WATER AND NITROGEN MANAGEMENT OPPORTUNITIES WITH DRIP IRRIGATION IN POTATO (*Solanum tuberosum* L.) PRODUCTION

by

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Appendix A

Opportunities for Irrigation and Nutrient Management with Drip Irrigation in Potato (*Solanum tuberosum* L.) Production

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In the Central Sands of Wisconsin, irrigated potato (*Solanum tuberosum* L.) production occurs in areas with coarse-textured soils with low water holding capacity. Large rain or irrigation events can cause nutrients and agroechemicals to leach into the shallow aquifer below, contaminating groundwater resources. Center-pivot irrigation is the predominant irrigation method used in the Central Sands, but concerns over groundwater quantity and quality have pushed growers to explore alternative management practices with improved water and nutrient use efficiency. The goal of this research was to evaluate the yield and quality of three potato cultivars as influenced by drip irrigation and nitrogen fertilization through two different experiments. The first study evaluated the effects of overhead sprinkler irrigation at 100% of crop evapotranspiration (ET_c) and drip irrigation at 100%, 86% and 75% of ET_c on yield and quality of potato, petiole nitrate levels, soil moisture and temperature in the crop root zone, and irrigation water use efficiency. Irrigation treatments influenced yield of Russet Norkotah but not Snowden or Russet Burbank. Soil moisture measurements indicated drip irrigated soils had lower moisture content beneath the furrow and were wetter following irrigation at 20 cm below the top of the hill in one of two years. Drip irrigation maintained yield with less irrigation water and therefore increased irrigation water use efficiency of multiple potato cultivars with no effects on internal defects, sugars or processing quality. A second study evaluated the effect of the aforementioned irrigation treatments together with three N rates, 202, 291, and 336 kg ha^{-1}, on Russet Norkotah yield and quality, petiole nitrate levels and N removal in harvested tubers. Total yield and quality were similar across drip irrigation treatments, but overhead irrigation did result in higher total and US#1 yield than the highest drip treatment in one of two years and higher yield of large-size tubers both years. There was no response in total and US #1 yield to N fertilizer rate, but higher N rates led to improved yield of large size potatoes in one of two years. Nitrogen removal in harvested tubers ranged from 150 to 170 kg ha^{-1} which is 57 to 92% higher than previously recorded in Wisconsin. This study demonstrated maximum total yield could be achieved with 25% less irrigation water in 2014 and at 28% of the current recommended rate of N fertilizer applied in both 2013 and 2014.

CHAPTER 1

Introduction and Literature Review: Water and Nitrogen Management in Irrigated Potato Production

Irrigated Potato Production in the Central Sands

Irrigated agriculture has expanded substantially since the 1970s to grow high value processing vegetables like potato. In this region, irrigation supplements rainfall and provides a more consistent water supply to insure maximum quality of the potato crop. Much of Wisconsin's irrigated acreage is concentrated in the central sand plain, or Central Sands, which is the location of 80,000 irrigated hectares, and much of the states 26,000 hectares of potatoes are produced here (*Solanum tuberosum* L.) (Hubell 2013; Keene and Mitchell 2010; Kraft 2012; USDA-NASS 2013a). Specialty crop production and processing in the state comprise a 6.4 billion dollar industry and provide 35,000 jobs (Keene and Mitchell 2010). Potato production alone accounts for nearly 3,000 jobs and $349 million in economic activity (Keene and Mitchell 2010). Wisconsin is the third largest potato producing area in the country and a top producer of snap beans, carrots, sweet corn, and green peas (Keene and Mitchell 2010). The success of Wisconsin's vegetable industry would not be possible without the use of irrigation. In the Central Sands it is both supplemental and necessary to produce yields of potato which has high water demand. The vast majority of producers in the region utilize center pivot irrigation as the predominant irrigation method (Wyman et al., *in press*). Along with the rise in irrigation, the number of high capacity wells in the Central Sands has also grown from 165 in the 1950s to over 3,000 (Weeks and Stangland 1971; WDNR 2015). High capacity wells are defined as having the ability to pump at least 3785 liters per day or 265 liters per minute (WDNR 1997).

Effects on Groundwater Quantity and Quality

The large increase in number of high capacity wells over the past 20 years has led to concerns about potential impacts of increased pumping on groundwater and surface water resources. In the great lakes region, the majority of irrigation water is sourced from ground water pumped from permeable, unconfined glacial aquifers that are strongly tied to surface water resources (Kniffin et al. 2014; Kraft et al. 2012). Consequently, even small reductions in groundwater can have consequences for lake levels and stream flows (Kraft 2012). In the Central Sands, the groundwater aquifer supplies water to about 300 lakes and over 1600 kilometers of streams (Kniffin et al. 2014). Increased urbanization in the region and resultant growth in municipal water use as well as climate change have also been pointed to as contributing to the drop in water levels and led to concerns about potential cumulative impacts of irrigation pumping. However, George Kraft et al. (2012) attribute declines in monitored well levels to irrigation pumping. They compared long-term well records in areas with high-density irrigation to analogous wells in areas of low-density, and found an effect of increased pumping to well level decline. High relative humidity combined with irrigation water sourced from groundwater at 10 to 15 °C cooler than air temperature results in high irrigation efficiency relative to Western states. Nevertheless, there is pressure on growers to further increase efficiency and reduce water use.

The public concern surrounding water resources is also due to groundwater quality issues. In the upper Midwest, irrigated agriculture has primarily expanded into areas that are more vulnerable to leaching and subsequent groundwater contamination because of coarse-textured soils and shallow aquifers. The majority of soils in the central sand plain of Wisconsin are coarse-textured with high hydraulic conductivity and low organic matter (Saffigna and Keeney 1977; Stites and Kraft 2001). Large rain or irrigation events can cause nutrients and agrochemicals to leach into groundwater resources, posing an environmental risk. Zebarth and Rosen (2007) comment that, “the risk of nitrate leaching is increased in shallow-rooted crops grown at high levels of N fertility, on coarse-textured soils low in organic matter, and located over shallow water tables." Thus, potato production systems in this region are highly susceptible leaching. Saffigna et al. (1977) found that careful irrigation and nitrogen (N) management decreased losses of water and N from over half of applied to less than 40%; however, this amount could still have economic and environmental impacts. Agricultural activity has been connected to elevated nitrate levels of both surface water and groundwater (Bronson et al. 2009; Randall et al. 2008; Saffigna and Keeney 1977), as has potato production specifically (Hill 1986; Richards et al. 1990).

Nitrate losses due to leaching pose environmental, health and economic concerns. Stites and Kraft (2000) found that water samples in irrigated areas in the Central Sands contained elevated nitrate levels that exceed U.S. drinking water maximum contaminant levels (MCLs) of 10 mg L^{-1} and were greater than levels found in samples taken at higher elevations relative to fields. This contamination can affect the use of the aquifer as a source of potable water as 66% of domestic wells located near agriculture land were found to have nitrate levels that exceed MCLs as compared to 22% in non-irrigated areas (LeMasters and Baldock 1995). Typical rates of nitrate loading are 203 kg ha^{-1}. However, as little as 24 kg ha^{-1} yr^{-1} can cause groundwater nitrate levels to exceed MCLs, and such amounts are likely to occur even when adhering to university nutrient management recommendations for best management practices (Stites and Kraft 2001). The presence of nitrates and agrochemical residues in groundwater has led to the discussion of several bills in the state legislature to further regulate production practices. It has also led the creation of the NRCS 590 standards that target nutrient rate, source, placement, and timing in order to limit non point source pollution of water resources among other goals (NRCS 2005).

Potato Crop Water Demand and Irrigation Management

Optimizing irrigation and nitrogen management on coarse textured soils, such as those found in the Central Sands, poses a challenge to irrigated land managers. According to Phene and Sanders (1976), "Ideal conditions for potato growth include high and nearly constant soil matric potential, high soil oxygen diffusion rate, adequate incoming radiation, and optimal soil nutrients." Maintaining soil moisture in sandy loam soils proves difficult as both water storage capacity and water retention abilities are low (Weisz et al. 1994). Most of the data suggests that potato is sensitive to water stress and must be irrigated to meet evapotranspiration (ET) demand, especially during critical growth stages (Epstein and Grant 1973; Fabeiro et al. 2001; Opena and Porter 1999; Phene and Sanders 1976; Porter et al. 1999; Shock et al. 1998; Weisz et al. 1994). Most potatoes in the United States, especially those grown on sandy soils, are irrigated in order to supplement precipitation and meet crop water demands that can range from 460 to 910 mm depending on the climate, soil, and cultivar (Shock 2010). To meet crop water demand in Wisconsin, this translates to about 15 supplemental water applications of 15 mm each during the growing season (Stites and Kraft 2001).

Potato's sensitivity to drought stress is due in part to its shallow root system (van Loon 1981; Weisz et al.1994). The vast majority of the crop's roots are located in the upper 0.3 meters of soil (Opena and Porter 1999; Steckel and Gray 1979; van Loon 1981). Potato also has an even shorter effective rooting depth in terms of moisture extraction capability (Weisz et al. 1994). Although roots can grow to a depth of one meter depending on soil characteristics, they only have an effective rooting depth of about 0.6 meters (Corey and Blake 1953; Shock 2010). Furthermore, leaf expansion rates of potato begin to slow at less severe soil moisture stress levels than for other crops, contributing to its hypersensitivity (Weisz et al. 1994).

Although drought intolerance is ubiquitous in potato, the extent to which drought stress will affect plant growth and development is cultivar dependent (Lynch and Tai 1989; Martin and Miller 1983; Miller and Martin 1987; Stark et al. 1991, 2013; Stark and McCann 1992; Wolfe et al. 1983). Drought stress is known to negatively affect the widely grown industry standard cultivar Russet Burbank. In a sandy soil, Miller and Martin (1987) induced water stress to stimulate irrigation system failure and found that Russet Burbank yielded fewer marketable tubers than the other cultivars. Stark et al. (2013) evaluated six cultivars under drought stress induced at different times in the season. They also found that drought conditions resulted in fewer marketable tubers for Russet Burbank relative to other cultivars, however, overall yields of this cultivar were generally higher than other varieties across all drought treatments. Russet Norkotah, a common fresh market and early season variety, yielded lower overall. However, Russet Norkotah yields did not differ between drought treatments, suggesting that this variety is somewhat tolerant to drought stress. There is some evidence to suggest that early season cultivars are less affected by drought, especially if it occurs later in the season because they are able to reach maturity prior to stress (Lynch and Tai 1989).

In general, moisture stress can negatively affect plant growth, overall yield, and yield of marketable tubers (Bradley and Pratt 1954; MacKerron and Jefferies 1998; van Loon 1981). The timing and duration of drought stress is also significant (Lynch and Tai 1989; Miller and Martin 1987; Stark and McCann 1992). Early season drought stress delays tuber initiation and result in fewer tubers per plant (van Loon 1981). Late season stress can affect tuber bulking and size of tubers. Prolonged periods of excess moisture are undesirable as well. Irrigating to higher percentages of ET has been shown to increase tuber number, but not quality (Yuan et al. 2003). Specific gravity is negatively correlated to irrigation amount while prevalence of internal tuber disorders, including hollow heart and scab ,were all shown to increase with irrigation application rate. Over irrigation resulting in high humidity conditions is also linked to increased incidence of disease including seed piece decay and late blight (Shock 2010). Irrigation frequency is also important for influencing tuber yield and quality due to effects on soil temperature. Kincaid et al. (1993) conducted a field trial in which Russet Burbank was irrigated to ET, +20% ET and -20% ET at varying frequencies (once a week versus three times per week). Lower soil temperatures were found in the more frequently irrigated plots, and this correlated with higher quality tubers with lower reducing sugar content. More frequent irrigation applications also result in increased uniformity of soil moisture, which has been linked to higher specific gravity measurements (Waddell et al. 1999). Effects of environmental stress will be further discussed in a subsequent section.

Nitrogen Management in Potato Production

In addition to soil moisture, nitrogen is a primary determinant of potato yield and quality in sandy soils, and is often the most limiting nutrient in the system (Porter and Sisson 1991; Timm et al. 1963; Waddell et al. 1999; Zebarth and Rosen 2007). Potatoes require the highest nitrogen inputs of crops found in a typical rotation in the sand plains of Wisconsin. This is due to a relatively long growing season and shallow rooting depth that prohibits plants from mining nutrients from deeper in the soil profile (Opena and Porter 1999). Nitrogen inputs for snap bean, sweet corn, field corn soybean and pea range from 67 to 200 kg ha^{-1} while a typical fertilizer application rate for potato is 258 kg N ha^{-1} (Stites and Kraft

2001). Current University of Wisconsin recommendations are even higher, at 280 kg ha^{-1} for a yield of 62 to 73 Mg ha^{-1} (Laboski and Peters 2012). In sandy soils, nitrogen rate is also a primary factor in determining leaching potential (Zvomuya et al. 2003). Therefore, adopting management practices that adjust application rate, method or timing and allow for reductions in fertilizer inputs could have important consequences for nitrate loading in the region.

Split applications and in-season crop nitrogen status monitoring are two methods typically employed by growers. Split applications can be beneficial because by allowing for nitrogen applications ahead of stages of highest crop demand in adherence with best management practices. In many cases, the bulk of nitrogen is applied at planting followed by two to four supplemental applications via banding or irrigation water (Ojala et al. 1990; Stites and Kraft 2001; Waddell et al. 2000). However, this timing does not necessarily match greatest crop demand. For Russet Burbank, only 10 to 15% of total nitrogen requirement is used during the early vegetative growth stage (Westermann and Kleinkopf 1981). By tuber initiation, the crop has taken up 30 to 40% of nitrogen and 58 to 71% during tuber bulking (Ojala 1990; Westermann and Kelinkopf 1981). Nitrogen application timing can also have important effects on yield and quality. Excessive application early in the season leads to delayed tuber growth, reduced yields and low specific gravity (Griffin and Hesterman 1991). Too little nitrogen can lead to smaller tubers, lower marketable yield, inability to outcompete weeds, and vulnerability to the early dying complex (Lang et al.1999; Rosen 1991).

Reducing nitrogen applications at planting through split applications has also been shown to decrease the chance of nitrogen loss to the system due to leaching (Porter and Sisson 1991; Rosen et al. 1995). However, split applications via fertigation through the center pivots or broadcast applications can still be inefficient. Over 50% of fertilizer can end up in the furrow of hilled potatoes due to several factors including hill geometry, canopy interception, development of dry zones, non-uniform wetting patterns, and loss of preferential stem flow later in the growing season (Arriaga et al. 2009; Robinson 1999; Saffigna et al. 1976). The use of drip irrigation and concurrent fertigation is a potential tool to increase ease of split applications and better target nutrients in the root zone of potatoes growing in hills as drip can deliver 100% of fertilizer to the crop row.

In the Western U.S., split applications have more clearly been shown to benefit nitrogen use efficiency, yield and quality (Ojala et al. 1990; Roberts et al. 1991). However, in the upper Midwest, research on the use of split applications has yielded disparate results. Rosen et al. (1995) found that split nitrogen applications resulted in less leaching and increased potato yield. Fixen and Kelling (1981) reviewed data from the Hancock Agricultural Research station in central Wisconsin and determined that 50% applied at emergence and 50% at hilling maximized yield and quality, and little yield gain was made by further splitting N applications. In the Central Sands of Wisconsin, decisions to split applications are likely based on concerns of groundwater nitrate levels rather than potential yield increases.

In-season crop N status monitoring can help to match N applications to demand (Lauer 1986; Westermann and Kleinkopf 1985). A commonly used indicator of crop nitrogen status is petiole nitrate concentrations (Belanger et al., 2003; Porter and Sisson 1991; Rodrigues 2004; Snapp and Fortuna 2003). There is a strong relationship between petiole nitrogen status, fertilizer application rates and final yield (Bundy et al. 1986; Doll et al. 1986; Gardner and Jones 1975; Roberts and Cheng 1988; Timm et al. 1963; Tyler et al. 1983; Porter and Sisson 1991). Prior research has informed the creation of petiole nitrate sufficiency ranges or critical concentrations for tissue samples at different growing stages that can be used to determine if supplemental nitrogen applications are necessary (Bussan et al. 2015; Kaiser et al. 2013; Kleinkopf et al. 1984; Roberts and Cheng 1988; Westcott et al. 1991; Williams and Maier 1990). Critical concentrations vary among cultivars due to differential nitrogen requirements (Doll et al. 1971; MacMurdo et al. 1988). Monitoring is especially critical during the early tuber bulking stage, 40 to 100 days after planting, when rapid nitrogen uptake occurs and nitrogen status can change quickly (Pan et al. 1994; Roberts et al. 1991). Later in the season, low petiole nitrate levels can reflect the inability of the plant to take up more nitrogen instead of insufficient nitrogen availability (Lang et al. 1999). Late season nitrogen applications are rarely taken up by plants and can instead contribute to nitrate loading.

Opportunities with Drip Irrigation

Growers are tasked with balancing yield, profitability and adhering to environmental regulations. Drip irrigation may have the potential to address some of the challenges associated with irrigation and nutrient management in potato production. It is widely used in many parts of the world, as well as the United States. However, few hectares in Wisconsin (about 1500 of 192,000 irrigated hectares) are currently under drip irrigation (USDA-NASSb 2013). This irrigation method can achieve nutrient and water savings by better localizing water and nutrients in crop root zones and maintaining a more consistent supply of water (Cooley 2007; Dasberg and Or 1999; Eldredge et al. 2003; Shock et al. 2007, 2013). This has been shown to allow for reduced water application without negatively affecting yield and quality (Chawla and Narda 2001; Starr et al. 2008; Waddell et al. 1999; Yuan et al. 2003). Additionally, direct application of water to the hill can help prevent development of hydrophobic “dry zones” that that have been found in sprinkler irrigated potato hills in sandy soils (Cooley et al. 2007; Robinson 1999; Starr et al. 2005; Saffigna et al. 1976). Dry zones can form in the root zone especially late in the season (Cooley and Lowery 2000; Dekker et al. 1999). As a result, this can cause much of the applied water and nutrients to runoff into the furrow and contribute to leaching instead of reaching the crop root zone (Cooley and Lowery 2000; Robinson 1999).

Drip irrigation has been extensively researched with a variety of field and vegetable crops (Bucks et al. 1974; Couto et al. 2013; Dukes et al. 2010; Tsipori and Shimshi 1979). There has also been some amount of research done on drip irrigation in potato (Chawla and Narda 2001; Mohammad et al. 1999; Onder et al. 2005; Patel and Rajput 2007; Shalhevet 1983; Starr et al. 2005; Waddell et al. 1999, 2000; Wang et al. 2006, 2007; Yuan et al. 2003). However, much of this has been limited to arid regions, and much less research has been conducted in humid regions such as the lake states of the upper Midwest. This is likely because relatively ample moisture in these regions does not make water-saving technologies an immediate priority (Waddell et al. 1999).

Many studies have looked at the water savings potential of drip irrigation as compared to conventional irrigation methods. Water savings via the use of drip varies depending on climate and soil type. Starr et al. (2008) compared drip irrigation to overhead sprinkler, and found that over a four-year period the use of surface drip irrigation allowed for a 52% reduction in irrigation applications without a significant yield decline. Reyes-Cabrera et al. (2014) compared drip irrigation to seepage irrigation and found similar results; surface drip allowed for water savings of 52 to 87% during the two-year trial. Both of these studies were conducted on coarse-textured soils such as those found in the Central Sands. When compared to furrow irrigation in India, drip irrigated treatments yielded comparably with 30% less water applied (Chawla and Narda, 2001). Deficit irrigation, or irrigating below crop ET may also be possible through the use of drip irrigation. Yuan et al. (2003) based application rates with drip on crop ET demand, and found that it was possible to decrease water application up to 75% of ET replacement without affecting yield. The ability to irrigate below crop ET demand and reduce overall application rates can improve irrigation water use efficiency of crop production.

Irrigation water use efficiency has been defined in agronomic terms as yield or economic yield per unit of irrigation water applied (El-Hendawy et al. 2008; Onder, 2005; Ozbahce 2010; Viets 1962). Howell et al. (1990) offer the following equation to express irrigation water use efficiency,

$$\text{IWUE} = \frac{E_y}{I}$$

Where E_y is yield in kg ha^{-1} and I is irrigation amount in mm or m^3. This definition stands in contrast to other agronomic definitions of water use efficiency that look at yield per unit of ET (Viets 1962) or irrigation efficiency that looks at proportion of irrigation water that is beneficially used by a crop (Burt et al. 1997). Improved irrigation efficiency can provide many benefits, the most important of which are conservation of water and energy resources and decreased leaching of agrochemicals into the groundwater (Curwen and Massie 1984). Some of the ways in which to address irrigation water use efficiency as outlined by Howell (2001) include increasing yield per unit of water applied and avoiding water losses to unusable sinks like deep percolation, runoff and evaporation. This research sought in part to assess the ability of drip irrigation to reduce application losses so that higher yield can be produced using less irrigation.

Optimizing irrigation management and decreasing overall volume of water applied through the use of drip irrigation can lead to other potential benefits such as reduced nutrient requirements and leaching (Eldredge et al. 2003; Reyes-Cabrera et al. 2014; Shock et al. 2007, 2013). Nitrogen rate is a primary factor in determining leaching potential in sandy soils, so the ability to reduce rates through the use of drip could help to mitigate negative environmental impacts (Zvomuya et al. 2003). Research conducted on sandy soils in Michigan showed that nitrogen rates could be decreased below standard practices while still obtaining comparable tuber yield with the use of drip irrigation (Joern and Vitosh 1995). Chawla and Narda (2001) compared drip irrigation to conventional furrow irrigation in potato and found potential water and nutrient savings of 30% and 70%, respectively. Results for potato agree with studies comparing nutrient savings under drip and conventional irrigation with other crops. Potential nutrients savings of 25 to 50% and 20 to 40% have been found in cotton and tomato, respectively (Janat 2008; Singandhupe et al. 2012).

Reduced leaching with the use of drip irrigation can lead to an interaction effect between irrigation amount and nitrogen application rates as shown by Badr et al. (2012) and Mohk et al. (2015) in Egypt and Tunisia. Yield was maximized at lower N rates under deficit drip irrigation treatments compared to higher irrigation levels (Badr et al. 2012; Mohk et al. 2015). Higher N rates negatively affected yields at lower irrigation levels (Badr et al. 2012). However, Kelling et al. (1998) found no significant interaction between irrigation and nitrogen rates in work done in the Central Sands of Wisconsin. Also, water deficit conditions have been found to decrease tuber size and yield in some studies (Yuan et al. 2003; Onder 2005), thus exploiting this interaction could lead to potential decreases in quality.

Environmental Stress and Quality

In Wisconsin and elsewhere, research on drip irrigation in potato production has focused primarily on potential water savings, water distribution patterns and nitrogen uptake (Cooley et al. 2007; Waddell et al. 1999, 2000). There is a lack of research relating drip irrigation to physiological defects, especially incidence of processing quality defects such as sugar end and stem-end chip defect. A significant proportion of potatoes in the United States are produced for processing. In 2012, almost 2.5 times the quantity of fresh market was sold for processing (National Potato Council 2014). Thus, it is important to look at management effects on processing quality attributes. Environmental stress during the growing season has been linked to defects that affect processing quality or fresh market suitability including sugar end disorder, stem-end chip defect, brown center or its more advanced manifestation, hollow heart. Although numerous factors have been linked to increased incidence of these defects, soil temperature, moisture, and fertilizer regime have been most closely tied, especially if stress occurs during the sensitive early tuber bulking growth stage (Bussan 2008; Thompson et al. 2008; Wang et al. 2012).

Sugar end defect, also known as jelly-end or translucent end, is characterized by low starch content at the basal end of the tuber and high reducing sugar content (Thompson et al. 2008). When the reducing sugars (glucose and fructose) undergo the Maillard reaction during processing at high temperatures, it results in dark, undesirable coloring (Gould and Plimpton 1985; Shallenberger 1959). High rates of sugar-end can lead to costly load rejections. Iritani and Weller (1978) identified three types of sugar end, and the most common is connected to early season stress. Previous research has attempted to parse out the respective effects of heat stress and intermittent water stress, but it appears that the interaction of the two lead to the greatest incidence of sugar end (Hiller and Thornton 1993; Iritani 1981; Kincaid et al. 1993; Kleinkopf et al. 1988, 1979; Shock et al. 1992, 1993). Research on the effect of water deficit and timing on sugar end incidence revealed that as much as a single occurrence of temporary water stress was enough to cause an increase in sugar end (Eldredge et al. 1996).

Environmental plant stresses are also linked to stem-end chip defect and hollow heart. Stem-end chip defect consists of dark coloration of the vasculature at the effected, stem or basal end of the tuber and concurrent dark coloration within vascular ring upon frying (Bussan et al. 2009; Wang et al. 2012). Stem-end is more unpredictable than sugar-end defect, and the severity, duration and timing of stress necessary to cause this defect are unclear (Bethke 2009). Work done by Wang et al. (2012) demonstrated that moderate environmental stress was not sufficient to cause an increase in severity of stem-end, in contrast to sugar end. Only heat stress for a period of 14 days resulted in increased incidence of stem-end, but water stress and differences in chemical maturity at harvest did not.

Hollow heart, or its incipient form, brown center, is also of economic importance. Defected tubers must be culled when sold for fresh market. Hollow heart also affects the specific gravity of tubers and as a result, the price (Bussan 2007). Unlike sugar and stem-end defects, hollow heart and brown center have been linked to cooler temperatures during early tuber bulking (Bussan et al. 2007). And, like the other two aforementioned defects, uneven soil moisture, transitory water deficit, and poor nutrient management are also linked to higher incidence (Bussan et al. 2007).

Drip irrigation has been shown to better maintain spatial soil moisture uniformity under a variety of vegetable production systems (Dukes et al. 2010; Tsipori and Shimshi, 1979). More uniform moisture could also influence soil temperatures and limit environmental stress that causes the development of these economically important physiological defects. For example, Reyes-Cabrera et al. (2014) found a reduction in hollow heart under drip irrigation when compared to seepage irrigation on a sandy soil. This research sought in part to further explore the effect of drip irrigation on incidence of physiological defects including sugar and stem end defect. Potential improvements in potato quality could offset some of the higher costs associated with the use of drip.

Challenges Associated with Drip Irrigation

Drip irrigation has likely not been widely adopted in the humid upper Midwest in potato production due to a variety of challenges associated with its use. In potato production, shallowly buried drip lines can interfere with cultural practices such as tilling, hilling and harvesting (Starr et al. 2008). Burying drip tape is also not recommended in coarse-textured soils. Deziel and Curwen (1996) compared drip tape placement on top of hill prior to final hilling to placement with seed piece at planting and found that placement on top of hill resulted in higher total and US #1 yield of Russet Burbank in central Wisconsin. Patel and Rajput (2006) also looked at tape placement depth and irrigation amount, and found that, below 10 cm placement, gravimetric forces prevailed over capillary forces that would have facilitated upward movement of water. The point-source nature of water application from drip emitters can cause non-uniform wetting if not managed well. And, in coarse-textured soils, there may not be sufficient lateral movement of moisture to overcome this. However, some have cited increased spatial wetting uniformity in the potato hill as a benefit to the use of drip irrigation (Wilner et al. 1996). Surface drip tape placement performed better than buried with regard to yield and irrigation water use efficiency (Starr et al. 2005). However, a draw back of surface placement is high re-occurring cost from annual installation and issues with drip tape disposal (Deziel and Curwen 1996; Waddell et al. 2000). Lastly, results concerning the effect of drip irrigation on tuber quality are somewhat inconclusive which may make growers hesitant to adopt this irrigation method. The researchers understand the limitations of drip irrigation in potato in the context of sandy soils, and the aim of this study is not to identify a replacement for all center-pivot irrigation. However, we sought to explore this technology as a potential alternative for areas in which groundwater withdrawal and contamination is of particular concern.

Research Objectives

The overall goal of this research was to assess the potential to reduce irrigation water and nitrogen application rates through the use of drip irrigation without negatively affecting yield and quality when compared to conventional, overhead sprinkler irrigation and nitrogen management practices. For the first part of the study, we evaluated cultivars that are important to the industry for both processing and fresh marking including Russet Burbank, Russet Norkotah, and Snowden. Specific objectives were to assess the effects of overhead irrigation and drip irrigation at three rates on 1) total yield and yield of size categories, 2) tuber quality response including fry color, stem-end chip defect, and reducing sugar content, 3) crop nitrogen status during the growing season as indicated by petiole nitrate concentrations, 4) soil moisture and temperature response in the crop root zone, and 5) irrigation water use efficiency in Mg of yield per mm of irrigation water applied. In the second part of this research we evaluated a single cultivar, Russet Norkotah, and assessed the effect of irrigation method and rate together with nitrogen fertilizer rate on 1) total yield, yield of size categories, and quality response, 2) petiole nitrate levels, 3) and nitrogen removal in harvested tubers.

Literature Cited

Arriaga, F.J., B. Lowery, and K.A. Kelling. 2009. Surfactant impact on nitrogen utilization and leaching in potatoes. *Am. J. Potato Res.* 86:383-390.

Badr, M.A., W.A. El-Tohamy, and A.M. Zaghloul. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. *Agr. Water Manage.* 110:9-15.

Belanger, G., J.R. Walsh, J.E. Richards, P.H. Milburn, and N. Ziadi. 2002. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am. J. of Potato Res.* 79:269–279.

Bethke, P.C., R. Sabba, and A.J. Bussan. 2009. Tuber water and pressure potentials decrease and sucrose content increase in response in moderate drought and heat stress. *Am. J. Potato Res.* 86:519-532.

Bradley, G.A. and A.J. Pratt. 1954. The response of potatoes to irrigation at different levels of available moisture. *Am. Potato J.* 31:305-310.

Bronson, K.F., A. Malapati, J.D. Booker, B.R. Scanlon, W.H. Hudnall, and A.M. Schubert. 2009. Residual soil nitrate in irrigated Southern high plains cotton fields and Ogallala groundwater nitrate. *J. Soil Water Conserv.* 64:98–104.

Bucks, D.A., F.S. Nakayama, and A. W.Warrick. 1982. Principles, practices, and Potentialities of trickle (drip) irrigation. *Adv. Irr.* 1:219-298.

Bundy, L.G., R.P. Wolkowski, and G.G. Weis. 1986. Nitrogen source evaluation for potato production on irrigated sandy soils. *American. Potato J.* 63:385-397.

Burt, C. M., A.J. Clemmens, A. J., T. S Strelkoff, K. H. Solomon, R. D.Bliesner, L.A. Hardy, T.A. Howell, and D.E. Eisenhauer. 1997. Irrigation Performance Measures:Efficiency and Uniformity. *J. Irrig. Drain. E-ASCE.* 123:423-442.

Bussan, A.J., P.C. Bethke, R. Sabba, W.G. Schmitt, and M.J. Drillias. 2009a. Managing stem end defect in stored potatoes. Proc. Wisconsin Ann. Potato Meet*.* 22:25-26.

Bussan, A.J. 2007. The Canon of Potato Science:45. Brown Centre and Hollow Heart. *Am. J. Potato Res.* 50:395-398.

Bussan, A.J., J.B. Colqhoun, E.M. Cullen, V.M. Davis, R.L. Groves, D.J. Heider, G.R.W. Nice, and M.D. Ruark. 2015. Commercial Vegetable Production in Wisconsin. University of Wisconsin Extension Publication A3422. pp 188-213.

Chawla, J.K. and N.K. Narda. 2001. Economy in water and fertilizer use in trickle fertigated potato. *Irrig. Drain.* 50:129-137.

Cooley, E., B. Lowery, K.A. Kelling and S. Wilner. 2007. Water dynamics in drip and overhead sprinkler irrigated potato hills and development of dry zones. *Hyrdol. Process.* 21:2390-2399

Cooley, E. and B. Lowery. 2000. Nitrogen leaching and use of surfactants to reduce the impacts of the potato dry zone. Proc. Wisconsin Ann. Potato Meet 14:89–93.

Corey, A.T., and G.R. Blake. 1953. Moisture available to various crops in some New Jersey soils. *Soil Sci. Soc. Am. J* 17:314-317.

Couto, A., R. Padín, B. Reinoso. 2013. Comparative yield and water use efficiency of two maize hybrids differing in maturity under sold set sprinkler and two different lateral spacing drip irrigation systems in León, Spain. *Agr. Water Manage.* 124:77-84.

Curwen, D. and L.R. Massie. 1984. Potato Irrigation Scheduling in Wisconsin. *Am. Potato J.* 61:245-241.

Dasberg, Samuel and D. Or. 1999. *Applied Agriculture:Drip Irrigation*. New York: Springer. pp. 4-14.

Dekker, L.W., C.J. Ritesma, O. Wendroth, N. Jarvis, K. Oostindie, W. Pohl, M. Larsson, and J.P. Gaudet. 1999. Moisture distributions and wetting rates of soils at experimental fields in the Netherlands, France, Sweden and Germany. *Journal of Hydrol.* 215:4–22

Deziel, G. and D. Curwen. 1996. Effect of drip irrigation on the growth and yield of Russet Burbank Potato. Proc. Wisconsin Ann. Potato Meet. 9:49-60.

Doll, E.C., D.R. Christenson and A.R. Wolcott. 1971. Potato yields as related to nitrate levels in petioles and soils. *Am. J. Potato Res.* 48:105-112.

Dukes, M.D., L. Zotarelli, and K.T. Morgan. 2010. Use of irrigation technologies for vegetable crops in Florida. *HortTecnology* 20:133–142.

El-Hendawy, S.E., E.A. Abd El-Lattief, M.S. Ahmed, and U. Schmidhalter. 2008. Irrigation rate and plant density effects on yield and water use efficiency of drip-irrigated corn. *Agr. Water Manage.* 95:836-844.

Eldredge, E.P., Z.A. Holmes,, A.R. Mosley, C.C. Shock, and T.D. Stieber. 1996. Effects of transitory water stress on potato tuber stem-end reducing sugar and fry color. *Am. Potato J.* 73:517-530.

Eldredge, E.P., C.C. Shock, and L.D. Saunders. 2003. Early and Late Harvest Potato Cultivar Response to Drip Irrigation. *Acta Hortic.* 619:233-239.

Epstein, E., and W.J. Grant. 1973. Water stress relations of the potato plant under field conditions. *Agron. J.* 65:400-404.

Fabeiro, C., F. M. de Santa Olalla, and J.A. de Juan. 2001. Yield and size of deficit irrigated potatoes. *Agr. Water Manage.* 48:255-266.

Fixen, P.E. and K.A. Kelling. 1981. Potato fertility requirements and recommendations: nitrogen. UWEX Potato Manual 81PF-B1. 16 pp.

Gardner, B. R., and J. P. Jones. 1975. Petiole analysis and the nitrogen fertilization of Russet Burbank potatoes. *Am. Potato J.* 7:195–200.

Griffin, T.S. and O.B. Hesterman. 1991 Potato response to legume and fertilizer N sources. *Agron. J.* 83:1004-1012

Gould, W.A., and S. Plimpton. 1985. Quality evaluation of potato cultivars for processing. North Central Regional Research Publication 305. Ohio Agricultural Research and Development Center, Wooster, Ohio. Research Bulletin 1172.

Hill, A.R. 1986. Nitrate and chloride distribution balance under continuous potato cropping. *Agr. Ecosyst. Env.* 15:267-280.

Howell, T.A., Cuenca, R.H. and Solomon, K.H., 1990. Crop Yield Response. In: G.J. Hoffman, T.A. Howell, and K.H. Solomon (Eds.) *Management of Farm Irrigation Systems*. ASAE. St Joseph, MI. pp. 311- 312

Howell, Terry. 2001. Enhancing Water Use Efficiency in Irrigated Agriculture. *Agron. Journal* 93:281-289.

Hubell, Audra. 2013. Wisconsin Vegetables 2012. USDA National Agricultural Statistics Servic*e*.http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Vegetables/vegannual.pdf accessed 12/20/13. 1 pp.

Iritani, W.M. 1981. Growth and preharvest stress and processing quality of potatoes. *Am. Potato J.* 58:71-80.

Iritani, W.M., and L.D. Weller. 1978. Influence of low fertility and vine killing on sugar development in apical and basal portions of Russet Burbank potatoes. *Am. Potato J* 55:239-246.

Janat, M. 2008. Response of cotton to irrigation methods and nitrogen fertilization: yield components, water-use efficiency, nitrogen uptake, and recovery. *Commun. Soil Sci. Plan.* 39:2282-2302.

Joern, B.C., and M.L. Vitosh. 1995. Influence of applied nitrogen on potato part I: yield, quality and nitrogen uptake. *Am. Potato J.* 54:51–63.

Laboski, C.A.M. and J.B. Peters. 2012. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. University of Wisconsin Extension Publication A2809. pp 66.

Lauer, D.A. 1986. Russet Burbank yield response to sprinkler-applied nitrogen fertilizer. *Am. J. of Potato Res.* 63:61-69.

Lang, N.S., R.G. Stevens, R.E. Thornton, W.L. Pan and S. Victory 1999. Potato nutrient management for central Washington. Wash. State. Univ., Pullman, Coop Ext. Bul. 1871. pp 4.

Kaiser, D.E., J.A. Lamb, C. Rosen. 2013. Plant Analysis Sampling and Interpretation. University of Minnesota Extension. FO-3176-B. 7pp.

Keene, A. and P. Mitchell. 2010. Economic Impact of Specialty Crop Production and Processing in Wisconsin. UW Extension. http://www.aae.wisc.edu/pubs/misc/docs/mitchell.crop.impacts.pdf accessed 19 December 2013. 10 pp.

Kelling, K.A., S.A. Wilner, R.F. Hensler, and L.M. Massie. 1998. Placement and irrigation effects on nitrogen fertilizer use efficiency. Proc. Wisconsin Ann. Potato Meet. 11:79–88.

Kincaid, D.C. and Westermann, D.T. and Trout, T.J. 1993. Irrigation and soil temperature effects on Russet Burbank quality. *Am. Potato J. 71:15-28.*

Kleinkopf, G.E. 1979. Translucent end of potatoes. University of Idaho Curr Info Series No 488. pp 4.

Kleinkopf, G.E., G.D. Kleinschmidt and D.T. Westermann. 1984. Tissue analysis: A guide to nitrogen fertilization of Idaho Russet Burbank potatoes. University of Idaho Curr Info Series No. 740. 4 pp.

Kleinkopf, G.E., D.T. Westermann, and M.J. Wille. 1988. 1. Soil temperature effects on sugar end development. *Proc. Univer. Idaho Winter Commodity Schools.* 20:180-181.

Kniffin, M., K. Potter, A.J. Bussan, K. Bradbury, and J. Colquhoun. 2014. Sustaining Central Sands Water Resources. University of Wisconsin-Madison. http://wisa.cals.wisc.edu/central-sands-white-paper. Accessed 30 March 2015. pp. 8-30.

Kraft, G.J., W. Stites and D.J. Mechenich. 1999. Impacts of irrigated vegetable agriculture on a humid north-central U.S. sand plain aquifer. *Ground Water* 37:572–580.

Kraft, George et al. 2012. Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited. *Ground Water.* 50: 308-318.

Lang, N.S., R.G. Stevens, R.E. Thornton, W.L. Pan and S. Victory 1999. Potato nutrient management for central Washington. Wash. State. Univ., Pullman, Coop Ext. Bul. 1871. pp 4.

LeMasters, G. and J. Baldock. 1995. A survey of atrazine in Wisconsin groundwater. Phase One Report. ARM Publ. no. 26. Wisconsin Dep. Agric. Trade and Consumer Protection, Madison.

Lynch, D.R., and G.C. Tai. 1989. Yield and yield component response of eight potato genotypes to water stress. *Crop Science* 29:1207-1211.

MacMurdo, W., R.K. Prange and R. Veinot. 1988. Nitrogen fertilization and petiole nitrate testing in production of whole seed tubers of the potato cultivars Sebago and Atlantic. *Can. J. Plant Sci.* 68:901-905.

MacKerron, D.K.L. and R.A. Jefferies. 1998. The distribution of tuber sizes in droughted and irrigated crops of potato. I. Observations on the effect of water stress on graded yields from different cultivars. *Potato Res.* 31:269-278.

Martin, M.W., and D.E. Miller. 1983. Variations in response of potato germplasm to deficit irrigation as affected by soil texture. *Am. Potato J.* 60:671-683.

Miller, D.E. and M.W. 1987. Effect of declining or interrupted irrigation on yield and quality of three potato cultivars grown on sandy soil. *Am. Potato J.* 64:109-117

Mohk, F.E., M.M. Masmoudi, and N.B. Mechlia. 2015. Yield and water productivity of drip-irrigated potato under different nitrogen levels and irrigation regime with saline water in arid Tunisia. *Amer. J. Plant Sci.* 6:501-510.

Mohammad, M.J., S. Zuraiqi, W. Quasmeh, and I. Papadopoulos. 1999. Yield response and nitrogen utilization efficiency by drip-irrigated potato. *Nutr. Cycl. Agroecosys.* 54:243-249.

NRCS (Natural Resources Conservation Service) 2005. Nutrient Management Code 590. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046896.pdf. Accessed 15 November 2014. 8 pp.

Ojala, J.C., J.C. Stark and G.E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. J. of Potato Res.* 67:29-42.

Onder, S., M.E. Caliskan, D. Onder, and S. Caliskan, S. 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agr. Water Manage.* 73:73–86.

Opena, G.B. and G.A. Porter. 1999. Soil management and supplemental irrigation effects on potato: II. Root growth. *Agron. J*. 91:426-431

Ozbahce, A. and A.F. Tari. 2010. Effects of different emitter space and water stress on yield and quality of processing tomato under semi-arid climate conditions. *Agr. Water Manage.* 97:1405-1410.

Patel, N., Rajput, T.B.S., 2007. Effect of drip tape placement depth and irrigation level on yield of potato. *Agr. Water Manage*. 88:209–223.

Phene, C.J. and D.C. Sanders. High-frequency trickle irrigation and row spacing effects on yield and quality of potatoes. *Agron. J.* 68:602-607.

Porter, G.A. and J.A. Sisson. 1991. Petiole nitrate content of Mainegrown Russet Burbank and Shepody potatoes in response to varying nitrogen rate. *Am. J. of Potato Res.* 69: 309-314.

Randall, G., Delgado, J.A., and Schepers, J.S. 2008. Nitrogen management to protect water resources. In *Nitrogen in Agricultural Systems*, eds. J.S. Schepers, and W.R. Raun, 911–945. SSSA Monograph. 49: Madison, WI.

Reyes-Cabrera, J., L. Zotarelli, D.L. Rowland, M.D. Dukes and S.A. Sargent. 2014. Drip as alternative irrigation method for potato in Florida sandy soils. *Am. J. Potato Res.* 91:504-516

Richards, J.E., P.H. Milburn, A.A. MacLean and G Dermerchang. 1990. Intensive potato production effects on nitrate-N concentration of rural New Brunswick well water. *Canadian Agricultural Engineering* 2:189-196.

Robinson, D. 1999. A comparison of soil-water distribution under ridge and bed cultivated potatoes. *Agric. Water Manage.* 42:189-204.

Rodrigues, M.A. 2004. Establishment of continuous critical levels for indices of plant and pre sidedress soil nitrogen status in the potato crop. Commun. Soil Sci. Plant Anal. 35:2067-2085.

Roberts, S., H.H. Cheng, and F.O. Farrow. 1991. Potato uptake and recovery of N-15 enriched NH4 /NO3 from periodic applications. *Agron. J.* 83:378–381.

Roberts, S. and H.H. Cheng. 1988. Estimation of critical nutrient range of petiole nitrate for sprinkler-irrigated potatoes. *Am. Potato J.* 65:119-124.

Rosen, C. 1991. Potato fertilization on irrigated soils. Vol. 2002. FO-3425-GO. Commun. Educ. Technol. Serv., Univ. Minn. Ext. Serv.

Rosen, C.J. 1995. Nitrogen management studies in Minnesota. *Proceedings of Wisconsin Annual Potato Meeting* 8:15–23.

Saffigna, P.G., and D.R. Keeney. 1977. Nitrate and Chloride in groundwater under irrigated agriculture in central Wisconsin. *Ground Water* 15:170–177.

Saffigna, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflow, and hilling. *Agron. Journal* 68:337-342.

Shalhevet J, Shimshi D, Meir T. 1983. Potato irrigation requirements in a hot climate using sprinkler and drip methods. *Agron. J.* 75:13–16.

Shallenberger, R.S., O. Smith and R.H. Treadway. 1959. Role of the sugars in the browning reaction in potato chips. *J. Agr. Food Chem.* 7: 274-277.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998. Potato yield and quality response to deficit irrigation. *HortScience* 33:1117-11121.

Shock, C.C., Z.A. Holmes, and T.D. Stieber. 1993. The effect of timed water stress on quality, total solids, and reducing sugar content of potatoes. *Am. J. Potato Res.* 70:227-241.

Shock, C.C. J.C. Zalewski, T.D. Stiver, and D.S. Burnett. 1992. Impact of early season water deficits on Russet Burbank plant development, tuber yield, and quality. *Am. Potato J.* 69:793-803.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007. Irrigation best management practices for potato. *Am. J. of Potato Res.* 84:29–37.

Shock, C.C. 2010. Water Requirements and Irrigation. In W. bohl and S. Johnson (Eds) *Commercial Potato Production in North America.* USDA Handobook 267. pp. 54-56.

Shock, C.C., F-X. Wang, R. Flock, E.P. Eldredge, A.B. Pereira, and J. Klauzer. 2013. Drip irrigation guide for potatoes, Sustainable agriculture techniques. Oregon State University Extension Service EM 8912. http://ir.library.oregonstate. edu/xmlui/bitstream. Accessed 10 April 2015. 8pp.

Singandhupe, R.B., G.G.S.N. Rao, N.G. Patil, P.S. Brahmanand. 2003. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopericonesculentum* L.). *European Journal of Agron.* 19:327-340.

Snapp, S.S. and A.M. Fortuna. 2003. Predicting nitrogen availability in irrigated potato systems. *Hort Technology.* 13:598-604.

Stark, J.C., S.L. Love, B.A. King, J.M. Marshall, W.H. Bohl, T. Salaiz. 2013. Potato Cultivar Response to Seasonal Drought Patterns. *Am. J. of Potato Res.* 90:207-216.

Stark, J.C., and I.R. McCann. 1992. Optimal allocation of limited water supplies for Russet Burbank potatoes. *Am. Potato J.* 69:413–421.

Stark, J.C., J.J. Pavek, and I.R. McCann. 1991. Using canopy temperature measurements to evaluate drought tolerance of potato genotypes. *J. Amer. Soc. Hort. Sci.*116:412–415.

Starr, G.C. 2005. Temporal stability and spatial variability of soil water patterns with implications for precision water management. *Agr. Water Manage.* 72:222-243.

Starr, G.C., D. Rowland, T.S. Griffin, O.M. Olanya. 2008. Soil water in relation to irrigation, water uptake and potato yield in a humid climate. *Agr. Water Manage.* 95:292-300

Steckel, J.R., and D. Gray. 1978. Drought tolerance in potatoes. *J. Agr. Sci.* 92:375-381.

Stites, W. and G.J. Kraft. 2000. Groundwater quality beneath irrigated vegetable fields in a North-Central U.S. sand plain. *J.Enviro. Qual. 29:1509-1517.*

Stites, W. and G.J. Kraft. 2001. Nitrate and chloride loading to groundwater from an irrigated North-Central U.S. sand-plain vegetable field. *Journal of Environmental Quality* 30:1176-1184.

Timm, H.,J.C. Bishop and V.H. Scweers. 1963. Growth, yield, and quality of White Rose potatoes as affected by plant population and levels of nitrogen. *Am Potato J.* 40:182-192.

Thornton, M., W. Buhrig and N. Olsen. 2010. The relationship between soil temperature and sugar ends in potato. *Potato Research* 53:289-296.

Thompson, A.L., S.L. Love, J.R. Sowokinos, M.K. Thornton, and C.C. Shock. 2008. Review of the sugar-end disorder in potato (Solanum tuberosum L.). *Am. J. of Potato Res.* 85:375–386.

Tsipori Y, Shimshi D. 1979. The effect of trickle line spacing on yield of tomatoes (Lycosperisicum esculentum Mill.). *Soil Sci. Soc. Am. J.* 43:1225-1228.

Tyler, K.B., F.E. Broadbent andJ.C. Bishop. 1983. Efficiency of nitrogen uptake by potatoes. Am PotatoJ 60:261-269.

USDA-NASS (US Department of Agriculture-National Statistics Service). 2013a. 2013 Wisconsin Agricultural Statistics. http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Annual_Statistical_Bulletin/bulletin2013_web.pdf. Accessed 10 March 2014. pp. 12.

USDA –NASS (US Department of Agriculture-National Agricultural Statistics Service. 2013b. 2012 Census of Agriculture: Farm and Ranch Irrigation Survey. http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris13_2_030_030.pdf. Accessed 25 March 2015. pp. 104

van Loon, C.D. 1981. The effect of water stress on potato growth, development, and yield. *Am. Potato J.* 58:51–69.

Viets, F.G. 1962. Fertilizer and efficient use o f water. *Adv. Agron.* 14:223-264.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation- and nitrogen-management effects on potato yield, tuber quality, and nitrogen uptake. *Agron. J.* 91:991–997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation- and nitrogen-management impacts on nitrate leaching under potato. *J. Env. Qual.* 29:251–261.

Wang, F.-X., Y. Kang, S.-P. Liu, and X.-Y. Hou. 2007. Effects of soil matric potential on potato growth under drip irrigation in the North China Plain. *Agr. Water Manage.* 88:34–42.

Wang, F.-X., Y. Kang, and S.-P. Liu. 2006. Effects of drip irrigation frequency on soil wetting pattern and potato growth in North China Plain. *Agr. Water Manage*. 79:49–58.

Wang, Y., Bussan, A.J. and P.C. Bethke. 2012. Stem-End defect in chipping potatoes (*Solanum tuberosum* L.) as influenced by mild environmental stress. *Am. J. Potato Res.* 89:392-399.

Weeks, E.P. and H.G. Stangland. 1971. Effects of irrigation on streamflow in the Central Sand Plain of Wisconsin. U.S. Geological Survey Open-File Report. Reston, Virginia:USGS http://wi.water.usgs.gov/pubs/OFR-sandplain.index.html accessed 15 April 2015.

Weisz, R., J. Kaminski, and Z. Smilowitz. 1994. Water deficit effects on potato leaf growth and transpiration:Utilizing fraction extractable soil water for comparison with other crops. *Am. Potato J.* 71:829-840.

Westcott, M.P., V.R. Steward, and R.E. Lund. 1991. Critical petiole nitrate levels in potato. *Agron. J.* 83:844-850.

Westermann, D.T., G.E. Kleinkopf, and L.K. Porter. 1988. Nitrogen fertilizer efficiencies on potatoes. *Am. J. of Potato Res.* 65:377-386.

Westermann, D.T., and G.E. Kleinkopf. 1985. Nitrogen requirements for potatoes. *Agron. Journal* 77:616-621.

Westermann, D.T. and G.E. Kleinkopf. 1981. Potato growth and nitrogen requirements. Proc. Wash. State Potato Conf. pp.121-128.

Williams, C.M.J., and N.A. Maier. 1990. Determination of the nitrogen status of irrigated potato crops. I. Critical ranges for nitrate-nitrogen in petioles. *Journal of Plant Nutrition* 13:971-984.

Wilner, S.A., K.A. Kelling, and L.R. Massie. 1996. Effect of irrigation system and nitrogen fertilization method on potatoes. Proc. Wisconsin Ann. Potato Meet. 9:81-90.

WDNR (Wisconsin Department of Natural Resources). 2015. Groundwater Monitoring Database. http://prodoasext.dnr.wi.gov/inter1/hicap$.startup. Accessed 15 February 2015.

WDNR (Wisconsin Department of Natural Resources). 1997. Status of Groundwater Quantity in Wisconsin. PUBL-DG-043-97 http://dnr.wi.gov/topic/Groundwater/documents/GCC/gw-quantity.pdf. Accessed 15 November 2013. pp. 29.

Wolfe, D.W., E. Fereres, and R.E. Voss. 1983. Growth and yield response of two potato cultivars to various levels of applied water. *Irrigation Sci.* 3:211–222.

Yuan, B.Z., S. Nishiyama, and Y. Kang. 2003. Effects of different irrigation regimes on the growth and yield of drip irrigated potato. *Agr. Water Manage.* 63:153–167.

Zebarth, B.J. and C.J. Rosen. 2007. Research perspective on nitrogen BMP development for potato. *Am. J. of Potato Res.* 84:3-18.

Zvomuya, F., C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. *J. Envir. Qual.* 32:480–489.

CHAPTER 2

Effects of Irrigation Regime on Tuber Yield and Quality, Soil Moisture Content, Petiole Nitrate Levels, and Irrigation Water Use Efficiency of Three Potato Cultivars

Abstract

In the Central Sands of Wisconsin, center-pivot irrigation is the predominant method used to deliver water in potato (*Solanum tuberosom* L.) production. However, concerns of groundwater quantity and quality have pushed growers to explore alternative management practices with improved water and nutrient use efficiency. A two-year trial was conducted in 2013 and 2014 to evaluate yield and quality of three potato varieties, Russet Burbank, Russet Norkotah and Snowden, as influenced by irrigation method and rate. Specific objectives were to assess the effects of overhead irrigation at 100% of crop evapotranspiration (ET_c) demand and drip irrigation at 100%, 86% and 75% ET_c on yield and tuber size categories, tuber quality parameters including fry color and reducing sugar content, petiole nitrate levels, soil moisture and temperature in the crop root zone, and irrigation water use efficiency. Total and US #1 yields were similar for all varieties across irrigation treatments except Russet Norkotah, which yielded higher under overhead irrigation relative to drip in 2013. Overhead irrigation also increased large tuber yield of this variety relative to the highest drip treatment. Soil moisture data and observed wilting in the drip irrigation treatments indicated moisture stress, but the crop did not respond negatively in terms of yield and quality. Ample precipitation both years, especially during critical growth stages, may have mitigated negative effects of deficit irrigation treatments. Drip irrigation led to greater volumetric moisture content 20 cm below the hill in the crop root zone in one of two years, and limited water to the furrow in both years. Our results indicate that it was possible to maximize total yield with 25% less irrigation water use for two of three cultivars in 2013 and all three cultivars in 2014.

Introduction

Much of Wisconsin's irrigated acreage is concentrated in the Central Sands, a major center for high-value vegetable production, including potato (USDA-NASS 2013a). Nearly all producers in the region utilize center pivot irrigation as the predominant method, using groundwater as the source (Wyman, *in press*). The drastic increase in number of high capacity wells has led to concerns about potential impacts of increased pumping on groundwater and surface water resources. In this region, groundwater and surface water are strongly tied due to the unconfined structure of the glacial aquifer underlying this region (Kniffin 2014; Kraft 2012). Thus, continued pumping and even small reductions in groundwater can have consequences for lake levels and stream flows (Kraft et al. 2012). High relative humidity combined with irrigation water sourced from groundwater at 10 to 15 °C cooler than air temperature results in high irrigation efficiency relative to Western states. The need to conserve groundwater resources has led to desire to increase water use efficiency and reduce pumping for irrigation.

The same characteristics that make the sandy soils of this region suitable media for potato production also require precise irrigation management to optimize yield and quality. These soils are coarse-textured with high hydraulic conductivity and low organic matter (Saffigna and Keeney 1977; Stites and Kraft 2001). Early research on potato production in this region revealed that over 50% of all water and nitrogen is lost due to drainage (Saffigna et al. 1977). This drainage then leads to subsequent contamination of groundwater with nutrients and agrochemicals (Starr et al. 2005). Maintaining soil moisture in sandy loam to loamy sand soils proves difficult as both water storage capacity and water retention abilities are low (Weisz et al. 1994). Research suggests that potato is sensitive to water stress and must be irrigated to meet evapotranspiration (ET) demand, especially during critical growth stages (Epstein and Grant 1973; Fabeiro et al. 2001; Hang and Marutani and Cruz 1989; Miller 1986; Opena and Porter, 1999; Phene and Sanders, 1976; Porter et al. 1999; Shalhevet et al. 1983; Shock et al. 1998; Weisz et al. 1994). This is in part due to the shallow effective rooting depth of potato (van Loon 1981, Weisz et al.1994).

The use of drip irrigation is one potential tool to improve irrigation efficiency, reduce irrigation pumping, and maintain yield and quality of the crop. Drip irrigation is widely used in many parts of the world as well as the United States. However, few acres in Wisconsin are currently under drip irrigation (USDA-NASS 2013b). Drip irrigation can achieve nutrient and water savings by better localizing water and nutrients in crop root zones and maintaining a more consistent supply of water than overhead sprinkler irrigation (Cooley 2007; Dasberg and Or 1999; Eldredge et al. 2003; Shock et al. 2007, 2013). This has been shown to allow for reductions in water application rates without negatively affecting yield and quality (Chawla and Narda 2001; Starr et al. 2008; Waddell et al. 1999; Yuan et al. 2003). Additionally, direct application of water to the potato hill can help prevent development of a hydrophobic “dry zone” that is common under sprinkler irrigation (Cooley et al. 2007; Robinson 1999). The dry zones can cause much of the applied water to runoff into the furrow and move beyond the crop root zone.

Drip irrigation has been extensively researched in a variety of vegetable crops (Bucks et al. 1974; Tsipori and Shimshi 1979) and in potato (Chawla and Narda, 2001; Mohammad et al. 1999; Onder et al. 2005; Patel and Rajput, 2007; Shalhevet 1983; Starr et al. 2005; Waddell et al. 1999, 2000; Wang et al. 2006, 2007; Yuan et al. 2003). However, much of this research in potato has been limited to arid regions, and less research has been conducted in humid regions such as the upper Midwest. This is likely due to ample water resources and high irrigation efficiency in these regions, which make water-saving technologies less of a priority relative to the high installation costs of drip systems (Waddell 1999). Demonstrated water savings via drip irrigation as compared to other irrigation methods varies depending on climate. Starr et al. (2008) compared drip irrigation to overhead sprinkler in potato production in Wisconsin, and found that over a four-year period the use of surface drip irrigation allowed for a 52% reduction in water use without a significant yield decline. Reyes-Cabrera et al. (2014) compared drip to seepage irrigation, a common form of irrigation in Florida in which a shallow water table is managed so that it reaches the crop root zone, and found similar results that surface drip allowed for water savings of 52 to 87% also in potato. Both of these studies were conducted on coarse-textured soils. In India, Chawla and Narda (2001) compared drip to furrow irrigation and found that drip allowed for a 70% decrease in water use. Yuan et al. (2003) found that it was possible to decrease water application up to 75% of ET without affecting yield in potato in Japan when basing drip application rates on ET.

In Wisconsin and elsewhere, research on drip irrigation in potato production has focused on potential water savings, water distribution patterns, and nitrogen uptake (Cooley et al. 2007; Waddell et al. 1999, 2000). However, there is a lack of research relating drip irrigation to physiological defects, especially incidence of processing quality defects in potato. A significant proportion of potatoes in the United States are produced for processing (National Potato Council 2014). Therefore, it is important to understand processing quality implications of management decisions such as the use of drip irrigation. Eldredge et al. (2003) looked at the effect of drip irrigation on fry color of russet varieties, but did not compare between drip and overhead, nor did they evaluate fry color of round, chipping varieties. This research aimed to further evaluate the effect of drip irrigation on processing defects in both a russet and round, chipping variety, as well as the ability of this irrigation method to limit environmental stresses that are linked to defect formation.

Environmental stress during the growing season such as high soil temperature and low soil moisture have been associated with defects that affect processing quality or fresh market suitability including sugar end disorder, stem-end chip defect, brown center, and hollow heart (Bussan 2008; Thompson et al. 2008; Wang et al. 2012). Sugar-end defect, also known as jelly-end or translucent end, is characterized by low starch content at the basal end of the tuber and high reducing sugar content (Thompson et al. 2008). When the reducing sugars (glucose and fructose) undergo the Maillard reaction when processed at high temperatures, it results in a dark, undesirable coloring (Gould and Plimpton 1985; Shallenberger 1959). High rates of sugar-end can lead to costly load rejections. Iritani and Weller (1978) observed that sugar-end formation was connected with early season moisture stress. Previous research has attempted to parse out the respective effects of heat stress and intermittent water stress, but it appears that the interaction of the two lead to the greatest incidence of sugar-end (Iritani 1981; Kincaid et al. 1993; Kleinkopf et al. 1979, 1988; Shock et al. 1992, 1993). Additional research focusing solely on the effect of water deficit and timing on sugar end incidence revealed that as much as a single occurrence of temporary water stress was enough to cause an increase in sugar end (Eldredge et al. 1996).

Plant stresses are also linked to stem-end chip defect and hollow heart. Stem-end chip defect consists of dark coloration of the vasculature at the effected, stem or basal end of the tuber and concurrent dark coloration within and surrounding the vascular ring upon frying

(Bussan et al. 2009a; Wang et al. 2012). Stem-end is more unpredictable than sugar-end defect, and the severity, duration and timing of stress necessary to cause this defect are not clear and independent of sugar-end seen in processing potatoes (Bethke et al. 2009). Work done by Wang et al. (2012) demonstrated that moderate environmental stress was insufficient to cause an increase in severity of stem-end, unlike sugar-end. Only heat stress for a period of 14 days during late tuber bulking resulted in increased incidence of stem-end chip defect, but water stress and differences in chemical maturity at harvest did not. Hollow heart, or its incipient form, brown center, is also of economic importance, as affected tubers must be culled when sold for fresh market. Hollow heart also affects the specific gravity of tubers and as a result, the price (Bussan 2007). Unlike sugar and stem-end defects, hollow heart and brown center have been linked to cooler temperatures during early tuber bulking (Bussan 2007). And, like the other two aforementioned defects, uneven soil moisture and transitory water deficit, and nutrient management are also linked to higher incidence (Bussan 2007).

Drip irrigation has been shown to better maintain spatial soil moisture uniformity by limiting areas of excess and insufficient irrigation (Dukes et al. 2010; Tsipori and Shimshi 1979) as compared to sprinkler irrigation (Cooley et al. 2007). And, improved moisture uniformity can limit physiological defects (Eldredge et al. 1996; Shock et al. 1993, 2007). Reyes-Cabrera et al. (2014) found a reduction in hollow heart in potato under drip irrigation when compared to seepage irrigation on a sandy soil. This research sought to further explore the effect of drip irrigation on physiological defects as potential improvements in potato quality could offset some of the higher costs associated with the use of drip irrigation. The researchers understand the limitations of drip irrigation in potato in the context of sandy soils, and the aim of this study was not to identify a replacement for all center-pivot irrigation. However, we sought to explore this technology as a potential alternative for areas in which groundwater withdrawal and contamination is a particular concern. The overall goal of this research was to assess the potential for drip irrigation methods to reduce irrigation water application rates on potato crops without negatively affecting yield and quality when compared to conventional, overhead irrigation in Snowden, Russet Burbank and Russet Norkotah cultivars. Specific objectives were to assess the effects of overhead irrigation and drip irrigation at three levels on 1) yield and tuber quality, 2) fry color and reducing sugar content, 3) crop nitrogen status during the growing season, 4) soil moisture and temperature in the crop root zone, and 5) irrigation water use efficiency in megagrams (Mg yield) per millimeter (mm) of irrigation water applied.

Materials and Methods

Field Management

The two-year field study was conducted during 2013 and 2014 at the Hancock Agricultural Research Station in Hancock, WI (latitude: 44°12.1413 N; longitude 89° 53.6840; elevation 328m) on a Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamments) with a field capacity estimated at 0.14 $cm^3\ cm^{-3}$ (Copas et al. 2008). The parent material is glacial outwash with underlying glacial till. Surface and subsurface horizons are sand with little structure (Cooley et al. 2007). The experimental design was a modified split-plot with three complete replications and restricted randomization on whole plot treatments. Whole plot treatments consisted of irrigation method (drip or overhead) and irrigation rate. Irrigation method was not randomized within year due to logistical constraints, but was across years. The high uniformity of soils at the Hancock research station likely tempers effects of blocking due to field variance. Irrigation treatments consisted of overhead irrigated to 100% crop evapotranspiration demand (ET_c) and three levels of drip irrigation with volume application rates equivalent to 75%, 86% and 100% ET_c as calculated for the overhead treatment. Split-plot treatment of potato variety was randomized within each replication and included potato cultivars Russet Norkotah, Snowden and Russet Burbank.

Prior to planting, potato rows spaced 91 cm apart were opened and starter fertilizer was applied. Plots were four rows wide, or 3.65 meters by 6 meters long for a total area of about 22 m^2. Planting dates were May 1st, and May 9th in 2013 and 2014, respectively. Certified seed tubers were machine cut and allowed to suberize for at least one week prior to planting. Russet Burbank and Russet Norkotah were hand planted to 30.5 cm spacing and Snowden to 23 cm. The rows were then closed and hilled, leaving seed pieces at a depth of about 15 cm below the surface of the soil. Previous crops for each year of the study were as follows: snap beans for 2013 and soybeans for 2014. It should be noted that in 2013 the overhead irrigation block was located slightly north of the drip blocks, and, although both areas were planted to snap beans the year prior, only the drip section had been planted to potato two years prior. Aside from the drip irrigation and nitrogen fertilizer applications, all other cultural practices followed University of Wisconsin recommendations for fertility, irrigation and pest management, which also follow area practices (Bussan et al. 2015).

Irrigation and Fertility Management

The overhead irrigation was applied via a T-L hydraulic drive linear with a flow rate of 890 liters per minute (38 liters per minute per nozzle) and an inlet operating pressure of 310 kPa. To achieve the three drip irrigation levels, tape with three different emitter spacings of 30.5, 35.6, and 40.6 cm was used to deliver rates equivalent to 1.0X (D 1.00), 0.86X (D

0.86) and 0.75X (D 0.75) ET_c as calculated for the overhead treatment, respectively. All drip tape, regardless of spacing, had an emitter flow rate of 0.91 liters per hour at an operating pressure of 69 kPa (Netafim Streamline Series 636-008 Fresno, CA). The drip system was configured so that each row had one lateral that was connected to a central manifold. The system also consisted of an initial pressure regulator, backflow preventer, filter and second pressure regulator, which maintained pressure near 69 kPa. The tape was hand-laid along the hill apex prior to emergence and shallowly covered with dirt every five feet to secure its placement. It was checked for leaks and application uniformity throughout the season.

The Wisconsin Irrigation Scheduling Program (WISP) along with reference ET and precipitation data from the Hancock ARS weather station was used to determine irrigation application rates to match 100% of ET_c demand. WISP utilizes a water balance, or checkbook, approach, and adjusted ET_c estimates based on reference ET, crop emergence date, and canopy cover to determine irrigation recommendations (Curwen and Masssie 1994). Allowable depletion was assumed to be 12.7 mm per day. Soil was sampled and inspected to confirm estimated soil moisture water balance. Drip tape run time was determined by the amount of time required to apply an equivalent volume of water to the D 1.00 treatment as the O 1.00 treatment. The wider emitter spacings of 35.6 and 40.6 cm were able to control application rates so that it was not necessary to alter run time in order to irrigate to 75% and 86% ET_c. Drip and sprinkler irrigation applications were made on the same day and as close to the same time as possible. However, the run time required to apply the target water volume was much longer for drip irrigation than for overhead irrigation. The O1.00 and D 1.00, D 0.86, and D 0.75 treatments received 385, 331 and 289 mm of irrigation water, respectively in 2013, and 359, 309 and 267 mm in 2014 (Figure 1).

All varieties received a nitrogen rate of 291 kg N ha^{-1}. All plots received 37 kg N ha^{-1} at planting in the form of ammonium sulfate, 84.6 kg N ha^{-1} at hilling, and the remaining nitrogen was split over three supplemental applications. At planting and hilling, fertilizer was side dressed in overhead and drip plots. For subsequent applications, granular ammonium nitrate was banded in the overhead block and watered in with the linear irrigation system, and liquid urea ammonium nitrate was injected through the drip system. The drip lines were equipped with shut off valves, and each drip treatment was run separately to ensure delivery of the same volume of nitrogen fertilizer as in the D 1.00 treatment.

Soil Water Content and Temperature Measurements

Throughout the growing season, CR10X data loggers (Campbell Scientific Incorporated, Logan, Utah) recorded volumetric water content and soil temperature quarter-hourly in the O 1.00, D 1.00 and D 0.75 treatments. To measure volumetric water content, water content reflectometer probes (WCR) (Campbell Scientific model CS616-L) were placed at 10 cm and 20 cm below the top of the hill and 10 cm below the furrow. Soil was removed from hills so that probes could be inserted perpendicular relative to the hills. A two-pronged guide resembling the length and spacing of the probes was used to aid probe insertion and promote even spacing. The soil was then returned to the hill along with any disturbed plants. The probes measured an output frequency, or period, of an electromagnetic pulse whose velocity is dependent on the dielectric permittivity of the surrounding material. The period was then transferred to and converted by the data logger to a volumetric water content reading using the following equation (Campbell Scientific 2014):

$$VWC = -0.0663 - 0.0063 * period + 0.0007 * period^2$$

Thermocouples were also inserted parallel to the WCR probes 10 cm below the hill. Water content reflectometer probes and thermocouples were placed in all three replications of Russet Norkotah plots in the O 1.00, D 1.00 and D 0.75 treatments. Tipping bucket rain gauges (Campbell Scientific model TE525-L) were connected to two of the data loggers in the D 1.00 and O 1.00 treatments, to record precipitation or overhead irrigation amounts. The buckets were programmed to tip after every 0.25 mm of precipitation or irrigation water collected. The data was used to corroborate Hancock ARS irrigation records and data from the Hancock weather station.

Petiole Nitrate Sampling

In order to evaluate nitrogen uptake via petiole nitrate (NO_3-N) levels, petioles were sampled every 10 days beginning one week after the first side dress fertilizer application and continuing for five collection dates. Samples were taken from the first fully expanded leaf from the apex in adherence to petiole sampling protocol for potato (Gardner and Jones 1975). Petioles were collected from 20 plants in each plot, which is sufficient if only analyzing for nitrate (Lang et al. 1999). Collections were made the day following an irrigation event and at a similar time point during the day (1000 to 1200 hours). Samples were then dried at 60°C in a forced-air oven, ground in a Thomas Wiley Mini-Mill (Model 3383-L10 Thomas Scientific, Inc. Swedesboro, NJ), passed through a 0.42 mm sieve (40 mesh), and stored until later nitrate analysis. Samples were analyzed using flow injection analysis (Ruzicka 1983).

Harvest

Harvest dates were September 16th and 17th in 2013 and 2014, respectively. The center two rows were harvested each year for estimating yield after removal of drip irrigation tubing. The tubers were washed, weighed and graded in accordance to standard industry categories, US #1 (USDA grading standard A, diameters >47.6 mm) and B (diameter<47.6 mm). A Gallenberg grader and AgRay X-ray sizer was used for grading potatoes. The grader recorded size and weight characteristics of every tuber. Additional size categories of interest included 170 to 283.5 g (medium) and >283.5 g (large) for Russets and 50 to 100 mm (premium) for Snowden. Rotten, green, misshapen and small (diameter< 38.1mm) tubers were culled prior to grading and weighed separately.

Ten medium-size tubers were selected randomly per plot to evaluate for internal defects and specific gravity. Internal defects evaluated included: brown center, hollow heart, internal brownspot, vascular discoloration, internal heat necrosis and jelly end. Specific gravity was evaluated using a Weltech PW-2050 Dry Matter Assessment System. The system uses the weight of tuber samples in air and in water and the following formula developed by Murphy and Groven (1959) to calculate specific gravity:

$$\frac{\textit{weight in air}}{(\textit{weight in air - weight in water})}$$

For Russet Burbank and Snowden plots, additional subsamples of six tubers were selected amongst medium tubers for later post-harvest sugar and fry color analysis. These tubers were placed in a storage locker at the Wisconsin Potato and Vegetable Storage Research Facility in Hancock, WI. Standard protocol was followed during equalization, wound healing and preconditioning phases of potatoes in storage (Bussan et al. 2015). Relative humidity was maintained at 95% per industry standards, and tubers were ramped down at a constant rate of 0.167 °C per day to a final set point of 9 °C.

Post-Harvest Analysis

At two time points, set point and 60 days following set point (125 and 180 days after harvest, respectively), stored samples were analyzed for stem and bud-end reducing sugar content and fry color. From each six-tuber sample, 200 g samples were cut from bud and stem-ends. These samples were then juiced separately in an Acme Supreme Juicerator (model 6001) and combined with 50mM phosphate buffer. The juiced samples were refrigerated for a minimum of 20 minutes to allow for solids to settle. A 1ml sample of the supernatant was then extracted. Sample was immediately analyzed or frozen and analyzed later for sucrose and glucose using the YSI 2700 Select Biochemistry Analyzer (Sigma-Aldrich, St. Louis, MO) in accordance with manufacturer protocol.

The same six-tuber samples were also analyzed for fry color. Snowden tubers were cut in half and then sliced. The first slice was discarded and the second of each six-tuber sample was fried for 2 minutes and 10 seconds at 182.2°C in cottonseed oil. Chip samples were then evaluated for severity of stem-end chip defect using the scoring chart developed by Wang et al. (2012) and for overall color using the USDA color scale. Russet Burbank samples were assessed for sugar-end defect. Lengthwise slabs were cut from the tubers and processed as fries for immediate evaluation using the USDA Frozen French Fried Potato Color Standards (2007 X-Rite Incorporated Munsell Color Services Grand Rapids, MI).

Data Analysis

Tuber yield and quality including reducing sugar content and average fry color, petiole nitrate, and irrigation water use efficiency data were analyzed using the PROC MIXED procedure in SAS ver. 9.4 (Littel et al. 2006). This procedure was able to account for any missing data points due to the use of a likelihood-based estimation approach. All tuber yield and quality, petiole nitrate, and irrigation water use efficiency data were subjected to an analysis of variance (ANOVA) to test the main effect of irrigation, variety and irrigation by variety interaction. Data were first analyzed across years, and then separated by year if year by treatment interactions occurred. Irrigation, variety and irrigation by variety interaction were treated as fixed effects. Replication, year and year by treatment interaction were treated as random effects. A two-factor nested model with fixed effects was use:

Model: $y_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} + \tau_k + \alpha_{\tau ik} + \delta_{ijk}$

$i = 1,\ldots,a$
$j = 1,\ldots,b$
$k = 1,\ldots,c$
μ = grand mean
α_i = the main effect for irrigation for ith treatment
β_j = the random effect of replication
ε_{ij} = is the error term for testing main plot effects
τ_k = the main effect of variety
$\alpha_{\tau ik}$ = the interaction term for irrigation and variety
δ_{ijk} = the error term for testing subplot effect

Tukey's honest significant difference (HSD) procedure was used to separate treatment means following ANOVA at a significance level of $p = 0.05$. Percentages of incidence of stem-end defect were compared using a Chi-square test, and the main effect tested was irrigation treatment (Wang et al. 2014).

Soil moisture and daily range, maximum, and low temperature data were analyzed using a mixed model analysis of repeated measures (Copas et al. 2008). An autoregressive correlation structure was chosen as moisture and temperature measurements were likely to be more closely related if taken at closer time points than farther apart. The main effect difference tested was irrigation treatment. Following repeated measures analysis treatment means were once again separated using Tukey's HSD and considered significant at $p = 0.05$.

Results

Yield, Tuber Size Categories and Quality

Total yield, US #1, B size, and average tuber size was affected by a year by irrigation treatment interaction at a p value <0.05, thus data were not pooled across years. The interaction can be attributed to the differential irrigation treatment response of Russet Norkotah in 2013 relative to 2014 (Table 1). There was no irrigation treatment effect on total yield for Snowden or Russet Burbank in either year. An irrigation treatment effect was only seen in Russet Norkotah in 2013; total yield and US #1 yield was lower under the D 1.00 treatment than the overhead treatment. Also, there was no difference in yield among the three drip irrigation levels in either year for Russet Norkotah. The D 0.75 and D 0.86 treatments yielded similarly to overhead irrigation for all varieties in both years. In general, US #1 yield mirrored total yield trends, and there was no treatment effect on US #1 as a percent of total yield, demonstrating that quality was similar across treatments. Average tuber size differed only for Russet Norkotah in 2014 when size was larger under overhead irrigation. However, for this variety, all treatments resulted in an average tuber size within the desirable range of 170 to 283.5 g.

Yield of different tuber size categories and specific gravity was influenced by a treatment by year interaction at a p value <0.05; therefore, data were analyzed separately by year (Table 2). Varieties were analyzed separately as size categories differed between russets (Norkotah, Burbank) and round potatoes (Snowden). There was no effect of irrigation on medium size tubers for either Russet variety. In 2013 and 2014, Russet Norkotah yielded a higher percentage of large tubers under the O 1.00 treatment than the D 1.00. Treatment effects on specific gravity were minimal, and only specific gravity of Russet Burbank responded to irrigation treatment in 2014, but not in 2013. There was no effect of treatment on internal defects (data not shown).

Reducing Sugar Concentration.

Glucose and sucrose concentrations were log-transformed in order to satisfy assumptions of normality. An irrigation treatment by year and sampling date interaction occurred for each cultivar, thus data were not pooled. There was little irrigation treatment effect on stem and bud-end sucrose and glucose concentrations. The greatest differences were seen in Russet Burbank in 2014 in which overhead irrigation resulted in potatoes with lower bud-end sucrose and higher bud-end glucose than one or more drip treatments for both sampling times (Table 3). For Russet Burbank, trends in stem-end sucrose were less consistent and differed by year. For this variety, there were no differences in sucrose or glucose between drip treatments. Across irrigation treatments, stem- and bud-end glucose concentrations trended higher in 2014 than 2013 at both sampling dates.

For the common chipping cultivar, Snowden, there was once again minimal irrigation treatment effect. The O 1.00 treatment resulted in higher stem-end glucose concentrations than the D 0.75 treatment in 2014 at the second sampling date, but this trend was not repeated across years. Bud-end glucose also differed only at one sampling date and in one year; D 0.75 resulted in higher values than D 0.86 in 2014. Sucrose or glucose did not differ across any other treatments either year.

Fry Color and Stem-end Chip Defect

No irrigation treatment interactions occurred for fry color. However, both year and sampling date affected fry color. Minimal irrigation treatment effects on reducing sugar content were reflected in lack of differences in fry color for both Snowden and Russet

Burbank. For Russet Burbank, all irrigation treatments resulted in fry color of 3 or higher except for the O 1.00 treatment in one of two sampling dates in 2014 (Table 4). Fry color trended darker in 2014 for Russet Burbank, which mirrors stem-end glucose trends. Within 2014, Russet Burbank fry color was darker in the second sampling date ($p = 0.015$). The opposite was true for Snowden in 2014, and fry color was darker the first sampling time ($p = 0.014$). Incidence of stem-end chip defect was low for all irrigation treatments between both years and among sampling dates (data not shown). The highest observed stem-end defect score was 3 on the scale from 0 to 5, and it occurred in low frequencies. As there was no stem-end incidence of concern observed in this study, we could not make inferences regarding differential impact of irrigation treatment on defect management in chips.

In-Season Crop Nitrogen Status

Petiole NO_3-N levels were affected by a year by irrigation treatment interaction and a treatment by collection date interaction at a p-value of <0.05, thus years and collection dates were analyzed separately. Data were pooled across varieties, as there was no treatment by variety interaction. The effect of irrigation treatment on petiole NO_3-N levels was minimal both years and did not appear to have a differential impact on crop NO_3-N status, except the last two sampling date in 2013 and first in 2014 (Figure 2). Lower petiole NO_3-N levels were found in the overhead treatment in 2013 at 50 DAE, and the D 1.00 treatment resulted in lower levels than the D 0.86 and the O 1.00 treatment in 2013 at 60 DAE and 2014 at 20 DAE, respectively (Figure 2). Overall, petiole nitrate levels were lower in 2014 than 2013.

Soil Moisture and Temperature

Two irrigation events that were representative of the larger data set were chosen each year to evaluate the volumetric soil moisture response to irrigation treatment. As the drip and overhead systems were not always run simultaneously, for each 48-hour period analyzed, the data were standardized to begin one hour prior to the upward tick in soil moisture that signified the beginning of an irrigation-induced wetting event. Water content revealed several general trends including: 1) large variance in moisture at 10 cm below the hill under all irrigation treatments, 2) higher water content under drip irrigation at 20 cm below the hill relative to overhead irrigation (Figure 3, c, d), and 3) higher water content under overhead at 10 cm below the furrow (Figure 3, e, f, i). No data is presented for 2014 at 10 cm below the furrow as there was no influence of irrigation treatment on volumetric soil moisture, and measurements frequently exceeded field capacity. At 20 cm below the hill, water content was higher under drip irrigation than overhead for both wetting events in 2013 (Figure 3, e, f). A similar numeric trend was observed in 2014 (Figure 3, g, h). Differences in soil moisture between irrigation treatments were most pronounced and consistent at 10 cm under the furrow. Soil moisture was greatest under overhead irrigation for three of the four wetting events (Figure 3 e, f, i, j).

Temperature was analyzed separately by year as there was an irrigation treatment by year interaction. Although there were treatment effects in both years, they were not consistent across years. In 2013, seasonal average minimum, maximum and ranges in soil temperatures were lower under overhead irrigation than both or at least one of the drip treatments (Table 5). In 2014, similar trends were evident for minimum, but not for maximum temperatures or temperature range.

Irrigation Water Use Efficiency

Irrigation water use efficiency in Mg of potatoes per mm of irrigation water applied was influenced by a year by irrigation treatment interaction at a p value of <0.05. Therefore, years were analyzed separately by year. There was no irrigation treatment by variety interaction and data were pooled across varieties. Yield per unit irrigation water applied ranged from 0.186 Mg mm^{-1} to over 0.27 Mg mm^{-1} (Figure 4). In both years, irrigation water use efficiency was highest under the D 0.75 treatment. The D 0.86 treatment also had higher water use efficiency than the D 1.00 in both years. The irrigation treatment by year interaction was due to the differential yield response of the O 1.00 treatment in 2013 versus 2014. Yield per mm of irrigation water was higher in year one under this treatment and not different from water use efficiency under the D 0.86 treatment relative to 2014.

Discussion

Tuber Yield and Quality

In general, we saw little effect of irrigation treatment on crop yield or quality. Abundant rainfall occurred in both years minimizing potential impacts of irrigation treatments on yield and quality parameters. In both years, precipitation and irrigation water application exceeded ET, but irrigation applications were necessary due to timing of rain events and intermittent drought stress that would have resulted without irrigation. Also, drip irrigation application rates were determined by percent volume equivalent to the water volume applied in the O 1.00 treatment, and ET was predicted with the modified Priestley-Taylor method from climatic data collected at the research station. Thus, there may not have been a true “deficit” irrigation treatment as we did not calculate drainage from the 1.00 treatments, but estimated that they matched crop ET demand. Plant wilting during tuber initiation and early tuber bulking was observed in the D 0.86 and D 0.75 treatments prior to irrigation applications, and water deficit was evident from soil moisture data. Regardless, we were able to demonstrate potential irrigation water reductions through the use of drip as compared to overhead irrigation with minimal yield or quality impacts.

The data demonstrated that for all varieties and over both years, it was possible to decrease irrigation water application through drip irrigation by 25% without negatively affecting total yield and tuber quality. The data are consistent with previous findings of the ability to limit irrigation water applications through the use of drip irrigation (Chawla and Narda 2001; Cooley 2007; Eldredge et al. 2003; Shock et al. 2007, 2013; Starr et al. 2008; Yuan et al. 2003; Waddell et al. 1999). There was little irrigation treatment effect on potato quality as seen in US #1 yield, and yield in different size categories for two of three varieties, specific gravity, internal defects, sugars, or fry color. However Russet Norkotah large tuber yield declined with the D 1.00 treatment relative to overhead which could have potential economic costs as this size class garners a premium market price.

The cultivars responded differentially to drip irrigation, and this has been observed previously (Eldredge et al. 2003; Reyes-Cabrera et al. 2014). Russet Norkotah was more affected by irrigation treatment than Russet Burbank or Snowden. Thus, cultivar selection is an important consideration when deciding whether to adopt drip irrigation and more importantly determining the level at which to irrigate. Overhead irrigation resulted in larger average tuber size in Russet Norkotah relative to drip irrigation treatments in 2014. This supports previous findings of smaller tuber sizes resulting from deficit irrigation treatments with drip irrigation (Onder et al. 2005; Yuan et al. 2003) and deficit irrigation in general (MacKerron and Jefferies 1988; Ojala et al. 1990; Shock et al. 1998).

Ample precipitation both years during sensitive growth stages such as tuber initiation and tuber bulking may have mitigated negative effects of deficit treatments. Frequent irrigation applications may also have regulated soil moisture fluctuations that have been associated with decreases in yield and quality (Shock et al. 2007). Lastly, the high yields under the D 0.75 treatments relative to the D 1.00 treatments demonstrate that use of emitter spacing to control irrigation application rate instead of run time likely did not confound application rates.

Processing Quality

We hypothesized that drip irrigation would result in better processing quality by limiting environmental stress associated with high reducing sugar content and dark fry color. The data presented here do not reveal a differential effect on processing quality. Across all irrigation treatments, Russet Burbank stem-end glucose levels were high, and fry color was dark. A fry color of 3 on the USDA scale is considered indicative of sugar end, and stem-end glucose concentrations of over 0.85 generally lead to a fry color of 3 or darker. These results were consistent with Bussan et al. (2009b) who found that in general, russet processing varieties grown in this region often had high stem-end glucose levels even given chemical maturity, and Russet Burbank in particular is more vulnerable to sugar end development. Eldredge (2003) found that under drip irrigation, Russet Burbank had a significantly higher proportion of sugar ends than the other evaluated varieties—30 to 49% versus the next highest variety at 3.6 to 7.2%.

The high average fry color suggests that environmental stress was sufficient in both growing seasons to cause formation of sugar end. A single, transitory drought stress event has been shown to be enough to induce sugar ends (Eldredge et al. 1996). However, any differences in drought or temperature stress between treatments were not reflected in corresponding differences in fry color. Eldredge et al. (1996) found a correlation between severity of drought stress and fry color, but we did not see this relationship with the drip irrigation treatments especially when drought stress and soil moisture deficit was documented to have occurred through visual observations and soil moisture data. Although minimum and maximum soil temperatures differed between treatments, variance may not have been sufficient to cause differences in sugars and fry color as a result of temperature stress. This suggests that the use of drip irrigation could temper potential negative effects of deficit irrigation and drought stress on fry color.

It is possible that soil temperature and moisture alone do not account for differences in sugar content and fry color. For example, 2013 was a warmer year than 2014, but stem-end glucose levels of Russet Burbank trended higher in 2014 at both sampling dates than in 2013 for all irrigation treatments (Table 3). Other factors thought to contribute to elevated stem-end glucose concentrations include over-maturation and early senescence (Iritani and Weller 1980; Sabba et al. 2007). However, we did not observe abnormally early crop senescence.

In contrast to sugar-end formation, environmental stress under the various irrigation treatments was insufficient to cause high incidence of stem-end chip defect. These results are consistent with Wang et al. (2012) findings that mild environmental stress did not increase incidence or severity of stem-end chip defect. Wang et al. (2012) found that high temperature somewhat contributed to increased severity. Temperature data showed that average maximum daily temperatures did not exceed the 30°C used by Wang et al. (2012) under any irrigation treatment either year. Furthermore, 2014 was a relatively cool summer and this may have limited incidence of stem-end defects observed. Moisture stress had little to no effect on stem-end chip defect.

Petiole Nitrate Status

In 2013, nitrate levels recovered from prior deficiency and remained closer to recommended levels for 60 days after emergence, which are 0.8-1.1 % for Snowden and Burbank and 1.3-1.9% for Norkotah (Figure 2; Bussan et al. 2015). A similar response to supplemental fertilizer application was not seen in 2014. This resulted in gross difference in petiole nitrate levels at 60 DAE compared to the prior season. This could be attributed to greater rainfall; the 2014 season received over 100 mm of additional precipitation and could have led to leaching in all treatments. While petiole NO_3-N levels were low, we applied supplemental N fertilizer until 45 days after tuber initiation, and this may have mitigated yield declines due to N deficiency. There was a general trend in the data that suggested slightly lower nitrate levels in the D 1.00 treatment. This could be reflective of more frequent leaching in this treatment. Attaher et al. (2003) demonstrated that over watering can lead to decreased yields due to leaching of nutrients out of the rooting zone. Higher leaching in the D 1.00 treatment could partially explain lower yields as compared to other irrigation treatments in Russet Norkotah.

Soil Moisture and Temperature

Soil moisture data shows that treatments were effective in causing differences in soil moisture content at 10 cm below the furrow and 20 cm below the top of the hill, but not at 10 cm below the hill (Figure 3). Soil moisture content less than 10% in Plainfield loamy sand is typically identified with limiting stomatal conductance and causes stress to potato. Soil moisture data shows potatoes at the 1.00 treatments were typically not stressed, but moisture was at a level that would be typically associated with stress at 0.75. Furthermore, 0.86 and 0.75 drip irrigation treatments had plants showing morphological symptoms consistent with drought stress, but this was limited to just prior to irrigation. Volumetric soil moisture data supports previous research showing that drip irrigation limits flow of water to the furrow (Cooley 2007; Eldredge et al. 2003; Shock et al. 2007, 2013). At 20 cm below the hill the low volumetric water content under overhead irrigation suggested the formation of dry zones like those previously observed in potato hills under overhead irrigation in sandy soils (Cooley et al. 2007; Copas et al. 2008; Starr et al. 2007). The higher soil moisture under drip irrigation at this depth supports Starr et al. (2007)'s findings that that drip irrigation is better able to overcome dry zones, and wet the potato hill than overhead irrigation.

Lack of treatment effects at 10 cm below the hill were unexpected, as it was hypothesized that drip irrigation better targets water in the crop root zone. However, potato hills are designed with a flat top to increase water infiltration allowing for similar wetting under overhead and drip treatments, so differences at 10 cm were less likely. High variability between probes could have limited our ability to detect treatment differences, especially in the second year. Probes recording soil moisture greater than 15% were measuring free water and thought to have grown inside a tuber. Given a 25% reduction in irrigation water application, we expected to see lower volumetric soil moisture content under the D 0.75 treatment relative to D 1.00. However, this was only observed in 2013 at 10 cm below the furrow. Data trends matched our expectations, but limited differences were detected most likely due to probe placement directly under emitters. In subsequent experiments, volumetric soil moisture should also be measured between emitters.

Treatment effects on soil temperature may not have been large enough to result in differences in temperature-related physiological defects such as specific gravity or sugar end in processing potatoes. Previous research showed that lower rates of sugar end occurred when temperature was between 15 and 25 °C (Kincaid et al. 1993). This range was observed for all treatments except for D 0.75 in one of two years. It would be expected that lower moisture would correlate to higher temperatures as moisture affects the warming potential of soil. The data presented here do not support that, as lowest daily fluctuations were found under the D 0.75 treatment. Once again, this could be more of an artifact of thermocouple placement rather than treatment effect. Soil temperature and water relationships are not always clear (Kincaid et al. 1993). Soil temperature could be affected by a multitude of other factors including canopy cover and localized cooling effects of irrigation. Loss of localized cooling effect has been cited as a potential drawback to the use of drip irrigation. Olanya et al. (2007) found no effect of irrigation method, sprinkler, surface or subsurface drip, on canopy temperature, but more research should be done on this theme.

Irrigation Water Use Efficiency

Across both years, the D 0.75 treatment resulted in the highest irrigation water use efficiency as defined by Mg of yield per mm of water applied (Figure 4). Previous research also found that the treatments with less water application generally resulted in higher irrigation water use efficiencies (Fabeiro et al. 2001; Islam et al. 1990; Kashyup and Panda 2003; Onder 2005; Yuan et al. 2003). However, until water use becomes economically limiting or more highly regulated, it is likely that overall yield, rather than IWUE will influence water application rates. The D 0.75 treatment performed well by both metrics. In data not shown, Russet Norkotah had higher irrigation water use efficiency than Russet Burbank, once again demonstrating a differential response to drip irrigation between cultivars.

The results of this study demonstrate potential reductions in irrigation water use of up to 25% through the use of drip irrigation. We found minimal negative effects of deficit drip irrigation treatments on total yield and quality parameters despite soil moisture data and observed wilting that indicated moistures stress. This suggests that it may be possible to mitigate negative effects of drought stress through the use drip irrigation. Lower yields observed under the D 1.00 treatment suggest that more frequent leaching occurred under this treatment, and this is a general concern with the use of drip. Given the high yields under the lowest drip treatment, further reductions in irrigation application may be possible; however, varietal selection and careful monitoring of soil moisture will be necessary to inform application rates and avoid yield and quality losses such as decreased yield of large tubers.

Literature Cited

Attaher, S.M., M.A. Medany, A.A. Abdel, and M.M. Mostafa. 2003. Energy requirements and yield of drip irrigated potato. *Acta Hortic.* 608:191–198.

Bethke, P.C., R. Sabba, and A.J. Bussan. 2009. Tuber water and pressure potentials decrease and sucrose content increase in response in moderate drought and heat stress. *Am. J. Potato Res.* 86:519-532.

Bucks D.A., L.J. Erie, and O.F. French. 1974. Quantity and frequency of trickle and furrow irrigation for efficient cabbage production. *Agronomy J.* 66:53–57.

Bussan, A.J. 2007. The Canon of Potato Science: 45. Brown Centre and Hollow Heart. *Am. J. Potato Res.* 50:395-398.

Bussan, A.J., P.C. Bethke, R. Sabba, W.G. Schmitt, and M.J. Drillias. 2009a. Managing stem end defect in stored potatoes. Proc. Wisconsin Ann. Potato Meet. 22:25-26.

Bussan, A.J., J.B. Colqhoun, E.M. Cullen, V.M. Davis, R.L. Groves, D.J. Heider, G.R.W. Nice, and M.D. Ruark. 2015. Commercial Vegetable Production in Wisconsin. University of Wisconsin Extension Publication No. A3422. pp. 188-213.

Bussan, A.J., R. Sabba, and M.J. Drilias. 2009b. Tuber maturation and potato storability: Optimizing skin set, sugars, and solids. University of Wisconsin Extension Publication No. A3884-02. pp. 1-11.

Campbell Scientific. 2014. Instruction Manual: CS616 and CS625: Water Content Reflectometers.Campbell Scientific, Inc. Logan Utah. p. 25.

Chawla, J.K. and N.K. Narda. 2001. Economy in water and fertilizer use in trickle fertigated potato. *Irrig. Drain.* 50:129-137.

Cooley, E., B. Lowery, K.A. Kelling and S. Wilner. 2007. Water dynamics in drip and overhead sprinkler irrigated potato hills and development of dry zones. *Hyrdol. Process.* 21:2390-2399

Copas, M.E., A.J. Bussan, M.J. Drilias and A. Charkowski. 2008. Influence of compaction and subsoil tillage on soil conditions and pink eye. *Am. J. Potato Res.* 85:342-352.

Curwen, D. and L. Massie. 1994. Irrigation Management in Wisconsin-the Wisconsin Irrigation Scheduling Program. University of Wisconsin Extension Publication A3600. pp. 1-10.

Dasberg, S. and D. Or. 1999. *Applied Agriculture: Drip Irrigation*. New York: Springer. pp. 4-14.

Dukes, M.D., L. Zotarelli, and K.T. Morgan. 2010. Use of irrigation technologies for vegetable crops in Florida. *HortTechnology* 20:133-142.

Eldredge, E.P., Z.A. Holmes,, A.R. Mosley, C.C. Shock, and T.D. Stieber. 1996. Effects of transitory water stress on potato tuber stem-end reducing sugar and fry color. *Am. Potato J.* 73:517-530.

Eldredge, E.P., C.C. Shock, and L.D. Saunders. 2003. Early and Late Harvest Potato Cultivar Response to Drip Irrigation. *Acta Hortic.* 619:233-239.

Epstein, E., and W.J. Grant. 1973. Water stress relations of the potato plant under field conditions. *Agronomy J.* 65:400-404.

Fabeiro, C., F. M. de Santa Olalla, and J.A. de Juan. 2001. Yield and size of deficit irrigated potatoes. *Agr. Water Manage.* 48:255-266.

Gardner, B. R., and J. P. Jones. 1975. Petiole analysis and the nitrogen fertilization of Russet Burbank potatoes. *Am. Potato J.* 7:195–200.

Gould, W.A., and S. Plimpton. 1985. Quality evaluation of potato cultivars for processing. North Central Regional Research Publication 305. Ohio Agricultural Research and Development Center, Wooster, Ohio. Research Bulletin 1172.

Iritani, W.M., and L.D. Weller. 1978. Influence of low fertility and vine killing on sugar development in apical and basal portions of Russet Burbank potatoes. *Am. Potato J* 55:239-246.

Iritani, W.M. and L.D. Weller. 1980. Sugar development in potatoes. Cooperative Extension, Washington State University Extension Bulletin 0717. Pub number. pp. 5-15.

Iritani, W.M. 1981. Growth and preharvest stress and processing quality of potatoes. *Am. Potato J.* 58:71-80.

Islam, T., Sarker, H., Alam, J., Rashid, H.U. 1990.Water use yield relationships of irrigated potato. *Agr. Water Manage.* 18:173–179.

Kashyap, P.S. and R. K. Panda. 2003. Effects of irrigation scheduling on potato crop p arameters under water stressed conditions. *Agr. Water Manage.* 59:49–66.

Kincaid, D.C., D.T. Westerman, and T.J. Trout.1993. Irrigation and soil temperature effects on Russet Burbank quality. *Am. Potato J.* 71:15-28.

Kleinkopf, G.E. 1979. Translucent end of potatoes. University of Idaho Curr Info Series No 488. pp 4.

Kleinkopf, G.E., G.D. Kleinschmidt, and D.T. Westermann. 1984. Tissue analysis, a guide to nitrogen fertilization for Russet Burbank potatoes. University of Idaho Curr Info Series no 743. 4 pp.

Kleinkopf, G.E., D.T. Westermann, and M.J. Wille. 1988. 1. Soil temperature effects on sugar end development. *Proc. Univer. Idaho Winter Commodity Schools.* 20:180-181.

Kniffin, M., K. Potter, A.J. Bussan, K. Bradbury, and J. Colquhoun. 2014. Sustaining Central Sands Water Resources. University of Wisconsin-Madison. http://wisa.cals.wisc.edu/central-sands-white-paper. Accessed 30 March 2015. pp. 8-30.

Kraft, G.J., K. Clancy, D.J. Mechenich, and J. Haucke. 2012. Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited. *Ground Water.* 50: 308-318.

Lang, N.S., R.G. Stevens, R.E. Thornton, W.L. Pan, and S. Victory. 1999. Potato Nutrient Management for Central Washington. Washington State University Extension Publication no EB1871. pp. 4.

Littell, R. C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2002. *SAS for Mixed Models***,** *Second Edition*. Cary, NC: SAS Institute Inc. pp. 663.

MacKerron, D.K.L. and R.A. Jefferies. 1998. The distribution of tuber sizes in droughted and irrigated crops of potato. I. Observations on the effect of water stress on graded yields from different cultivars. *Potato Res.* 31:269-278.

Murphy, H.J. and M.J. Groven. 1959. Factors affecting the specific gravity of the white potato. Maine Agric Exp Stn. Bull No 583.

National Potato Council. 2014. National Potato Council Potato Statistical Yearbook 2014. http://nationalpotatocouncil.org/2014-potato-statistical-yearbook/.15 April 2015. pp 61-73.

Ojala, J.C., J.C. Stark and G.E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* 67:29-42.

Olanya, O.M., G.C. Starr, C.W. Honeycutt, T.S. Griffin, D.H. Lambert. 2006. Microclimate and potential for late blight development in irrigated potato. *Crop Protection* 26:1412-1421.

Onder, S., M.E. Caliskan, D. Onder, and S. Caliskan. 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agr. Water Manage.* 73:73-86.

Opena, G.B. and G.A. Porter. 1999. Soil management and supplemental irrigation effects on potato: II. Root growth. *Agron. J.* 91:426-431

Patel, N., T.B.S. Rajput. 2007. Effect of drip tape placement depth and irrigation level on yield of potato. *Agr. Water Manage.* 88:209–223.

Phene, C.J. and D.C. Sanders. High-frequency trickle irrigation and row spacing effects on yield and quality of potatoes. *Agronomy J.* 68:602-607.

Reyes-Cabrera, J., L. Zotarelli, D.L. Rowland, M.D. Dukes and S.A. Sargent. 2014. Drip as alternative irrigation method for potato in Florida sandy soils. *Am. J. Potato Res.* 91:504-516

Robinson, D. 1999. A comparison of soil-water distribution under ridge and bed cultivated potatoes. *Agric. Water Manage.* 42:189-204.

Ruzicka, J. 1983. Flow Injection Analysis – From Test Tube to Integrated Microconduits. *Analytical Chemistry* 55: 1040A-1053A.

Sabba, R.P., A.J. Bussan, B.A. Michaelis, R. Hughes, M.J. Drilias and M.T. Glynn. 2007. Effect of planting and vine-kill timing on sugars, specific gravity and skin set in processing potato cultivars. *Am. J. Potato Res.* 84:205-215.

Saffigna et al. 1977. Nitrogen, chloride, and water balance with irrigated Russet Burbank potatoes in a sandy soil. *Agron. J.* 69:251-257.

Shalhevet J, Shimshi D, Meir T. 1983. Potato irrigation requirements in a hot climate using sprinkler and drip methods. *Agron. J.* 75:13–16.

Shallenberger, R.S., O. Smith and R.H. Treadway. 1959. Role of the sugars in the browning reaction in potato chips. *J. Agr. Food Chem.* 7: 274-277.

Shock, C.C., F-X. Wang, R. Flock, E.P. Eldredge, A.B. Pereira, and J. Klauzer. 2013. Drip irrigation guide for potatoes, sustainable agriculture techniques. Oregon State Univ. Ext Service. EM 8912. pp. 8.

Shock, C.C., Pereira, A.B., and E.P. Eldredge. 2007. Irrigation best management practices for potato. *Am. J. Potato Res.* 84:29-37

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998. Potato yield and quality response to deficit irrigation. *HortScience* 33:1117-11121.

Shock, C.C., Z.A. Holmes, and T.D. Stieber. 1993. The effect of timed water stress on quality, total solids, and reducing sugar content of potatoes. *Am. J. Potato Res.* 70:227-241.

Shock, C.C. J.C. Zalewski, T.D. Stiver, and D.S. Burnett. 1992. Impact of early season water deficits on Russet Burbank plant development, tuber yield, and quality. *Am. Potato J.* 69:793-803.

Starr, G.C. 2005. Temporal stability and spatial variability of soil water patterns with implications for precision water management. *Agr. Water Manage.* 72:222-243.

Starr, G.C., E.T. Cooley, B. Lowery and K. Kelling. 2005. Soil water fluctuations in a loamy sand under irrigated potato. *Soil Sci.* 170:77-89.

Starr, G.C., D. Rowland, T.S. Griffin, O.M. Olanya. 2008. Soil water in relation to irrigation, water uptake and potato yield in a humid climate. *Agr. Water Manage.*. 95:292-300.

Thompson, A.L., S.L. Love, J.R. Sowokinos, M.K. Thornton, and C.C. Shock. 2008. Review of the sugar-end disorder in potato (*Solanum tuberosum* L.). *Am. J. Potato Res.* 85:375–386.

Tsipori Y, Shimshi D. 1979. The effect of trickle line spacing on yield of tomatoes (Lycosperisicum esculentum Mill.). *Soil Sci. Soc. Am. J.* 43:1225-1228.

USDA-NASS (US Department of Agriculture-National Statistics Service. 2013a. 2013 Wisconsin Agricultural Statistics. http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Annual_Statistical_Bulletin/bulletin2013_web.pdf. Accessed 10 March 2014. pp. 12.

USDA –NASS (US Department of Agriculture-National Agricultural Statistics Service. 2013b. 2012 Census of Agriculture: Farm and Ranch Irrigation Survey. http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris13_2_030_030.pdf. Accessed 25 March 2015. pp. 104

van Loon, C.D. 1981. The effect of water stress on potato growth, development, and yield. *Am. Potato J.* 58:51–69.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation- and nitrogen-management effects on potato yield, tuber quality, and nitrogen uptake. *Agron. J.* 91:991–997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation- and nitrogen-management impacts on nitrate leaching under potato. *J. Env. Qual.* 29:251–261.

Wang, F.-X., Y. Kang, and S.-P. Liu. 2006. Effects of drip irrigation frequency on soil wetting pattern and potato growth in North China Plain. *Agr. Water Manage*. 79:49–58.

Wang, F.-X., Y. Kang, S.-P. Liu, and X.-Y. Hou. 2007. Effects of soil matric potential on potato growth under drip irrigation in the North China Plain. *Agr. Water Manage.* 88:34–42.

Wang, Y., Bussan, A.J. and P.C. Bethke. 2012. Stem-End defect in chipping potatoes (*Solanum tuberosum* L.) as influenced by mild environmental stress. *Am. J. Potato Res.* 89:392-399.

Weisz, R., J. Kaminski, and Z. Smilowitz. 1994. Water deficit effects on potato leaf growth and transpiration: Utilizing fraction extractable soil water for comparison with other crops. *Am. Potato J*. 71:829-840.

Yuan, B.Z., S. Nishiyama, and Y. Kang. 2003. Effects of different irrigation regimes on the growth and yield of drip irrigated potato. *Agr. Water Manage.* 63:153–167.

Table 1 Total yield, USDA size class, and average tuber size as affected by irrigation treatment for three potato cultivars in Hancock, WI, in 2013 and 2014.

	2013						**2014**					
Irrigation by	Total*†	US #1‡		B-size**		Tuber Size	Total	US #1		B-size		Tuber Size
Variety	Mg ha^{-1}	Mg ha^{-1}	%	Mg ha^{-1}	%	g	Mg ha^{-1}	Mg ha^{-1}	%	Mg ha^{-1}	%	g
Norkotah												
D 0.75	72.7 ab	67.8 ab	93.3	1.78	2.5	249.1	74.1	71.4	96.3	0.73	1.0	215.6 b
D 0.86	69.4 ab	66.2 ab	95.5	1.45	2.1	234.6	73.1	69.3	94.8	0.63	0.9	216.0 b
D 1.00	67.4 b	62.8 b	93.2	1.35	2.0	225.9	70.8	67.4	95.2	0.69	1.0	200.8 b
O 1.00	85.0 a	80.5 a	94.7	1.21	1.4	259.7	71.0	66.0	93.0	0.30	0.4	253.3 a
Burbank												
D 0.75	76.0	69.2	91.1	3.31	4.4	153.5	67.9	64.9	95.7	0.98	1.4	129.2
D 0.86	73.9	65.8	88.9	3.30	4.5	159.8	65.8	62.2	94.5	1.22	1.9	123.1
D 1.00	67.5	60.8	90.2	2.85	4.2	153.2	66.3	62.1	93.7	1.54	2.3	122.4
O 1.00	74.1	68.4	92.4	2.18	3.0	154.4	64.9	59.6	92.0	1.60	2.5	143.1
Snowden												
D 0.75	90.5	81.3	89.8	8.15	9.0	192.7	64.0	61.3	95.8	1.27	2.0	156.8
D 0.86	84.7	76.0	89.7	7.41	8.8	193.4	61.9	58.8	94.9	1.42	2.3	157.6
D 1.00	84.2	76.9	91.4	6.32	7.5	172.3	65.4	62.5	95.6	1.44	2.2	154.2
O 1.00	91.1	82.3	90.4	6.08	6.7	211.3	64.5	61.3	95.1	0.67	1.0	151.1

*Values are means of the three replicates per treatment. Letters indicate statistical difference within column for each variety at the alpha=0.05-level as determined by Tukey HSD following ANOVA.

† Total yield includes the weight of culls (rotten, misshapen, and green tubers), which can be calculated as Total - US #1 - B's. Mean cull weights were not significantly different at the alpha = 0.05-level either year.

‡ US #1 includes tubers >47.6mm

** B-size includes tubers <47.6mm

% are based on % of total yield

Table 2 Russet Norkotah and Burbank medium and large size category yield, Snowden premium size category yield, and specific gravity as influenced by irrigation treatment in Hancock, WI, in 2013 and 2014.

Irrigation by Variety	2013 Size Distribution* Medium † Mg ha^{-1}	%‡	Large or Premium Mg ha^{-1}	%	specific gravity	2014 Size Distribution Medium Mg ha^{-1}	%	Large or Premium Mg ha^{-1}	%	specific gravity
Norkotah										
D 0.75	23.9	32.9	32.6 ab	44.8	1.073	29.5	39.8	27.5 ab	37.0	1.072
D 0.86	28.1	40.5	23.9 b	34.4	1.072	26.9	36.7	28.2 ab	37.9	1.076
D 1.00	24.2	35.9	25.1 ab	37.3	1.071	25.9	36.6	24.5 b	34.6	1.073
O 1.00	28.1	33.1	40.6 a	47.8	1.071	22.0	31.0	35.3 a	49.7	1.074
Burbank										
D 0.75	31.9	42.0	16.6	21.8	1.083	24.2	35.6	10.6	15.6	1.080 ab
D 0.86	28.3	38.3	14.2	19.2	1.083	23.8	36.1	8.7	13.2	1.084 a
D 1.00	25.7	38.1	11.7	17.3	1.079	24.0	36.2	9.6	14.5	1.081 ab
O 1.00	24.4	32.9	23.4	31.6	1.082	21.7	33.4	9.2	14.2	1.071 b
Snowden										
D 0.75			75.4	83.3	1.087			59.6	93.1	1.086
D 0.86			70.6	83.4	1.083			56.8	91.8	1.085
D 1.00			73.1	80.2	1.083			60.8	93.0	1.080
O 1.00			78.2	85.8	1.083			58.9	91.3	1.085

†Values are means of the three replicates per treatment. Letters indicate statistical difference within column for each variety at the alpha = 0.05-level as determined by Tukey HSD following ANOVA.
*Norkotah and Burbank medium and large size categories refer to 170 to 283.5 g and >283.5 g tubers, respectively. Snowden premium size category refers to tubers with a diameter of 50 to 100 mm.
‡ % is based on % of total yield

Table 3 Effect of irrigation treatment on tuber bud- and stem-end sucrose and glucose concentrations from potatoes taken out of storage after being grown in Hancock, WI, in 2013 and 2014.

		At Set Point‡				Set Point + 60 Days			
		Sucrose		Glucose		Sucrose		Glucose	
Cultivar	Irrigation	Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
Russet Burbank									
2013	D 0.75	1.162 †	1.154 a*	0.281	1.345	0.643	0.509	0.341	1.326
	D 0.86	1.308	0.913 b	0.446	1.991	0.717	0.464	0.603	1.643
	D 1.00	1.089	0.918 b	0.281	1.462	0.665	0.589	0.396	1.181
	O 1.00	1.116	0.922 b	0.410	1.480	0.823	0.572	0.319	1.319
2014	D 0.75	0.819 a	0.390 ab	0.425 b	1.833	0.720 ab	0.395	0.496 ab	2.033
	D 0.86	0.896 a	0.234 b	0.472 ab	2.392	0.869 a	0.440	0.363 b	1.875
	D 1.00	0.790 a	0.611 a	0.592 ab	1.899	0.749 a	0.612	0.625 ab	2.044
	O 1.00	0.537 b	0.615 a	0.833 a	1.909	0.558 b	0.563	0.716 a	2.142
Snowden									
2013	D 0.75	0.488	0.810	0.007	0.084	0.414	0.584	0.057 a	0.089
	D 0.86	0.465	0.797	0.006	0.030	0.416	0.593	0.034 b	0.077
	D 1.00	0.446	0.794	0.010	0.042	0.500	0.668	0.044 ab	0.070
	O 1.00	0.455	0.779	0.011	0.054	0.385	0.536	0.040 ab	0.089
2014	D 0.75	0.489	0.608	0.048	0.077	0.615	0.620	0.042	0.043 b
	D 0.86	0.472	0.571	0.061	0.155	0.554	0.583	0.061	0.060 ab
	D 1.00	0.462	0.600	0.062	0.167	0.604	0.727	0.044	0.064 ab
	O 1.00	0.458	0.635	0.052	0.082	0.609	0.810	0.040	0.076 a

‡ Potatoes were sampled when bin temperatures reached minimum set point of 9 °C and 60 days later, approximately, 125 and 185 days after harvest.

* Numbers within a column in a given year with the same letter are not significantly different at the alpha = 0.05-level as determine by Tukey HSD following ANOVA.

† All values represent means of three replicates presented in mg g^{-1} of fresh weight.

Table 4 Mean USDA fry color for French fries from Russet Burbank and chips from Snowden at two sampling dates after being grown in Hancock, WI, in 2013 and 2014.

		Mean Fry Color			
		Russet Burbank		**Snowden**	
Time†	**Irrigation**	**2013**	**2014**	**2013**	**2014**
Set Point	D 0.75	3.78	3.44	4.06	3.28
	D 0.86	4.05	3.44	4.00	3.33
	D 1.00	3.39	3.33	3.76	3.39
	O 1.00	3.61	2.61	4.12	3.56
Set Point + 60 days	D 0.75	3.38	5.22	2.39	3.28
	D 0.86	3.83	4.83	2.50	3.67
	D 1.00	3.44	5.39	2.33	3.78
	O 1.00	3.22	5.06	2.50	3.89

† Potatoes were sampled when bin temperature reached minimum set point of 9 °C and 60 days later which was approximately, 125 and 185 days after harvest, respectively. Data were analyzed separately for Russet Burbank and Snowden due to differences in fry process and rating scale for evaluating French fries and potato chips.

Table 5 The mean of daily minimum, maximum and soil temperature range at 10 cm below this hill are shown for three irrigation treatments in 2013 and 2014. Different letters indicate differences in the means at a p-value of <0.05. Temperature measurements were taken from day of year 178 to 252 and 167 to 252 in 2013 and 2014, respectively.

	2013						2014					
Irrigation Treatment	Min		Max		Range		Min		Max		Range	
D 0.75	18.17	a	25.13	a	6.95	a	18.49	a	21.95	b	3.69	b
D 1.00	18.41	a	24.96	a	6.54	ab	17.68	b	22.77	a	5.09	a
O 1.00	17.69	b	22.78	b	5.09	b	17.64	b	22.9	a	5.26	a

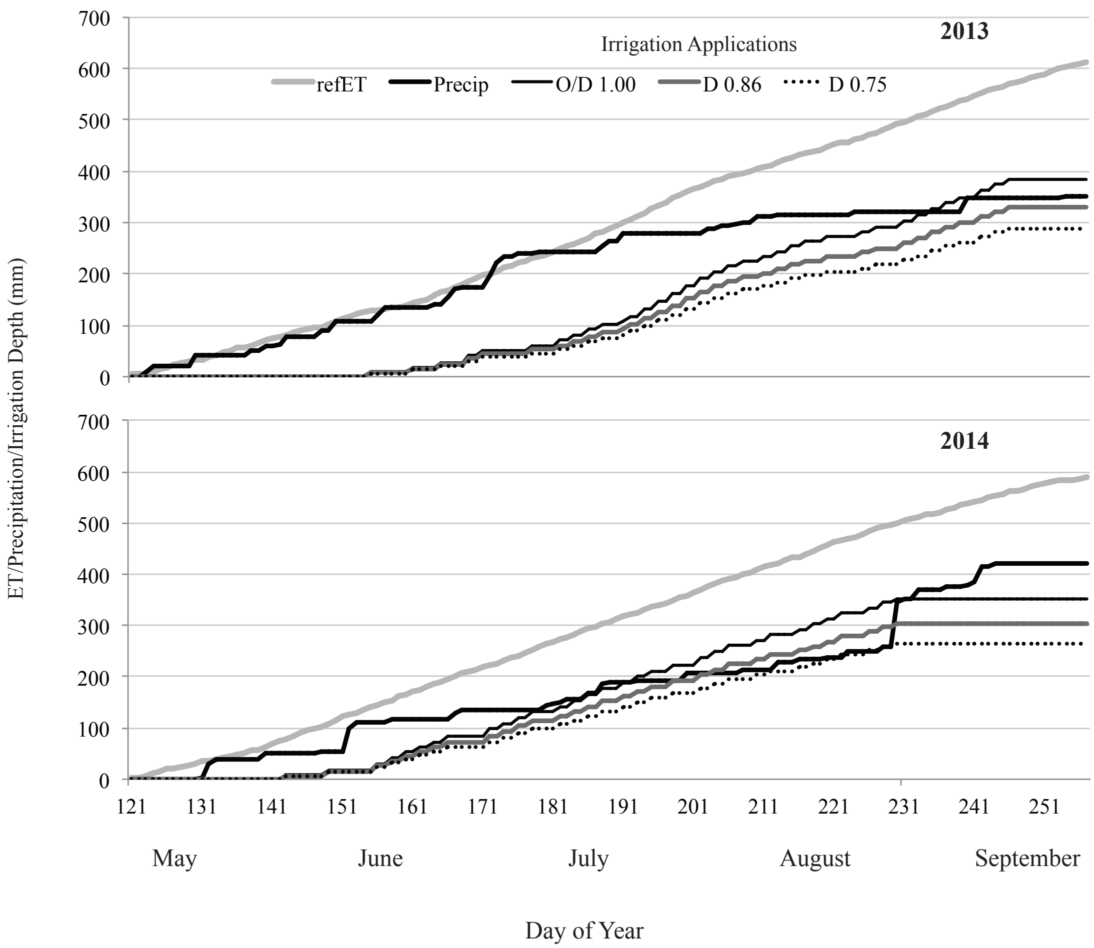

Figure 1 Cumulative reference ET, precipitation, and irrigation applications for each irrigation treatment in Hancock, WI, 2013 and 2014. Planting dates were May 1st (DOY 121) in 2013 and May 9th (DOY 129) in 2014. Harvest dates were September 16th (DOY 260) and September 17th (DOY 261) in 2013 and 2014, respectively.

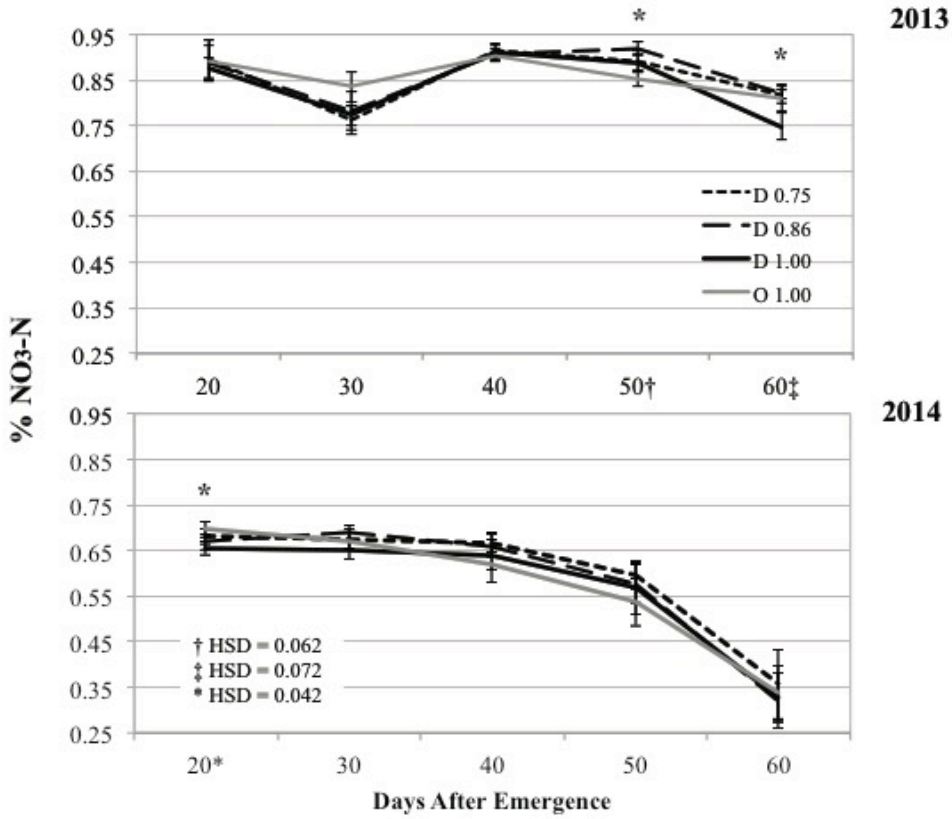

Figure 2 Mean petiole NO_3-N on a dry-weight basis across three potato cultivars as influenced by irrigation treatment in Hancock, WI, in 2013 and 2014. Irrigation treatments were drip at 75% of crop evapotranspiration (ET_c) (**D 0.75**), drip at 86% of ET_c (D **0.86**), drip at 100% of ET_c (D **1.00**) and overhead at 100% of ET_c (**O 1.00**) at 5 collection dates. Error bars represent standard error of the mean, and asterisks indicate differences within a collection date at a *p*-value of <0.05. Supplemental fertilizer applications were made at **17, 30, and 43** days after emergence (DAE) in **2013** and at **20, 32 and 45** DAE in **2014**.

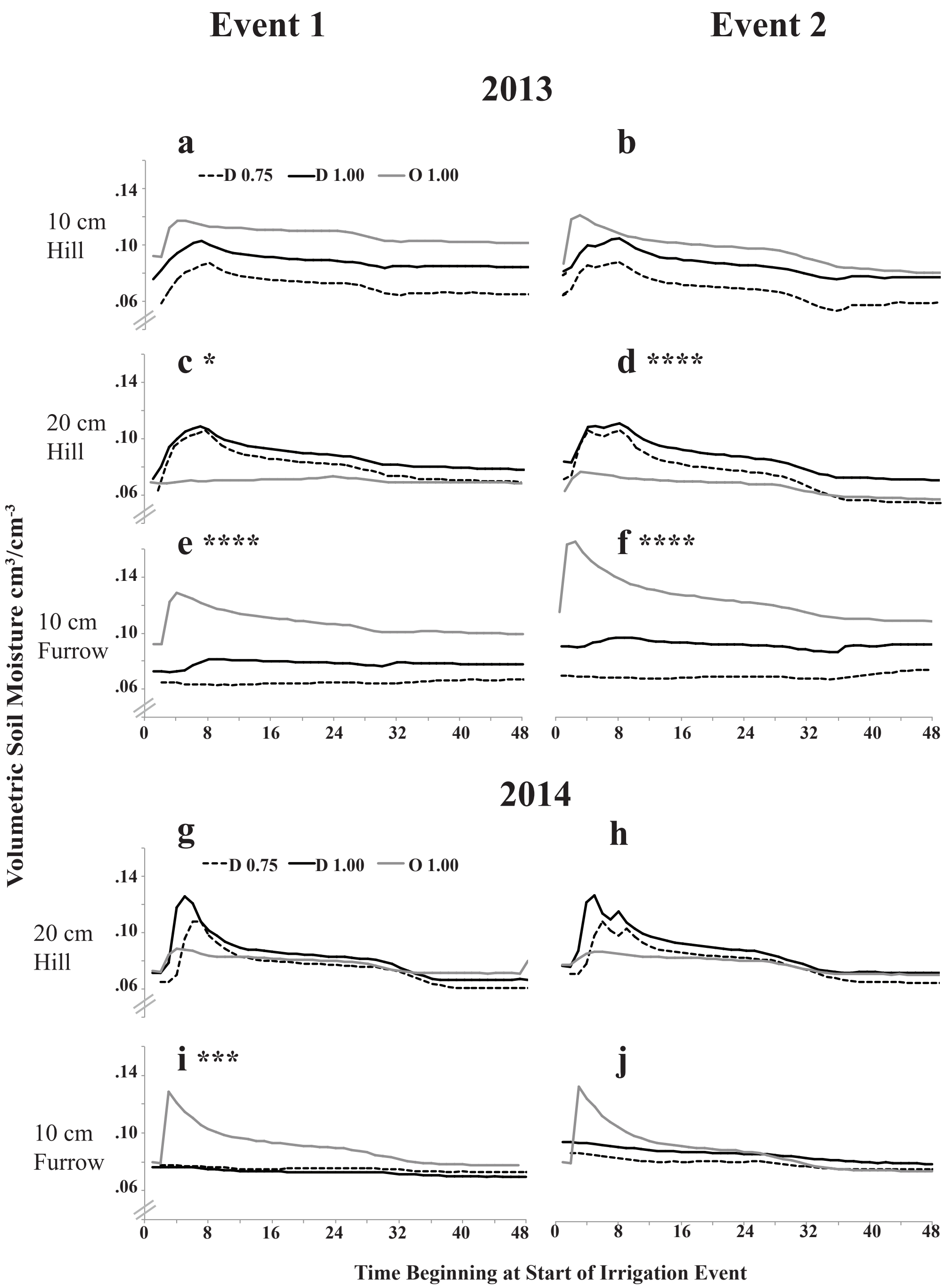

Figure 3. Volumetric water content as influenced by irrigation treatment at 10 cm (**a, b**) and 20 cm below the hill (**c, d, g, h**) and 10 cm below the furrow (**e, f, i, j**) during a 48 hour period on day of year 204 (left) and 227 (right) in 2013 and 210 (left) and 218 (right) in 2014, respectively, at Hancock, WI. Irrigation treatments were drip at 75% of crop evapotranspiration (ET_c) (**D 0.75**), drip at 100% of ET_c (D **1.00**) and overhead at 100% of ET_c (**O 1.00**). No data is shown at 10 cm below hill in 2014 due to probe malfunctions. Asterisks denote significance at a *p*-value of <0.05 (*), <0.01 (**), <0.001 (***) and <0.0001 (****) as determined by repeated measures analysis.

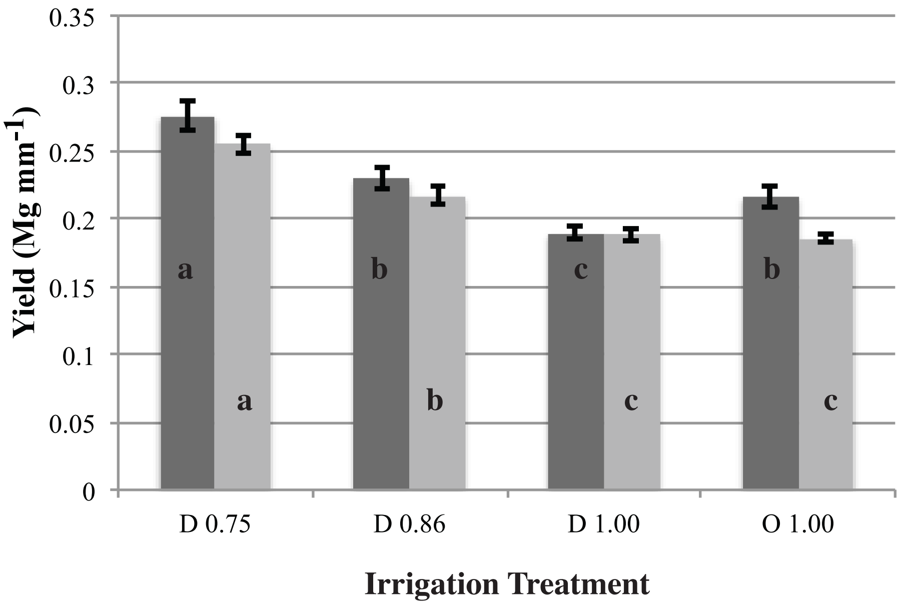

Figure 4 Average total potato yield (Mg) per mm of irrigation water averaged across three potato varieties in Hancock, WI, in 2013 (**dark gray bars**) and 2014 (**light gray bars**) for each irrigation treatment. Irrigation treatments were drip at 75% of crop evapotranspiration (ET_c) (**D 0.75**), drip at 86% of ET_c (D **0.86**), drip at 100% of ET_c (D **1.00**) and overhead at 100% of ET_c (**O 1.00**). Error bars represent standard error of the mean, and different letters indicate differences within a year at a p-value of <0.05 as determined by Tukey HSD following ANOVA.

CHAPTER 3

Effects of Irrigation Regime and Nitrogen Fertilizer Rate on Tuber Yield and Quality, Petiole Nitrate Levels, and Nitrogen Removal in Harvested Tubers of Russet Norkotah

Abstract

In the Central Sands of Wisconsin, irrigated potato (*Solanum tuberosum* L.) production occurs in areas with coarse-textured soils with low water holding capacity. Large rain or irrigation events can cause nutrients and agrochemicals to leach into the shallow aquifer below, contaminating groundwater resources. Precise irrigation and nitrogen (N) management are required to optimize yield and quality and mitigate negative environmental impacts. The goal of this research was to evaluate the potential to reduce irrigation and N fertilizer rates through drip irrigation relative to overhead sprinkler irrigation without negatively affecting yield and quality of the potato crop. In 2013 and 2014 we evaluated the effect of irrigation method and rate in combination with N rate on yield and quality response, petiole nitrate levels, and N removal in harvested tubers. Treatments applied were overhead irrigation at 100% crop evapotranspiration (ET_c) demand and drip at 100%, 86%, and 75% ET_c together with three N rates of 202, 291, and 336 kg ha^{-1}. Total yields ranged from 70 to 83 Mg ha^{-1} among all experimental irrigation and fertility treatments. Total yield and quality were similar across drip irrigation treatments, but overhead irrigation did result in higher total and US#1 yield than drip irrigation in one of two years and higher yields of large-size tubers in both years. There was no response in total yield and US #1 yield to N fertilizer rate, but higher nitrogen rates led to improved yield of large size potatoes in one of two years. Nitrogen removal in harvested tubers ranged from 150 to 170 kg ha^{-1} which is 57 to 92% higher than previously recorded in Wisconsin. Petiole nitrates were lowest under the 202 kg ha^{-1} N rate and proved an important tool to detect N deficiencies and potential yield declines associated with the higher-value, large tubers. This study demonstrated that it was possible to maximize total yield with 25% less irrigation water in 2014 and at 28% less N fertilizer than

the current recommended rate in 2013 and 2014 under conditions of ample precipitation. However, potential irrigation water and nutrient savings under drip could come at an economic cost due to observed decline in the proportion of large tuber yield.

Introduction

In the humid upper Midwest, irrigated agriculture has primarily expanded into areas with coarse-textured soils and shallow aquifers such as the Central Sands of Wisconsin. Central Sands soils were formed under Glacial Lake Wisconsin and subsequent eolian events and are vulnerable to leaching of nitrates and other agrochemicals (Kniffin et al. 2014). Irrigation is used in this region to secure consistent yield and quality of high value vegetables and potatoes. Large rain or irrigation events can cause nutrients and agrochemicals to leach into groundwater resources. This contamination can affect the use of the aquifer as a source of potable water (Kraft et al. 1999). Stites and Kraft (2000) found that water samples in irrigated areas within the Central Sands contained nitrate levels that exceed U.S. drinking water maximum contaminant levels of 10 mg L^{-1} and were greater than levels found upgradient from sampled fields. Nutrient loss to the groundwater has important economic consequences in addition to environmental. Sixty to seventy percent of N fertilizer in irrigated potato production can contribute to nitrate loading, and over half of all inputs can be lost to drainage (Saffigna and Keeney 1977; Stites and Kraft 2001). Nitrate loading can occur even when adhering to university nutrient management recommendations for best management practices (Stites and Kraft 2001). Thus, precise irrigation and N management are required to optimize yield and quality and mitigate negative environmental impacts.

Nitrogen rate and timing are two primary factors that determine leaching potential in sandy soils (Zvomuya et al. 2003). Therefore, identifying management practices that can allow for reduced application rates and better application timing to meet crop needs could have important consequences for nitrate loading to groundwater. The use of drip irrigation is one potential management practice that could address these issues. Drip irrigation allows for more targeted water application, thus making it possible to reduce the overall volume of water applied. As a result, this can reduce leaching of nutrients from the root zone (Eldredge et al. 2003; Reyes-Cabrera et al. 2014; Shock et al. 2007, 2013). Shock et al. (2001) found they were able to use less N than area standard N rates to produce similar yields of 'Umatilla Russet' through the use of drip irrigation. However, this work was conducted in a silt loam, not a coarse-textured soil like those found in the Central Sands. Chawla and Narda (2001) compared drip irrigation to conventional furrow irrigation in potato in India and found potential water and nutrient savings of 30 and 70%, respectively.

Split applications and in-season crop N status monitoring are two methods typically employed by growers to prevent N losses and avoid unnecessary applications. Split applications are designed to coordinate N applications to crop demand. Improving N application timing can avoid delayed tuber growth, reduced yields, and low specific gravities associated with excessive early season application (Ojala 1990) as well as lower marketable yield and vulnerability to *Verticillium* wilt infection which translates into the early dying complex that can result from N deficiencies (Davis et al. 1990; Errebhi et al.1998). Presumably, reducing at-plant N applications will also decrease the chance of N loss to groundwater (Errebhi et al. 1998; Joern and Vitosh 1995; Porter and Sisson, 1991; Rosen 1995; Waddell et al. 2000; Westermann et al. 1988). However, although fertigation with N in overhead sprinkler irrigation and split application of N fertilizer is common, it is not always efficient. Over 50% of fertilizer can end up in the furrow of hilled potatoes due to several factors including hill geometry, canopy interception, development of dry zones, non-uniform wetting patterns, and loss of preferential stem flow later in the growing season (Arriaga et al. 2009; Robinson 1999; Saffigna et al. 1976). The use of drip irrigation and concurrent fertigation is a potential tool to increase ease of split applications and better target nutrients in the root zone of potatoes growing in hills as drip can deliver 100% of fertilizer to the crop row.

Monitoring crop N status throughout the season is another important tool to inform N application decisions and avoid losses (Lauer 1986; Westermann and Kleinkopf 1985). Petiole nitrate concentrations are a commonly used indicator of crop N status (Belanger et al. 2003; Porter and Sisson 1991; Rodrigues 2004; Snapp and Fortuna 2003). There is a strong relationship between petiole nitrate level, fertilizer application rates, and yield (Bundy et al. 1986; Doll et al. 1971; Gardner and Jones 1975; Porter and Sisson 1991; Roberts and Cheng 1988; Timm et al. 1963; Tyler et al. 1983). Considerable research has been conducted to create petiole nitrate sufficiency ranges for different growth stages that can inform supplemental fertilizer application rates (Kleinkopf et al. 1984; Roberts and Cheng 1988; Westcott et al. 1991; Williams and Maier 1990).

In the humid upper Midwest, drip irrigation research has looked at the effect of irrigation application rate and N source (Waddell et al. 1999, 2000), N application method (Kelling et al. 1998) and timing (Wadell et al. 2000; Wilner et al. 1997) on yield parameters, potential water and nutrient savings and leaching. Potential interactions between N rate and irrigation rate have not been studied. In potato production systems in Tunisia and Egypt, reduced leaching with the use of drip irrigation has been shown to lead to an interaction between irrigation amount and N application rates (Badr et al. 2012, Mohk et al. 2015). Yield was maximized at lower N rates under deficit drip irrigation treatments compared to higher irrigation levels (Badr et al. 2012; Mohk et al. 2015). Higher N rates negatively affected yields at lower irrigation levels (Badr et al. 2012). However, water deficit conditions have been found to decrease tuber size and yield in some studies (Yuan et al. 2003; Onder 2005), thus exploiting this interaction effect could affect tuber quality.

The goal of this research was to evaluate the potential of drip irrigation to allow for a reduction in N fertilizer and water application rates without negatively affecting yield and quality of Russet Norkotah potato. Specific objectives were to determine the effect of three N rates together with irrigation method (overhead or drip at three rates) on 1) total yield, yield of size categories, and tuber quality response, 2) in-season petiole nitrate-N status, and 3) N removal in harvested tubers.

Materials and Methods

Field Management

The two-year field study was conducted during 2013 and 2014 at the Hancock Agricultural Research Station in Hancock, WI (latitude: 44°12.1413 N; longitude 89° 53.6840; elevation 328m) on a highly uniform Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamments) with a field capacity estimated at 0.14 $cm^3\ cm^{-3}$ (Copas et al. 2008). The parent material is glacial outwash with underlying glacial till. Surface and subsurface horizons are loamy sand to sand (Cooley et al. 2007). The experimental design was a modified split-plot with three complete replications and restricted randomization on whole plot treatment of irrigation. Whole plot treatments consisted of irrigation method (drip or overhead) and rate. Irrigation method was not randomized within year due to logistical constraints, but was across years. The high uniformity of soils at the Hancock research station likely tempers effects of blocking due to field variance. Irrigation treatments consisted of overhead irrigated to 100% crop evapotranspiration demand (ETc) and three levels of drip irrigation with volume application rates equivalent to 75%, 86% and 100% of ET_c as calculated for the overhead treatment. The split-plot treatment was N rate, which was randomized within each replication and included 202, 291, and 336 kg ha^{-1}.

Prior to planting, potato rows spaced 91 cm apart were opened and starter fertilizer was applied. Plots were four rows wide or 3.65 meters by 6 meters long for a total area of about 22 m^2. Planting dates were May 1st, and May 5th in 2013 and 2014, respectively. Certified seed tubers of Russet Norkotah (line selection CO#8) were machine cut, allowed to suberize for a week, and hand planted with 30.5 cm spacing between seed pieces. The rows were then closed and hilled, leaving seed pieces at an approximate depth of 15 cm below the top of the hill. Previous crops for each year of the study were as follows: snap beans for 2013 and soybeans for 2014. It should be noted that in 2013 the overhead irrigation block was located slightly north of the drip blocks, and, although both areas were planted to snap beans the year prior, only the drip section had been planted to potato two years prior. Aside from the drip irrigation and N fertilizer applications, all other cultural practices followed University of Wisconsin recommendations for fertility, irrigation and pest management, which also follow area practices (Bussan et al. 2015).

Irrigation and Fertility Management

The overhead irrigation was applied via a T-L hydraulic drive linear system with a flow rate of 890 liters per minute (38 liters per minute per nozzle) and an inlet operating pressure of 310.3 (O 1.00). To achieve the three drip irrigation levels, tape with three different emitter spacings of 30.5, 35.6, and 40.6 cm was used to deliver rates equivalent to 1.00X (D 1.00), 0.86X (D 0.86) and 0.75X (D 0.75) of ET_c of the volume applied to the overhead (O 1.00) treatment, respectively. All drip tape, regardless of spacing, had an emitter flow rate of 0.91 liters per hour at an operating pressure of 69 kPa (Netafim Streamline Series 636-008 Fresno, CA). The drip system was configured so that each row had one lateral, which was connected to a central manifold. The system also consisted of an initial pressure regulator, backflow preventer, filter and second pressure regulator, which maintained pressure near 69 kPa. The tape was hand-laid prior to plant emergence along the apex of the hills and shallowly covered with dirt every five feet in order to secure its placement. It was checked for leaks and uniformity of application throughout the season.

The Wisconsin Irrigation Scheduling Program (WISP) along with reference ET and precipitation data from the Hancock ARS weather station was used to determine irrigation application rates to match 100% of ET_c demand. WISP utilizes a water balance, or checkbook, approach, and adjusted ET_c estimates based on reference ET, crop emergence date, and canopy cover to determine irrigation recommendations (Curwen and Masssie 1994). Allowable depletion was assumed to be 12.7 mm per day. Soil was sampled and inspected to confirm estimated soil moisture water balance. Drip tape run time was determined by the amount of time required to apply an equivalent volume of water to the D 1.00 treatment as the O 1.00 treatment. The wider emitter spacings of 35.6 and 40.6 cm were able to control application rates so that it was not necessary to alter run time in order to irrigate to 75% and 86% ET_c. Drip and sprinkler irrigation application were made on the same day and as close to the same time as possible. However, the run time required to apply the target water volume was much longer for the drip irrigation than for the overhead irrigation due to large differences in water flow rates. The O1.00 and D 1.00, D 0.86, and D 0.75 treatments received 385, 331 and 289 mm of irrigation water, respectively in 2013, and 359, 309 and 267 mm in 2014 (Chapter 2, Figure 1).

Nitrogen fertilizer was applied at 202, 291, and 336 kg ha^{-1} total over five timings from planting through 75 days later. All plots received 37 kg N ha^{-1} at planting, 84.6 kg N ha^{-1} at hilling, and the remaining N was split over three supplemental applications (Table 1). Rates were differentiated beginning with the first supplemental application. At planting and hilling, fertilizer was side dressed in overhead and drip plots in the form of ammonium sulfate. For subsequent applications, granular ammonium nitrate was banded in the overhead block and watered in with the linear irrigation system, and liquid urea ammonium nitrate was injected through the drip system. Drip lines were equipped with shutoff valves, and a base rate corresponding to the 202 kg ha^{-1} treatment was injected by irrigation treatment so that the appropriate amount of urea ammonium nitrate could be applied. Additional urea ammonium nitrate was hand applied with watering cans to simulate fertigation for plots receiving higher N rates.

Petiole Nitrate Sampling

Petioles were sampled every 10 days beginning one week after the first side dress fertilizer application and continuing for five time points. Samples were taken from the first fully expanded leaf from the apex (Gardner and Jones 1975), and 20 petioles were collected from each plot, which is sufficient for analyzing nitrate (Lang et al. 1999). Collections were made the day following an irrigation event and at a similar time point (1000 to 1200 hours). Samples were then dried at 60°C in a forced-air oven, ground in a Thomas Wiley Mini-Mill (Model 3383-L10 Thomas Scientific, Inc. Swedesboro, NJ), passed through a 0.42 mm sieve (40 mesh), and stored until later nitrate analysis. Samples from 2013 and 2014 were analyzed using flow injection analysis (Ruzicka 1983).

Harvest

Harvest dates were September 16th and 17th for 2013 and 2014, respectively. The center two rows were harvested each year to estimate yield after removing drip tubing. The tubers were washed, weighed and graded in accordance to industry categories, US #1 (USDA grading standard A, diameter >47.6 mm) and B (diameter<47.6 mm). A Gallenberg grader and AgRay X-ray sizer was used for grading potatoes. The grader recorded size and weight characteristics of every tuber. The yield of size categories within the tuber weight range of 170 to 283 g (medium) and >283 g (large) was determined. Rotten, green, misshapen and small (<38.1mm) tubers were culled prior to grading and weighed separately.

Ten medium-size tubers were selected randomly per plot to evaluate for internal defects and specific gravity. Internal defects evaluated included: brown center, hollow heart, internal brown spot, vascular discoloration, internal heat necrosis and jelly end. Specific gravity was evaluated using a Weltech PW-2050 Dry Matter Assessment System. The system uses the weight of tuber samples in air and in water and the following formula developed by Murphy and Groven (1959) to calculate specific gravity:

$$\frac{\textit{weight in air}}{(\textit{weight in air - weight in water})}$$

Tuber Total N Content and N removal in Harvested Crop

Additional subsamples of eight tubers were selected amongst medium-size tubers to evaluate for total N content. A longitudinal slice was taken from each tuber, cut into small pieces for ease of drying and dried to a constant weight at 60°C in a forced-air oven. Samples were then ground in a Thomas Wiley Mill (Model 4), passed through a 0.42 mm sieve (40 mesh), and stored until elemental N analysis with a Costech ECS 4010 CHNSO Analyzer. Dry matter was measured in 2013 to calculate N removal in harvested crop. In 2014, dry matter values were modeled from specific gravity on a per plot basis for 2014 tuber samples using the following equation presented by Kleinkopf et al. (1987):

$$\%\, dry\ matter = -214.9206 + 218.181852\ (specific\ gravity)$$

Modeled and measured percent dry matter for 2013 differed by an average of -0.09% using the equation presented by Kleinkopf et al. (1987) versus 0.9% using the equation developed by Schippers (1976) (data not shown), thus the former equation was chosen to model 2014 dry matter values.

Data Analysis

Tuber yield and quality, N uptake, and petiole nitrate data were analyzed using the PROC MIXED procedure in SAS ver. 9.4 (Littel et al. 2006). This procedure was able to account for any missing data points due to the use of a likelihood-based estimation approach. All yield and size, distribution data was subjected to an analysis of variance (ANOVA) to test the main effect of irrigation treatment, N rate, and irrigation by N rate interaction. Data were first analyzed across years, and then separated by year if year by treatment interactions occurred. Irrigation, N rate, and irrigation by N rate interaction were treated as fixed effects.

Replication, year, and year by treatment interaction were treated as random effects. A two-factor nested model with mixed effects was use:

Model: $y_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} + \tau_k + \alpha_{\tau ik} + \delta_{ijk}$

$i = 1,\ldots,a$
$j = 1,\ldots,b$
$k = 1,\ldots,c$
μ = grand mean
α_i = the main effect for irrigation for ith treatment
β_j = the random effect of replication
ε_{ij} = is the error term for testing main plot effects
τ_k = the main effect of N rate
$\alpha_{\tau ik}$ = the interaction term for irrigation and N rate
δ_{ijk} = the error term for testing subplot effect

Tukey's honest significant difference (HSD) procedure was used to separate treatment means at a significance level of $p = 0.05$ following ANOVA. The same procedure was used to test main effects and interaction effects on petiole nitrate concentrations and N removal in harvested crop.

Results

Total Yield and Yield of Tuber Size Categories

Year by irrigation treatment interactions occurred due to differential performance of the O 1.00 treatment in 2013 relative to 2014. Thus, data were analyzed separately by year. Irrigation treatment by N rate interactions did not occur for any yield or tuber size category. Total yield and US #1 yield were affected by irrigation treatment in 2013. US #1 yield, B-size, their proportions of total yield, and tuber size were affected by irrigation in 2014 (Table 2). Total yield was highest under the O 1.00 treatment in 2013, but there was no irrigation treatment effect in 2014. US #1 yield was highest under the O 1.00 treatment in 2013, but lower than the D 0.75 treatment in 2014. B-size yield was lower in O 1.00 than D 1.00 and average tuber size was higher in O1.00 and O 0.86 than D 1.00 in 2014. US #1 and B-size yield as a percent of total yield followed US #1 and B-size yield trends in 2014. Only average tuber size in 2014 was affected by N rate, and the 202 kg ha^{-1} N produced smaller tubers than the other two rates.

Irrigation treatment also had a more pronounced effect on yield of different tuber size categories than did N rate. Irrigation treatment affected yield of large tubers in 2013 and medium and large tubers in 2014 (Table 3). Large tuber yield was higher under the O 1.00 treatment than one or more drip treatments in 2013 and 2014. Medium size tuber yield was lower under the O 1.00 than D 0.75 treatment in 2014 but not different in 2013. There was no effect of N rate on medium-sized yield either year, but large tuber yield was lower under the lowest N rate as was the percentage of large tubers. Specific gravity was not influenced by irrigation treatment or N rate. Incidence of hollow heart and other internal defects was minimal both years, and no irrigation or N rate treatment effects were detected either year (data not shown).

Petiole Nitrate Status

There were irrigation treatment by year and by collection date interactions for the majority of the sampling dates for petiole nitrate, thus data were analyzed separately by year and collection date. Petiole NO_3-N was lower, on average, over all treatments in 2014 (Figure 1). Irrigation treatment by N rate interactions again did not occur in either year with respect to petiole NO_3-N. A main effect of N rate, and to lesser extent, irrigation treatment affected petiole NO_3-N levels. In 2013, the 202 kg ha^{-1} N rate resulted in lower petiole NO_3-N levels than the other two N rates at 50 and 60 DAE and lower than the highest N rate 40

DAE. The lowest N rate resulted in lower petiole NO_3-N levels at 40, 50, and 60 DAE in 2014. Petiole NO_3-N was influenced by irrigation treatment 50 DAE in 2013 and 20 DAE in 2014. D 1.00 resulted in lower petiole NO_3-N levels than O 1.00 and D 0.75 in 2013, but the O 1.00 treatment had lower levels than D 0.86 and D 0.75 in 2014.

Total N Removal in Harvested Crop

Total N in the harvested crop in 2013 was affected by an irrigation treatment by year interaction, thus data were analyzed separately by year. There was no irrigation treatment by N rate interaction. Nitrogen removal was not influenced by main effect either year (Table 4). Within drip irrigation treatments, N removal tended to decrease as irrigation rate increased. The same trends were not evident in 2014. Nitrogen removal under the O 1.00 treatment trended higher than drip in 2013 and lower than drip in 2014. Across irrigation treatments, N removal in harvested tubers tended to be lower at the 202 kg ha^{-1} N rate compared to the higher rates. Nitrogen removal per unit total yield ranged from 2.5 to 2.75 kg Mg^{-1}, and fluctuated little among irrigation treatments in 2013 and 2014. Nitrogen removed per unit of total yield increased with fertilization both years and was lower under the lowest N rate relative to the higher rates. Lastly, N removed in harvested crop per unit of N applied was similar across years, was not affected by irrigation treatment, and was lower under the 202 kg ha^{-1} N rate.

Discussion

We hypothesized that there would be an interaction between irrigation treatment and N rate, and maximum yield would occur at lower N rates under deficit drip irrigation treatments as found previously (Badr et al. 2012, Mohk et al. 2015). However, no interaction effect was seen and total yield, US #1 yield, and yield of large tubers trended higher under the two highest N rates for all irrigation treatments (Table 2). The lack of an irrigation rate by N rate interaction seen in this study may be due to split N applications that allowed for better N recovery in all treatments. This would concur with Stark et al. (1993) who did not find irrigation by N interactions after split applying N.

Total and US #1 yield was similar between the lowest and highest N rate both years across irrigation years. Yield was high under low N rates, and the Russet Norkotah line selection CO#8 generally requires less nitrogen than standard Norkotah (Bohl and Love 2003; Rykbost and Charlton 2000). Low average tuber size under the lowest N rate was expected as low N rates have been shown to lead to smaller tuber size (Table 3, Lang et al. 1999; Rykbost and Maxwell 1989). Increasing N rate might have contributed to more vegetative than tuber growth as would be consistent with the findings of King et al. (2011), potentially or partially explaining why we did not see a yield increase with N in this study (Table 2).

Increasing N rate led to higher yield of potatoes in the large size category in 2014 (Table 3). Large sized category potatoes, > 283.5 g, are worth \$40 to \$160 Mg^{-1} more than smaller sized potatoes in the fresh market depending on year (USDA 2015). Increasing yield of large sized potatoes by nearly 8 Mg would increase the economic value of the crop to a producer by \$320 to \$1280 ha^{-1} at a cost of \$90 ha^{-1} in N fertilizer assuming N is worth \$1 kg ha^{-1}. While N recovery in both years suggests the environmental impact of applying more than 290 kg ha^{-1} would increase relative to the low rate, there was a potential for economic gain by additional N applications in one of two years. And, the latter may be a larger motivating factor for growers when determining N application rates.

Yield was maximized under drip irrigation at 100% of ET_c in 2013, but drip irrigation maximized yield at 75% of ET_c in 2014 (Table 2). Total and US #1 yield were higher under the overhead irrigation in 2013, possibly due to differential cropping history among whole plots. The area of the field where the overhead plots were situated had not been planted to potato for some years prior to 2013 while drip irrigated whole plots had been planted to potatoes 24 months previously. The high yield of the D 0.75 treatment supports Stark et al. (2013) findings that persistent drought treatments did not negatively impact yield; whereas, yield declines were observed under intermittent drought stress. The D 0.75 treatment did not produce smaller tubers than the higher drip treatments, which was counter to prior findings by Fabeiro et al. (2000) who observed declines in tuber size with regulated deficit, drip irrigation treatments in Spain. However, the stress under the D 0.75 treatment may not have been severe enough to impact tuber size. Lastly, although there were no differences between drip treatments in either year for any yield parameter, D 0.86 and D 1.00 experienced lower overall yield trends (Table 2). This suggests that there may have been nutrient leaching under the two higher drip treatments due to possible overwatering in these treatments.

We also hypothesized that there would be higher petiole NO_3-N levels and N content in harvested biomass under deficit drip treatments across N rates due to decreased leaching of N fertilizer. Petiole NO_3-N was seldom affected by irrigation and no difference in N removal occurred in response to irrigation rate in either year (Figure 1, Table 4). These findings disagree with Cappaert et al. (1992) who observed lower petiole NO_3-N concentrations under higher drip irrigation levels. Treatment effects may have been masked by high precipitation in 2014 causing leaching across treatments (Chapter 2, Figure 1). The differential cropping history of the overhead irrigation plots may have contributed to trends in higher petiole NO_3-N levels and N removal observed in 2013 due to unaccounted for residual N credits (Figure 1, Table 4). This trend was not repeated in 2014. Waddell et al. (1999) similarly found no effect of drip irrigation on N uptake in tuber biomass relative to overhead irrigation.

This study supported petiole NO_3-N monitoring as an important tool for making informed fertility management decisions and to capture economic gain and avert negative impacts of excess N applications. Petiole sampling revealed N deficiencies especially under the lowest N rate in 2014 but not 2013. If additional supplemental N applications were made in 2014 based on petiole results, this could have led to an increase in large size tuber yield and economic gain. Petioles did not indicate N deficiency in 2013. Use of sampling to inform supplemental N applications in this year would have prevented excess N application, for which there was no economic gain potential, and thus mitigated leaching to groundwater.

Nitrogen removal in harvested biomass was 57 to 92% higher than previously reported in Wisconsin across all treatments (Table 4, Bundy and Andraski 2005). The authors conducted research in Hancock, WI, and found maximum N removal amounts in Russet Burbank tubers of 107 kg ha^{-1} under an N fertilizer rate of 224 kg ha^{-1} and yield from 34.97 to 44.80 Mg ha^{-1}. Higher removal rates seen in this study were likely due to yields 50 to 100% higher than those reported by Bundy and Andraski (2005). Lack of treatment effects on total N removal in harvested tubers was unexpected. However, the data did suggest a slight response to N rate and drip rate in 2013 (Table 4). High precipitation may have caused some leaching in all irrigation treatments, making it difficult to detect treatment differences. That being said, the high relative amount of N removal observed in this set of experiments may be due to better timing of N, more precise irrigation, and better management tools available such as fumigation for management of early dying and fungicides for the control of late blight.

This research demonstrates that it was possible to obtain similar yields with 25% less irrigation water in one of two years under conditions of ample precipitation. In both years, total and US #1 yield was maximized using 28% less N fertilizer than the current recommended rate of 280 kg ha^{-1} for 62 to 73 Mg ha^{-1} yields (Laboski and Peters 2012). However, while yields were similar, slight shifts in yield of tubers within the large market category could have substantial economic impact on the crop within a single production year. Growers who decide to adopt drip irrigation should closely monitor irrigation and N applications as potential benefits of localized nutrient applications could be lost due to increased leaching potential. Lastly, the response of Russet Norkotah to drip and deficit irrigation treatments was not consistent across years, and further research should look at the response of more varieties in order to fully the explore the extent to which irrigation water and N applications can be decreased through the use of drip irrigation.

Literature Cited

Arriaga, F.J., B. Lowery, and K.A. Kelling. 2009. Surfactant impact on nitrogen utilization and leaching in potatoes. *Am. J. Potato Res.* 86:383-390.

Badr, M.A., W.A. El-Tohamy, and A.M. Zaghloul. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. *Agr. Water Manage.* 110:9-15.

Belanger, G., J.R. Walsh, J.E. Richards, P.H. Milburn, and N. Ziadi. 2002. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am. J. of Potato Res.* 79:269–279.

Bohl, W.H. and S.L. Love. 2003. Cultural Management of Russet Norkotah Potatoes. University of Idaho Extension Bulletin CIS 863. http://www.cals.uidaho.edu/edcomm/pdf/CIS/CIS1106.pdf accessed 06/05/2015.

Bundy, L.G., T.W. Andraski. 2005. Recovery of fertilizer nitrogen in crop residues and cover crops on an irrigated sandy soil. *Soil Sci. Soc. Am. J.* 69:640-648.

Bundy, L.G., R.P. Wolkowski, and G.G. Weis. 1986. Nitrogen source evaluation for potato production on irrigated sandy soils. *American. Potato J.* 63:385-397.

Bussan, A.J., J.B. Colqhoun, E.M. Cullen, V.M. Davis, R.L. Groves, D.J. Heider, G.R.W. Nice, and M.D. Ruark. 2015. Commercial Vegetable Production in Wisconsin. University of Wisconsin Extension Publication A3422. pp 188-213.

Cappaert, M.R., M.L. Powelson, N.W. Christensen, and F.J. Crowe. 1992. Influence of irrigation on severity of potato early dying and tuber yield. *Phytopathology* 82:1448-1453.

Chawla, J.K. and N.K. Narda. 2001. Economy in water and fertilizer use in trickle fertigated potato. *Irrig. Drain.* 50:129-137.

Cooley, Eric, B. Lowery, K.A. Kelling, and S. Wilner. 2007. Water dynamics in drip and overhead sprinkler irrigated potato hills and development of dry zones. *Hydrol. Process.* 21:2390-2399

Copas, M.E., A.J. Bussan, M.J. Drilias, and A Charkowski. 2008. Influence of compaction and subsoil tillage on soil conditions and pink eye. *Am. J. Potato Res.* 85:342-352.

Curwen, D. and L.R. Massie. 1984. Potato Irrigation Scheduling in Wisconsin. *Am. Potato J.* 61:245-241.

Davis, J.R., L.H. Sorensen, J.C. Stark, and D.T. Westermann. 1990. Fertility and management practices to control Verticillium wilt of the Russet Burbank potato. *Amer. Potato J.* 67:55-65.

Doll, E.C., D.R. Christenson and A.R. Wolcott. 1971. Potato yields as related to nitrate levels in petioles and soils. *Am. Potato J.* 48:105-112.

Eldredge, E.P., C.C. Shock, and L.D. Saunders. 2003. Early and late harvest potato cultivar response to drip irrigation. *Acta Hort.* 619:233–239.

Errebhi, M., C.J. Rosen, S.C. Gupta and D.E. Birong. 1998. Yield response and nitrate leaching as influenced by nitrogen management. *Agron. J.* 90:10-15.

Fabeiro, C., F. Martín de Santa Olalla, and J.A. de Juan. 2000. Yield and seize of deficit irrigated potatoes. *Agr. Water Manage.* 48:255-266.

Gardner, B.R. and J.E Jones. 1975. Petiole analysis and the nitrogen fertilization of Russet Burbank potatoes. *Am. Potato J.* 52:195-200.

Joern, B.C., and M.L. Vitosh. 1995. Influence of applied nitrogen on potato part I: yield, quality and nitrogen uptake. *Am. Potato J.* 54:51–63.

Kelling, K.A., S.A. Wilner, R.F. Hensler, and L.M. Massie. 1998. Placement and irrigation effects on nitrogen fertilizer use efficiency. Proc.Wisconsin Ann. Potato Meet. 11:79–88.

King, B.A., D.D. Tarkalson, D.L. Bjorneberg, and J.P. Taberna Jr. 2011. Planting system effect on yield response of Russet Norkotah to irrigation and nitrogen under high intensity sprinkler irrigation. *Am. J. Potato Res.* 88:121-134.

Kleinkopf, G.E., G.D. Kleinschmidt and D.T. Westermann. 1984. Tissue analysis: A guide to nitrogen fertilization of Idaho Russet Burbank potatoes. University of Idaho Curr Info Series No. 740. 4 pp.

Kleinkopf, G.E., D.T. Westermann, M.J. Wille, and G.D. Kleinschmidt. 1987. Specific gravity of Russet Burbank potatoes. *Am. Potato J.* 64:579-587.

Kraft, G.J., W. Stites, and D.J. Mechenich. 1999. Impacts of irrigated vegetable agriculture on a humid north-central U.S. sand plain aquifer. *Ground Water* 37:572–580.

Laboski, C.A.M. and J.B. Peters. 2012. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. University of Wisconsin Extension Publication A2809. pp 66.

Lang, N.S., R.G. Stevens, R.E. Thornton, W.L. Pan and S. Victory 1999. Potato nutrient management for central Washington. Wash. State. Univ., Pullman, Coop Ext. Bul. 1871. pp 4.

Lauer, D.A. 1986. Russet Burbank yield response to sprinkler-applied nitrogen fertilizer. *Am. J. of Potato Res.* 63:61-69.

Littell, R. C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2002. *SAS for Mixed Models**,** Second Edition*. Cary, NC: SAS Institute Inc. pp. 663.

Meyer, R.D. and D.B. Marcum. 1998. Potato yield, petiole nitrogen, and soil nitrogen response to water and nitrogen. *Agron. J.* 90: 420-429.

Mokh, F.E., M.M. Masmoudi, and N.B. Mechlia. 2015. Yield and water productivity of drip-irrigated potato under different nitrogen levels and irrigation regime with saline water in arid Tunisia. *Am. J. Plant Sci.* 6:501-510.

Murphy, H.J. and M.J. Groven. 1959. Factors affecting the specific gravity of the white potato. *Maine Agric Exp Stn. Bull* No 583.

Ojala, J.C., J.C. Stark and G.E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* 67:29-42.

Onder, S., M.E. Caliskan, D. Onder, and S. Caliskan. 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agr. Water Manage.* 73:73-86.

Porter, G.A. and J.A. Sisson. 1991. Petiole nitrate content of Maine grown Russet Burbank and Shepody potatoes in response to varying nitrogen rate. *Am. Potato J.* 69:309-314.

Reyes-Cabrera, J., L. Zotarelli, D.L. Rowland, M.D. Dukes and S.A. Sargent. 2014. Drip as alternative irrigation method for potato in Florida sandy soils. *Am. J. Potato Res.* 91:504-516.

Rodrigues, M.A. 2004. Establishment of continuous critical levels for indices of plant and pre-sidedress soil nitrogen status in the potato crop. *Commun. Soil Sci. Plan.* 35:2067–2085.

Roberts, S. and H.H. Cheng. 1988. Estimation of critical nutrient range of petiole nitrate for sprinkler-irrigated potatoes. *Am. Potato J.* 65:119-124.

Rosen, C.J. 1995. Nitrogen management studies in Minnesota. Proc. Wisconsin Ann. Potato Meet 8:15-3.

Ruzicka, J. 1983. Flow Injection Analysis – From Test Tube to Integrated Microconduits. *Anal. Chem.* 55: 1040A-1053A.

Rykbost, K.A., and B.A. Charlton. 2000. Potato variety response to nitrogen fertilizer rate. 2000. Annual Report Klamath Experiment Station. Oregon State University. http://oregonstate.edu/dept/kbrec/sites/default/files/documents/ag/ar00chpt5.pdf accessed 05/05/15. pp 39-43.

Rykbost, K.A. and J. Maxwell. 1989. Effects of planting density and nitrogen rate on performance of new potato varieties and advanced selections. Research in the Klamath Basin 1989 Annual Report. Oregon State University Special Report. http://oregonstate.edu/dept/kbrec/sites/default/files/10_-_89potatomanagement.pdf Accessed 15 May 2015. pp 70-78.

Saffigna, P.G., and D.R. Keeney. 1977. Nitrate and Chloride in groundwater under irrigated agriculture in central Wisconsin. *Ground Water* 15:170–177.

Saffigna, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemfow and hilling. *Agron. J.* 68:337-342.

Schippers, P.A. 1976. The relationship between specific gravity and percentage dry matter in potato tubers. *Am. Potato J.* 53:111-122.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007. Irrigation best management practices for potato. *Am. J. Potato Res.* 84:29–37.

Shock, C.C., E.P. Eldredge, and L.D. Saunders. 2001. Drip irrigation management factors for 'Umatilla Russet' potato production. Malheur Experiment Station Annual Report. Oregon State University. Special Report 1038. pp. 121-126.

Shock, C.C., F-X. Wang, R. Flock, E.P. Eldredge, A.B.. Pereira, and J. Klauzer. 2013. Drip irrigation guide for potatoes, Sustainable agriculture techniques. Oregon State University Extension Service EM 8912, 8p. http://ir.library.oregonstate.edu/xmlui/bitstream Accessed 3 March 2015. pp. 1-8.

Snapp, S.S. and A.M. Fortuna. 2003. Predicting nitrogen availability in irrigated potato systems. *Hort Technol.* 13:598-604.

Stark, J.C., S.L. Love, B.A. King, J.M. Marshall, W.H. Bohl, and T. Salaiz. 2013. Potato cultivar response to seasonal drought patterns. *Am. J. of Potato Res.* 90: 207-216.

Stark, J.C., I.R. McCann, D.T. Westermann, B. Izadi, and T.A. Tindall. 1993. Potato response to split nitrogen timing with varying amounts of excessive irrigation. *Am. Potato J.* 70:765–777.

Stites, W. and G.J. Kraft. 2001. Nitrate and chloride loading to groundwater from an irrigated North-Central U.S. sand-plain vegetable field. *J.Enviro. Qual.* 30: 1176-1184.

Stites, W. and G.J. Kraft. 2000. Groundwater quality beneath irrigated vegetable fields in a North-Central U.S sand plain. *J.Enviro. Qual. 29:1509-1517.*

Timm, H., J.C. Bishop, and V.H. Scweers. 1963. Growth, yield, and quality of White Rose potatoes as affected by plant population and levels of nitrogen. *Am. Potato J.* 40:182-192.

Tyler, K.B., F.E. Broadbent, and J.C. Bishop. 1983. Efficiency of nitrogen uptake by potatoes. *Am. Potato J.* 60: 261-269.

USDA (United States Department of Agriculture Agricultural Marketing Service). 2015. National Potato and Onion Report. http://www.ams.usda.gov/mnreports/fvdidnop.pdf. Accessed 18 May 2015. 2 pp.

Waddell, J.T., Gupta, S.C., Moncrief, J.F., Rosen, C.J., and D.D. Steele. 1999. Irrigation and nitrogen management effects on potato yield tuber quality, and nitrogen uptake. *Agron. J.* 91:991-997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation- and nitrogen-management impacts on nitrate leaching under potato. *J.Enviro. Qual.* 29:251-261.

Westcott, M.P., V.R. Stewart, and R.E. Lund. 1991. Critical petiole nitrate levels in potato. *Agron. J.* 83: 844-850.

Westermann, D.T., and G.E. Kleinkopf. 1985. Nitrogen requirements for potatoes. *Agron. J.* 77: 616-621.

Westermann, D.T., G.E. Kleinkopf, and L.K. Porter. 1988. Nitrogen fertilizer efficiencies on potatoes. *Am. J. Potato Res.* 65:377-386.

Williams, C.M.J. and N.A. Maier. 1990. Determination of the nitrogen status of irrigated potato crops. I. Critical nutrient ranges for nitrogen in petioles. *J. Plant Nut.* 13:971-984.

Wilner, S.A., K.A. Kelling, and L.R. Massie. 1997. Influence of nitrogen timing and irrigation methods on Russet Burbank Potatoes. Proc.Wisconsin Ann. Potato Meet 10:43-52.

Yuan, B.Z., S. Nishiyama, and Y. Kang. 2003. Effects of different irrigation regimes on the growth and yield of drip irrigated potato. *Agr. Water Manage.* 63: 53–167.

Zvomuya, F., C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. *J. Enviro. Qual.* 32:480–489.

Table 1 Nitrogen application timing for three N rates in relation to days after planting (DAP) in Hancock, WI, in 2013 and 2014.

		N Rate (kg ha^{-1})		
Year	DAP	202*	291	336
2013	0	37.0	37.0	37.0
	14	84.6	84.6	84.6
	44	28.0	50.4	72.9
	57	26.9	94.2	116.6
	75	25.2	25.2	25.2
2014	0	37.0	37.0	37.0
	14	84.6	84.6	84.6
	33	26.9	49.3	71.7
	54	34.7	102.0	124.4
	67	18.5	18.5	18.5

*N rates are rounded to nearest whole kilogram.

Table 2 Total yield, USDA #1, and B size yield and proportion of total yield, and average tuber size for Russet Norkotah as affected by irrigation treatment and N rate in Hancock, WI, in 2013 and 2014.

	2013						**2014**					
		US #1‡		B-size**				US #1		B-size		
Treatment	Total† ($Mg\ ha^{-1}$)	$Mg\ ha^{-1}$	% of total	$Mg\ ha^{-1}$	% of total	Tuber Size (g)	Total ($Mg\ ha^{-1}$)	$Mg\ ha^{-1}$	% of total	$Mg\ ha^{-1}$	% of total	Tuber Size (g)
Irrigation												
D 0.75	73.8 b*	65.2 b	93.3	1.6	2.2	254.0	75.0	71.9 a	95.8 a	0.6 ab	0.8 ab	216.9 ab
D 0.86	69.6 b	65.2 b	93.7	1.7	2.4	234.5	71.2	67.7 ab	95.1 ab	0.7 a	0.9 ab	209.3 b
D 1.00	69.6 b	65.1 b	93.5	1.5	2.3	224.9	70.3	66.9 ab	95.2 ab	0.8 a	1.1 a	200.2 b
O 1.00	82.9 a	78.4 a	94.6	1.3	1.6	256.1	70.4	66.0 b	93.7 b	0.4 b	0.6 b	238.8 a
N Rate $kg\ ha^{-1}$												
202	73.0	68.7	94.0	1.5	2.1	239.5	70.3	66.8	95.0	0.7	0.9	202.0 b
291	73.6	69.3	94.1	1.4	2	242.3	72.3	68.5	94.8	0.6	0.8	221.4 a
336	75.3	70.2	93.3	1.7	2.3	245.3	72.7	69.1	95.1	0.6	0.8	225.5 a

† Total yield includes the weight of culls (rotten, misshapen, and green tubers), which can be calculated as Total - US #1 - B's.
Mean cull weights were not significantly different at the alpha = 0.05-level either year.
* Different letters within a column and treatment category indicate statistical difference at p=0.05-level as determined by Tukey HSD following ANOVA
‡ US #1 includes tubers diamter>47.6mm
** B-size includes tubers diameter<47.6mm

Table 3 Russet Norkotah yield for medium and large size categories and specific gravity as influenced by irrigation treatment and N rate in Hancock, WI, in 2013 and 2014.

Treatment	2013					2014				
	Medium*		Large			Medium		Large		
	Mg ha^{-1}	% Total	Mg ha^{-1}	% Total	specific gravity	Mg ha^{-1}	% Total	Mg ha^{-1}	% Total	specific gravity
Irrigation										
D 0.75	23.8†	32.1	32.9 ab	44.7	1.074	29.6 a	39.4	28.1 ab	37.4 ab	1.074
D 0.86	27.0	38.9	24.0 b	34.2	1.072	27.2 ab	38.3	25.3 ab	35.4 b	1.076
D 1.00	24.5	35.4	27.3 ab	38.7	1.072	26.4 ab	37.5	23.2 b	32.9 b	1.075
O 1.00	26.7	32.1	39.2 a	47.3	1.071	24.2 b	34.5	31.6 a	44.6 a	1.076
N Rate kg ha^{-1}										
202	25.6	35.0	30.1	40.9	1.0729	28.2	40.2	22.0 b	31.2 b	1.076
291	26.1	35.7	30.6	40.8	1.0718	26.1	36.0	28.9 a	39.9 a	1.074
336	24.9	33.3	31.9	41.9	1.0723	26.2	36.0	30.3 a	41.6 a	1.075

†Values are means of three replicates per treatment. Letters indicate statistical difference at p= 0.05-level within column and irrigation or N rate as determined by Tukey HSD following ANOVA.
*Medium size class referes to 170 to 283.5 g tubers and large class refers to tubers > 283.5 g.

Table 4 N removal in harvested Russet Norkotah tubers, N removed per Mg harvest yield and per unit N applied as affected by irrigation treatment and N rate in Hancock, WI, in 2013 and 2014.

Treatment	2013				2014			
	N removed* (kg ha^{-1})	kg N per Mg yield	kg Tuber N per kg N applied		N removed (kg ha^{-1})	kg N per Mg yield	kg Tuber N per kg N applied	
Irrigation								
D 0.75	189.1	2.56			188.5	2.51		
D 0.86	175.1	2.51			174.8	2.46		
D 1.00	168.1	2.41			193.2	2.74		
O 1.00	206.0	2.48			187.7	2.66		
N Rate (kg ha^{-1})								
202	167.8	2.30	0.83	a	171.0	2.43	0.85	a
291	191.5	2.60	0.66	b	194.2	2.69	0.67	b
336	194.5	2.58	0.58	b	192.9	2.65	0.57	b

*Refers to total N removed in harvested tubers.

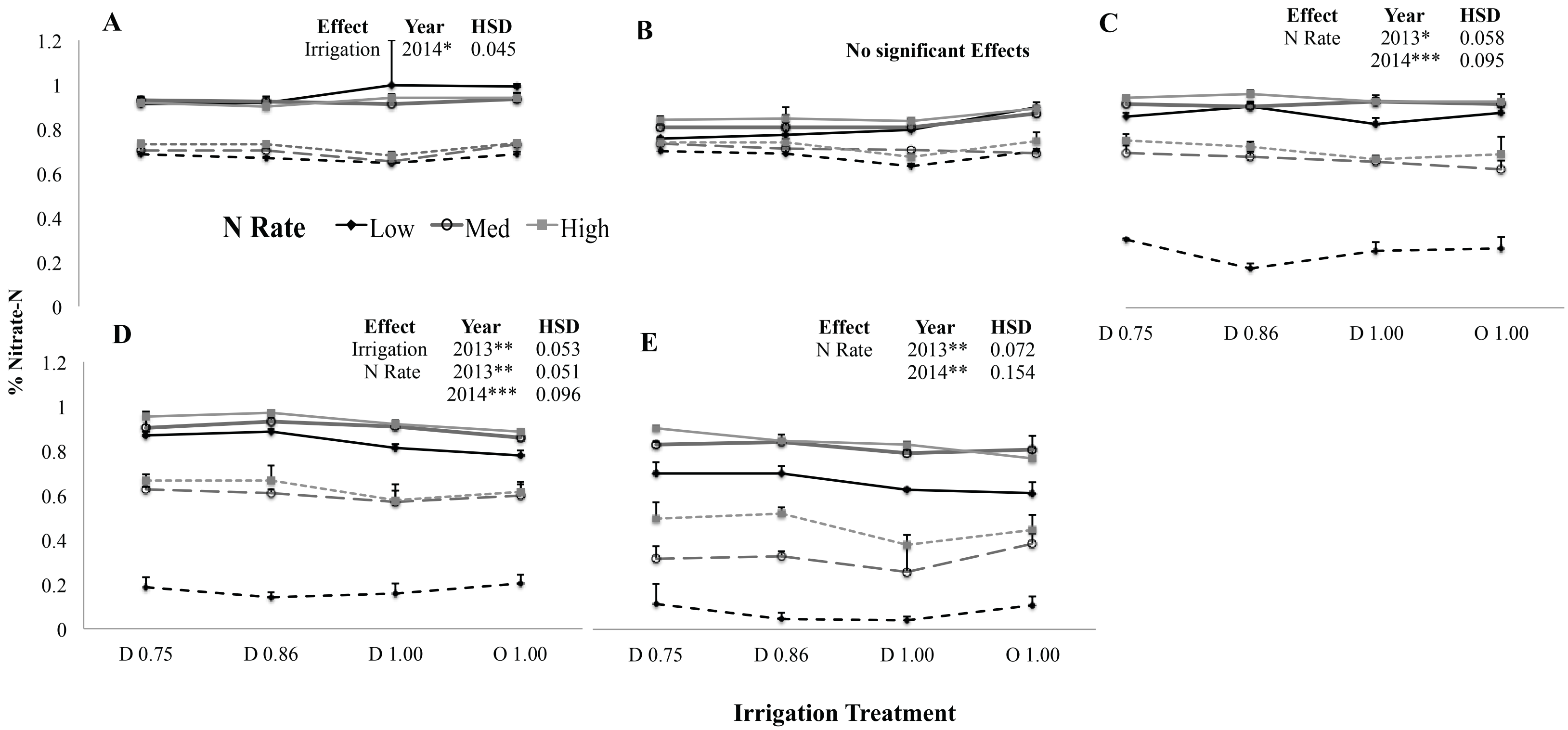

Figure 1 Petiole NO_3-N concentrations for five time points – 20 (**A**), 30 (**B**), 40 (**C**), 50 (**D**), and 60 (**E**) days after emergence (DAE) in 2013 (**solid lines**) and 2014 (**dashed lines**) as influenced by irrigation treatment and N rate. Values are the mean of NO_3-N concentration for irrigation and nitrogen rate treatment. N rates of low, medium and high refer to 202, 291 and 336 kg ha^{-1}. Error bars represent standard error of the three-replicate mean. Significant effects are shown for main affects at each time point at a *p*-value of less than 0.05 (*), 0.01 (**) and 0.001 (***).

APPENDIX A

HYDRUS 2D/3D Modeling of Soil Wetting Patterns under Three Emitter Spacings

Table A Soil characteristic, initial wetting area, and flow rate assumptions for HYDRUS 2D/3D model (PC-Progress Ver. 2.04)

Model Assumptions		
Soil Characteristics		
	Soil Type	Sand
	Available Water Storage (cm cm^{-1})	3.3
	% Organic Matter	0.65
	% Clay	3.6
	% Sand	91.2
	% Silt	91.2
	Water Content 15 Bar (% Moisture)	3.4
	Water Content 1/3 Bar	9.4
	Saturated Hydraulic Conductivity (μm s^{-1})	92
	Available Water Capacity (cm cm^{-1})	0.07
	EC (dS m^{-1})	0.1
Other		
	Initial Wetting Area Radius (cm)	4
	Flow Rate (cm h^{-1})	18.11

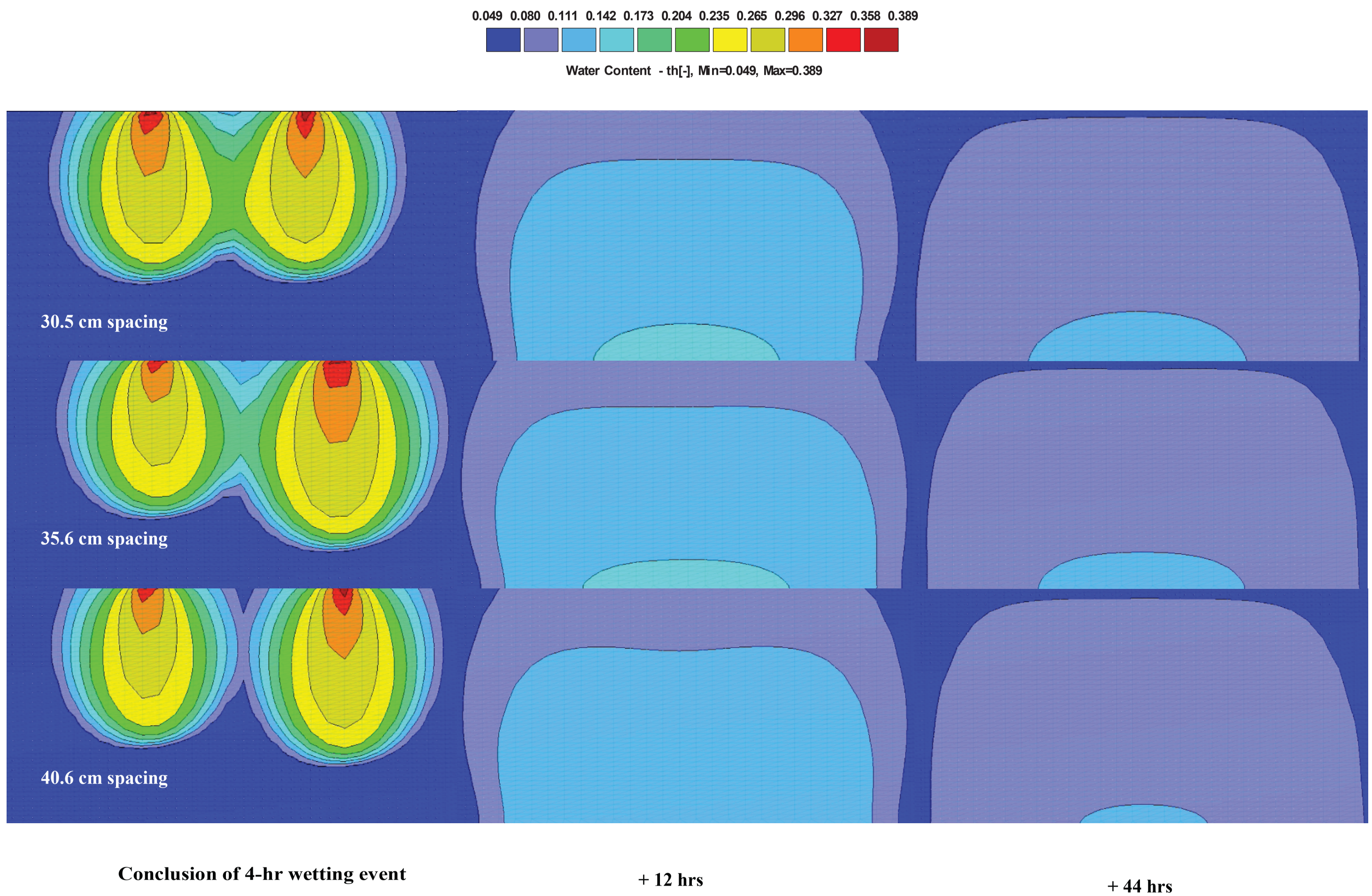

Figure A Graphic output from the Hydrus 2D/3D (PC-Progress Ver. 2.04) simulation model depicting soil-wetting patterns under three spacings at the conclusion of a four-hour irrigation event, 12 hours, and 44 hours following conclusion. Irrigation treatments were drip at 75% of crop evapotranspiration (ET_c) – 40.6 cm spacing, drip at 86% of ET_c – 35. 6 cm spacing, and drip at 100% of ET_c – 30.6 cm spacing. We assumed a flow rate of 18.11 cm h^{-1} and an initial 4 cm radius wetting area.