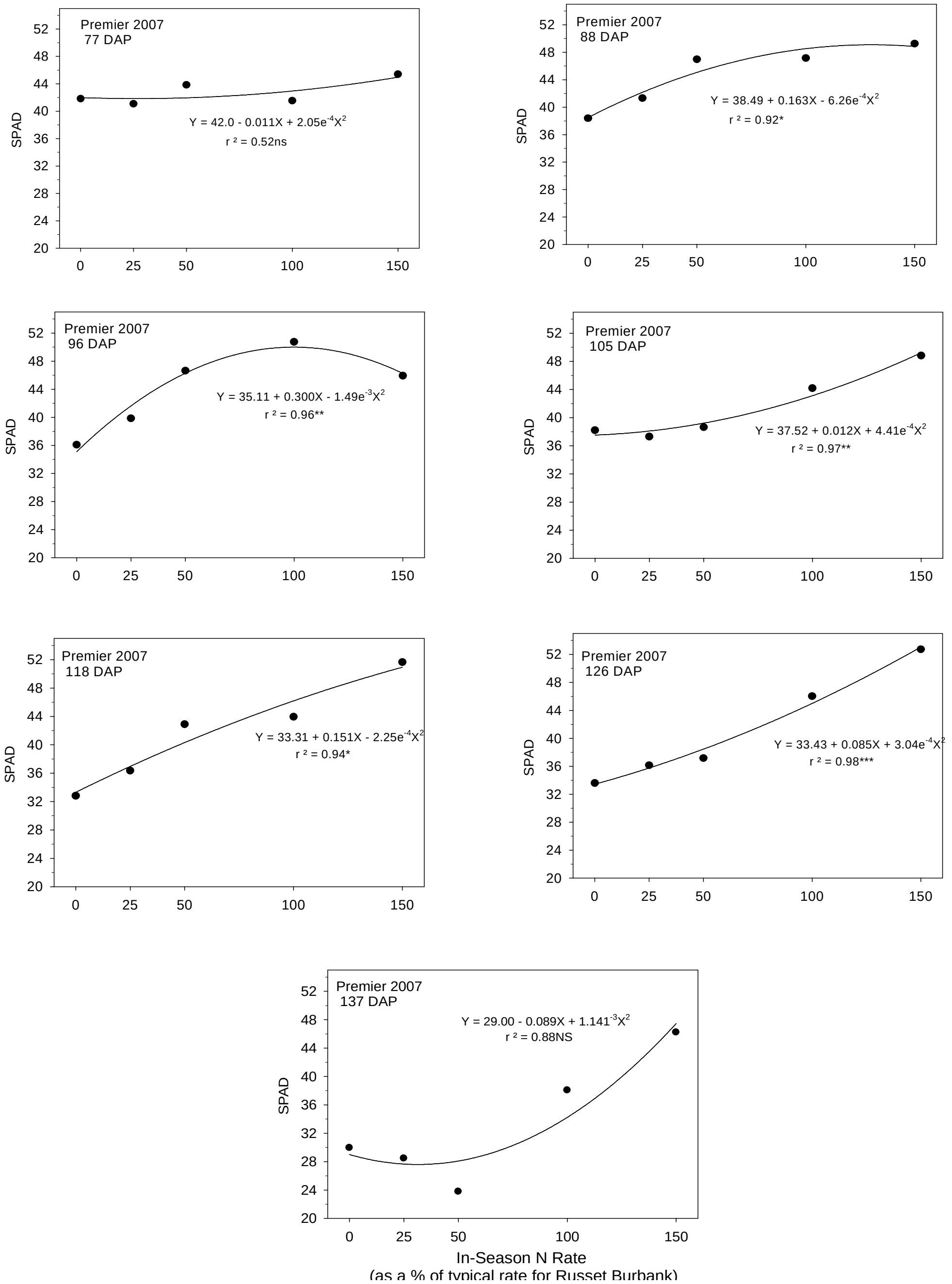

Fig. 3. Relationship between leaf SPAD and in-season N treatments at seven different DAP dates for Premier in 2007.

*, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

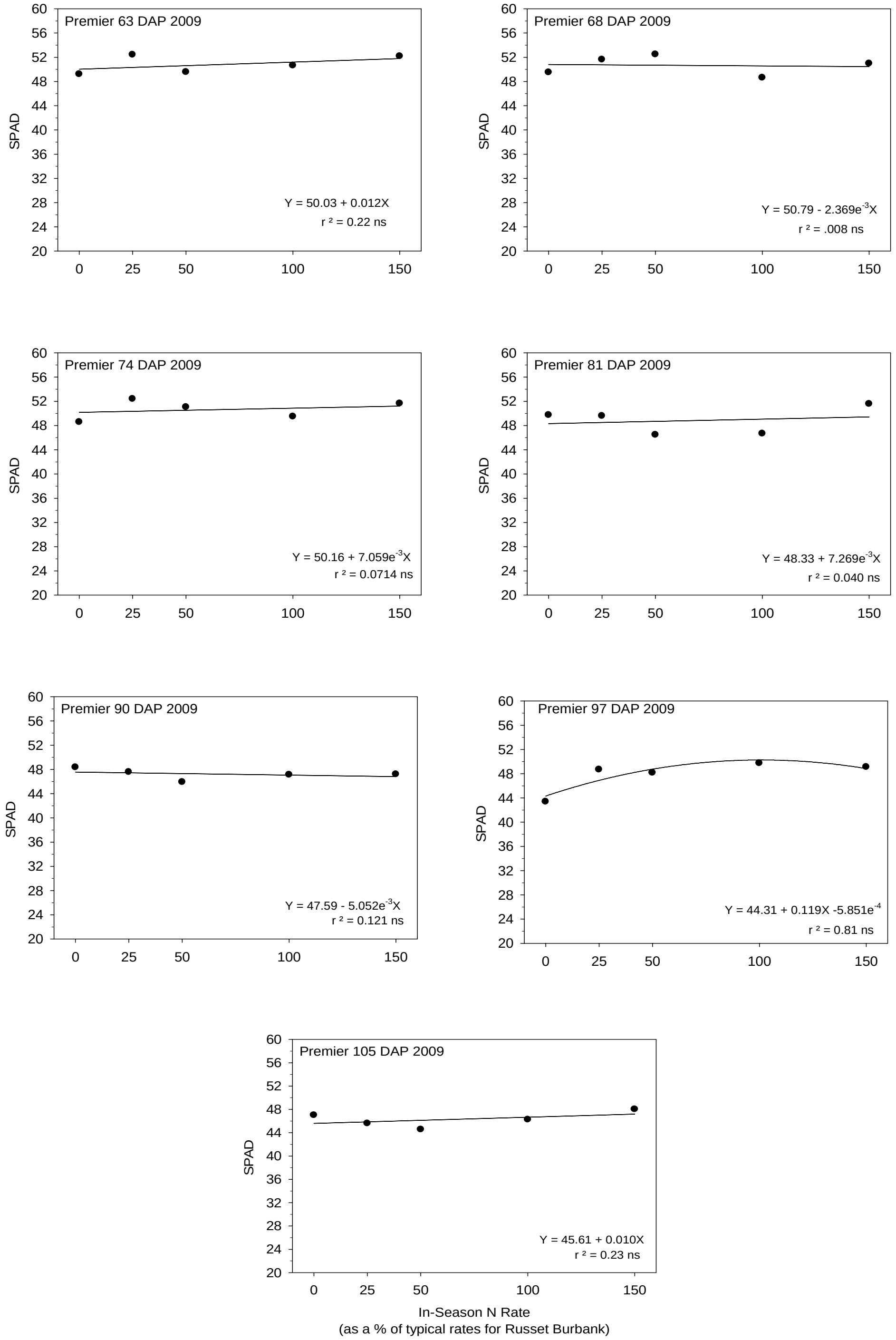

Fig. 4. Relationship between leaf SPAD and in-season N treatments at seven different DAP dates for Premier in 2009.

*, **, ***, ns: correlation coefficient significant at P ≥ 0.05, 0.01, or 0.001 respectively, or non-significant.

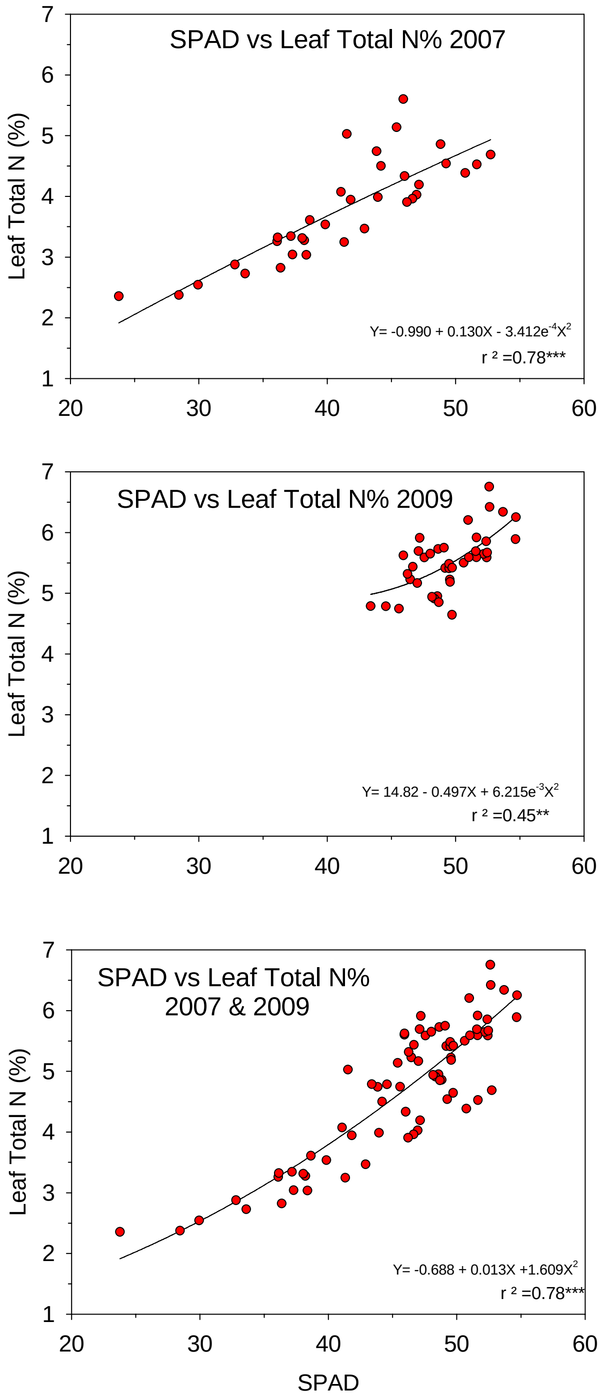

Fig. 5. Relationship between SPAD and leaf total N% (dry matter) for Premier during 2007 and 2009.

*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

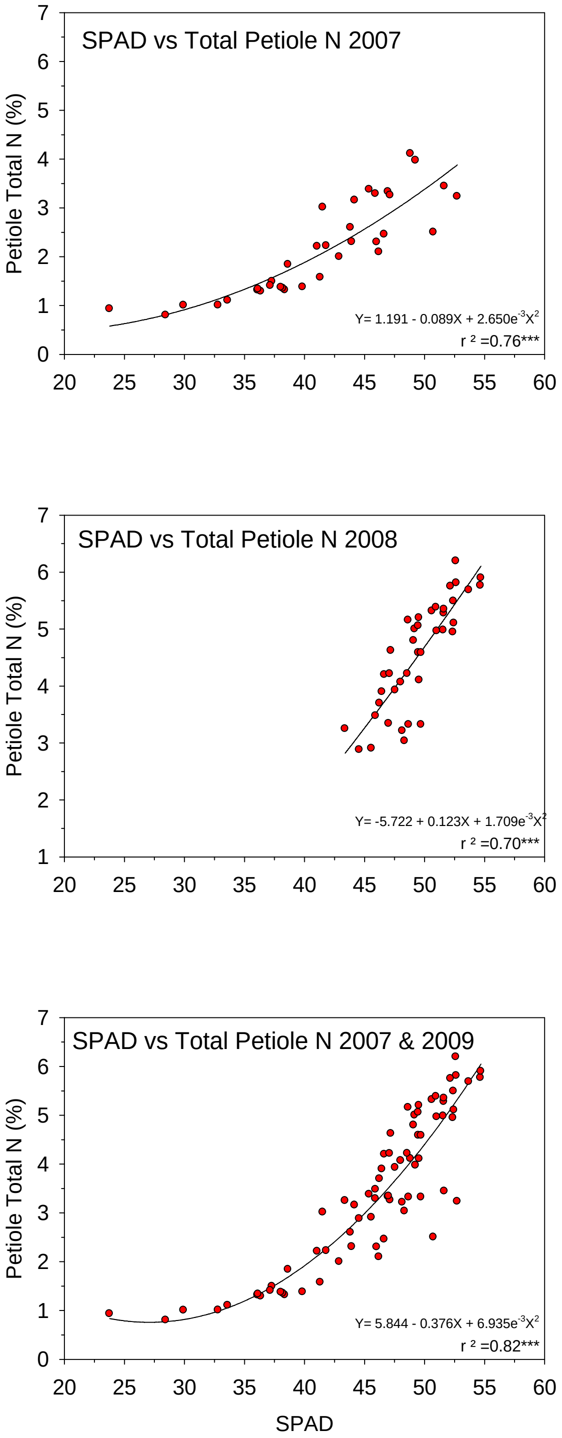

Fig. 6. Relationship between SPAD and total petiole N% (dry matter) for Premier during 2007 and 2009.

*, **, ***, ns: correlation coefficient significant at $P \geq 0.05$, 0.01, or 0.001 respectively, or non-significant.

Table 1. Preplant, in-season, and total season nitrogen for 2007 and associated in-season N expense for five rates of in-season N applied to Premier

Treatment As a % of Standard RB Rate	**Applied Pre-plant N + Soil Residual**[a]	**Measured At-Emergence Soil N**[b]	**Applied In-Season N**	**Applied In-Season N Via Phos Applications**	**Total Applied In-season N**	**Total N Applied in 2007**	**In-season N Fert Expense ($0.44/lb)**
%	--lbs/A------------------------------						$/A
0	125	127	0	30	30	155	0
25	125	127	58	30	88	213	23
50	125	127	115	30	145	270	46
100	125	127	230	30	260	385	92
150	125	127	345	30	375	500	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (75 lbs/A) plus soil N (NO_3^- 8 lbs/A, NH_4^+ 42 lbs/A) = 125 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 100 lbs/A, NH_4 27 lbs/A).

Table 2. Preplant, in-season, and total season nitrogen for 2008 and associated in-season N expense for five rates of in-season N applied to Premier

Treatment As a % of Standard RB Rate	**Applied Pre-plant N + Soil Residual**[a]	**Measured At-Emergence Soil N**[b]	**Applied In-Season N**	**Applied In-Season N Via Phos Applications**	**Total Applied In-season N**	**Total N Applied in 2008**	**In-season N Fert Expense ($0.44/lb)**
%	--lbs/A------------------------------						$/A
0	152	168	0	9	9	161	0
25	152	168	58	9	67	219	23
50	152	168	115	9	124	276	46
100	152	168	230	9	239	391	92
150	152	168	345	9	354	506	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (80 lbs/A) plus soil N (NO_3^- 24 lbs/A, NH_4^+ 48 lbs/A) = 152 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 159 lbs/A, NH_4 9 lbs/A).

Table 3. Preplant, in-season, and total season nitrogen for 2009 and associated in-season N expense for five rates of in-season N applied to Premier

Treatment As a % of Standard RB Rate	Applied Pre-plant N + Soil Residual[a]	Measured At-Emergence Soil N[b]	Applied In-Season N	Applied In-Season N Via Phos Applications	Total Applied In-season N	Total N Applied in 2009	In-season N Fert Expense ($0.44/lb)
%	--lbs/A------------------------------						$/A
0	152	171	0	10	10	162	0
25	152	171	58	10	68	220	23
50	152	171	115	10	125	277	46
100	152	171	230	10	240	392	92
150	152	171	345	10	355	507	138

[a] Soil residual values derived from a composite of twenty, 1 ft soil samples across trial location prior to planting; urea application (90 lbs/A) plus soil N (NO_3^- 30 lbs/A, NH_4^+ 32 lbs/A) = 152 lbs/A.

[b] At-emergence soil N values derived from 120, 1 ft soil samples across trial location upon >90% plant emergence (NO_3 163 lbs/A, NH_4 8 lbs/A).

Table 4. Rate scheme for five in-season N rates for 2007-2009

Treatment as a % of standard	Number of Applications*			
	Two	Four	Two	Two
%	-----------------------------N lbs/A-----------------------------			
0	0	0	0	0
25	5	7.5	6	3
50	10	15	13	5
100	20	30	25	10
150	30	45	38	15

***Applications started approximately 10 days after >90% emergence**

Table 5. Estimated SPAD and petiole NO_3-N concentrations related to the most profitable in-season N rate for Premier. Estimates derived from data from the 2007 growing season only. Data from 2009 was non-significant.

DAP	Estimated SPAD	Estimated Petiole NO3-N(%)
88	48.5	1.8
96	50.1	2.11
105	43.1	0.95
118	45.9	1.36
126	45.1	1.21
137	31.5	0.01

Table 6. Differences in SPAD readings between the optimum N rate (385 lbs total season N) and the well fertilized (500 lbs total season N) reference plot in 2007. Data for 2009 was insignificant and is not shown.

Sampling DAP 2007	**Optimum N Rate SPAD**	**Reference SPAD**	**Differential**
88 (July 2)	47.1	49.3	2.1
105 (Jul 19)	44.2	48.8	4.6
118 (Aug 1)	44.0	51.7	7.7
137* (Aug 20)	38.1	46.2	8.2

*Plants had senesced approximately 15% and 21% at the reference and optimum N rate, respectively. Higher differentials at the later dates perhaps reflect that the higher N plants (150%) remained greener longer into the season while the optimum N plots were beginning to senesce earlier.