COMPARISON OF SITE-SPECIFIC AND CONVENTIONAL UNIFORM IRRIGATION MANAGEMENT FOR POTATOES

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ABSTRACT. *Site-Specific Irrigation Management (SSIM) can be defined as irrigation management (depth, timing) based on crop need to defined sub-areas of a field referred to as management zones. Implementation of SSIM will require additional irrigation system hardware, labor, and information on soil and/or plant water status in each management zone. Costs associated with these additional requirements will need to be offset by increased receipts from improved crop yield and quality in order for the technology to be adopted by producers. The potential for SSIM to increase crop yield, quality, and economic return has not been evaluated in field studies. Crops such as potatoes, for which yield and quality are highly sensitive to soil water availability, are most likely to show an economic benefit from site-specific irrigation management. A two-year field study was conducted to evaluate the potential for SSIM to increase yield and quality of potatoes relative to Conventional Uniform Irrigation Management (CUIM). Near real-time soil water content was used to schedule irrigations under both irrigation management treatments. Field average water application was nearly the same for the irrigation management treatments, 503 mm (19.8 in.) in 2001 and 445 mm (17.5 in.) in 2002. In both study years, tuber yield distributions trended 4% greater under site-specific irrigation management but were not significantly different ($p < 0.05$). Total tuber yield per unit of water applied from irrigation and precipitation was 4% greater in 2001 and 6% greater in 2002 under SSIM. Based on a local tuber quality adjusted potato processing contract price structure, the trend in gross income averaged across the field site was \$159/ha (\$65/acre) greater with SSIM. This increase in gross income is likely about half the actual cost of commercial site-specific irrigation technology. The required 3- to 5-year crop rotation for potato disease management means that the site-specific irrigation system needs to be mobile or an economic benefit must also be realized from other crops in the rotation. The economic benefit of SSIM needs to be increased or realized for other crops in the rotation for it to be an economically viable technology in potato production systems in Idaho.*

Keywords. *Irrigation, Center pivot, Potato, Irrigation scheduling, Irrigation control.*

Excessive and deficit soil water availability during the growing season normally has a substantial adverse affect on crop yield and quality. In irrigated agriculture, proper water application depth and timing relative to crop growth and development is paramount for optimum economic return and maximum water use efficiency. Traditional studies of crop response to water typically have reported values of means across replications in space and employed statistical designs to block spatial influences that are inherently present. Conventional Uniform Irrigation Management (CUIM) which treats the field uniformly in terms of water application depth and timing based on mean values of crop response to water and evapotranspiration, ignores spatial variability in crop response to water and may result in both excess and deficit water availability and sub-optimal economic return at some field locations. This realization along with successful commercialization of other site-specific application technologies in irrigated agriculture has increased interest in the concept of Site-Specific Irrigation Management (SSIM) where irrigation management (depth, timing) is independently applied to sub-areas of the field called management zones.

Implementation of SSIM will require additional irrigation system hardware, labor, and information on soil and/or crop water status in each management zone. Costs associated with these additional requirements will need to be covered by increased receipts from improved crop yield and quality in order for the technology to be adopted by producers. Site-specific irrigation management will not likely be an economically viable practice for all crops and all growing conditions. However, it may be universally beneficial in regards to reducing the impact of irrigated agriculture on regional water resources through improved field-scale water use efficiency and reduced localized leaching of nitrogen from the crop root zone.

The economic requirement of increased receipts to offset increased irrigation costs limits site-specific management to commodities such as potatoes where yield and quality are highly sensitive to root zone water availability (Wright and Stark, 1990) and the commodity price structure is heavily

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Submitted for review in May 2005 as manuscript number SW 5909; approved for publication by the Soil & Water Division of ASABE in June 2006. Presented at the 2002 ASAE Annual Meeting as Paper No. 022175.

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dependent upon crop quality. In Idaho, which provides more than 25% of total U.S. fall potato production, sales contracts for processing potatoes normally include a base price plus tuber quality incentives and disincentives, thus total crop receipts are strongly influenced by soil water availability throughout the growing season.

Center pivot irrigation is predominately used for irrigated potato production in the Pacific Northwest of the U.S. Center pivot irrigation systems provide a natural platform upon which to develop site-specific irrigation technologies due to their current and increasing usage and high degree of automation. Experimental center pivot and lateral-move irrigation systems equipped to implement SSIM have been reported in the literature (e.g. Fraisse et al., 1995; Evans et al., 1996; King et al., 1996; Sadler et al., 1996; Harting, 1999; Perry et al., 2003). The emphasis of these previous studies has been on control systems and hardware for achieving spatially variable water application along the irrigation system length. In each case, spatially variable water application was successfully achieved. However, many issues such as system reliability, management, profitability, and environmental benefits need to be addressed before commercialization and producer adoption can be expected.

Very few studies have been conducted to evaluate the profitability of SSIM thus far. Ritchie and Amato (1990) used a simulation approach and 30 years of weather data to compare SSIM and CUIM in a 4.6-ha (11.4-acre) field with pre-defined management zones based on lowest, highest, and intermediate levels of available water holding capacity (AWHC). SSIM resulted in the best management option in terms of yield but not water use. Watkins et al. (2002) used a simulation approach to evaluate the economic and environmental benefits of SSIM for seed potatoes in Idaho. They concluded that SSIM was more likely to be both economically and environmentally beneficial than variable rate nitrogen application for the study conditions. Watkins et al. (2002) acknowledged that the model was not calibrated to simulate nitrogen losses and neither yield nor nitrogen loss predictions were validated. Sensitivity analysis of the results showed that a small increase in estimated costs for SSIM over CUIM would result in the latter being more economical. Nijbroek et al. (2003) used a process-oriented crop model for soybeans to compare the gross margin of SSIM versus CUIM for a 9.94-ha (24.5-acre) field delineated into five irrigation management zones based on AWHC. The simulation procedure was applied using 25 years of climatic data and 10-year low market price for soybeans. Yield, water use, and leaching were not significantly different ($p \leq 0.05$) between SSIM and CUIM. Over the 25-year simulation period, SSIM tended to provide a \$16/ha (\$6/acre) greater gross margin. However, the increased cost of equipment, maintenance, and management associated with implementation of SSIM was not considered in computing gross margin. These costs would likely be greater than \$16/ha, thus CUIM would result in greater net return. Oliveira et al. (2005) also used a simulation approach to evaluate the economic return of site-specific drip irrigation management for tomatoes in Tennessee. Based on 30 years of historical climate data they found that CUIM using an area weighted AWHC to schedule irrigations versus SSIM arrangements with as many as five management zones did not require significantly different ($p \leq 0.05$) amounts of water. The CUIM strategy based on the soil with the lowest AWHC resulted in the highest net return.

Sadler et al. (2002) conducted a three-year field study to measure the mean response of corn to irrigation and compare variation in crop response within and among soil map units. Variation in crop response to irrigation was significant both between and among soil map units. Over the three-year study, the optimum irrigation amount varied from 61% to 120% of the irrigation base rate calculated as 100% of evapotranspiration minus precipitation. One conclusion of the study was that achieving optimum SSIM based on *a priori* information will be a significant challenge. Spatial variation in crop response to irrigation by year, soil map unit, and within soil map unit highlighted the need to use empirically derived site-specific crop response data to adequately simulate crop growth to SSIM in any economic analysis. The study of Sadler et al. (2002) represents the only known data set of empirical site-specific crop response to water. It is not feasible to develop empirical crop response relationships for all crops, conditions, and locations in order to assess the economic return from site-specific irrigation management. Thus, field experimentation of site-specific irrigation management based on real-time measurements of soil and/or crop water status will play a substantial role in evaluating the economic and environmental benefits of site-specific irrigation management.

In each study comparing SSIM and CUIM, spatial variability in AWHC was considered as the only factor influencing crop yield and the basis for needing SSIM. All other sources of yield variability such as genetic factors, biotic factors including pests, diseases, and weeds, and nutrient availability was held constant at optimum levels. In reality, many factors influence crop yield and quality besides soil water availability, although it generally has a predominant adverse affect when well outside the optimum range.

Redulla et al. (2002) investigated the causes of within-field spatial variability of potato yield in a 3-year field study. Four commercial uniformly managed potato fields ranging in size from 30 to 40 ha (74 to 99 acre) were soil sampled on a 0.4-ha (1-acre) grid interval prior to planting. The soil samples were analyzed for nitrate-N, ammonium-N, P, K, organic matter, pH, and texture. Four or five days before commercial harvest, potato yield components were measured at each soil sampling location. Correlation and step-wise regression analysis were conducted to test relationships between soil-based and yield variables. Only 31% to 41% of the variability in potato yield was accounted for by measured soil variables. Negative relationships with sand fraction and positive relationships with clay fraction were found in three of the four fields. Yield was negatively correlated with pH in three of the four fields. This negative correlation was believed to be an indicator of the variability in P availability, which is highly pH dependent. In summary, Redulla et al (2002) found that soil texture had the most significant impact on yield. They concluded that this was most likely an indirect relationship as soil texture is related to AWHC, and hence, soil water availability. The low correlation between yield and measured factors was attributed to unmeasured variables such as irrigation uniformity, soil depth, and pest pressure from weeds, insects, and diseases. They suggested that further studies should include *in-situ* monitoring of soil water availability as many factors associated with potato yield and quality are implicitly related with soil water availability.

The underlying thesis of CUIM is that soil water availability must remain within an established optimum range throughout the growing season for maximum crop yield and quality. However, this does not alone ensure maximum yield and quality as many other factors can affect crop yield and quality. As a first step to field experimentation, site-specific water management based on site-specific soil water monitoring to maintain soil water content within an established optimum range throughout the growing season is the basis for the current research. The objectives of this study were to compare SSIM against CUIM based on continuous soil water monitoring and evaluate the potential increase in potato yield, quality, and resulting increase in crop receipts, if any.

MATERIALS AND METHODS

The field study was conducted during the 2001 and 2002 growing seasons using a four-span 191-m long (628-ft) site-specific center pivot system on the University of Idaho Aberdeen Research and Extension Center (44.493° N, 112.973° W). King et al. (2005) and Wall and King (2005) provide details of the center pivot system and the Distributed Control and Data Acquisition System (DCADAS) for real-time site-specific irrigation management. Variable rate water application along the center pivot lateral is achieved using two parallel sprinkler packages sized with application rates of 1X and 2X. Solenoid actuated diaphragm values on each sprinkler provide ON/OFF control of each sprinkler to obtain application rates of 0X, 1X, 2X, and 3X along the center pivot lateral using ON/OFF sequencing of parallel sprinklers. The sprinklers are spinning plate spray sprinklers (S3000, w/D6 plates, Nelson Irrigation Co., Walla Walla, Wash.). Each sprinkler is equipped with a 103-kPa (15-psi) fixed pressure regulator. Sprinkler spacing is 4.3 m (14.1 ft) for a given sprinkler package with a 1.4-m (4.7-ft) radial offset between sprinkler packages. The sprinklers are mounted on drop tubes at approximately 1.8 m (6 ft) above ground level. The last sprinkler is located inside the last tower and the center pivot is not equipped with a end gun or overhang beyond the last tower. Valve control is provided by a DCADAS that utilizes power line carrier and low-power radio frequency (RF) communication media to link system mounted controls and in-field stationary data loggers to a master control computer. The DCADAS consists of network nodes at each center pivot tower for valve control and RF communications to upload logged soil water content and water application data from in-field sensors when the center pivot lateral is within RF range. The data is stored at the master control computer located at the pivot point and downloaded to a portable computer for analysis and site-specific irrigation scheduling decisions.

One-half of the 14.7-ha (36-acre) square field area was soil sampled using a 0.09-ha (0.23-acre) hexagonal [30.5-m (100-ft)] grid pattern. Soil samples were collected along the field perimeter to facilitate modeling of soil texture spatial variation resulting in a total of 88 sampling locations. Each grid soil sample was a composite of soil samples collected 5 m (16.4 ft) in each principle direction from the grid point. Soil samples were collected from the upper 0.6 m (2 ft) of the soil profile in 0.3-m (1-ft) depth increments. Soil particle fractions (sand, silt, clay) of each soil sample were determined using the hydrometer method (Gee and Bauder, 1986). Block kriging, which uses generalized linear regression techniques for minimizing an estimation variance as defined by a prior model for covariance that represents the spatial dependence between sample locations (Deutsch and Journel, 1992), was used to model the spatial distribution of soil particle fractions (sand, clay) on a smaller grid basis. Block kriging software Gstat (Pebesma and Wesseling, 1998), which is included as a module within the GIS software package IDRISI (Clark Labs, Clark University, Worcester, Mass.) was used to model the spatial distribution of soil particle fractions. Block size was 7.6 × 7.6 m (25 × 25 ft) and the discretizing grid was 4 × 4.

The modeled spatial distributions of soil sand and clay fractions in the top 0.3 m (1 ft) of the soil profile for the 7.3-ha (18-acre) study site are shown in figures 1 and 2, respectively. The measured sand fraction ranged from 14.0% to 72.9% and measured clay fraction ranged from 11.3% to 28.3%. The modeled distribution of sand fraction ranged from 11.7% to 73.8% and the clay fraction from 12.2% to 26.9%. The measured clay fraction was highly negatively correlated with measured sand fraction with a correlation coefficient of 0.92. The irrigation system pivot point is located along the east field boundary midway between the north and south boundaries, which is also the general location of the soil with the greatest sand fraction.

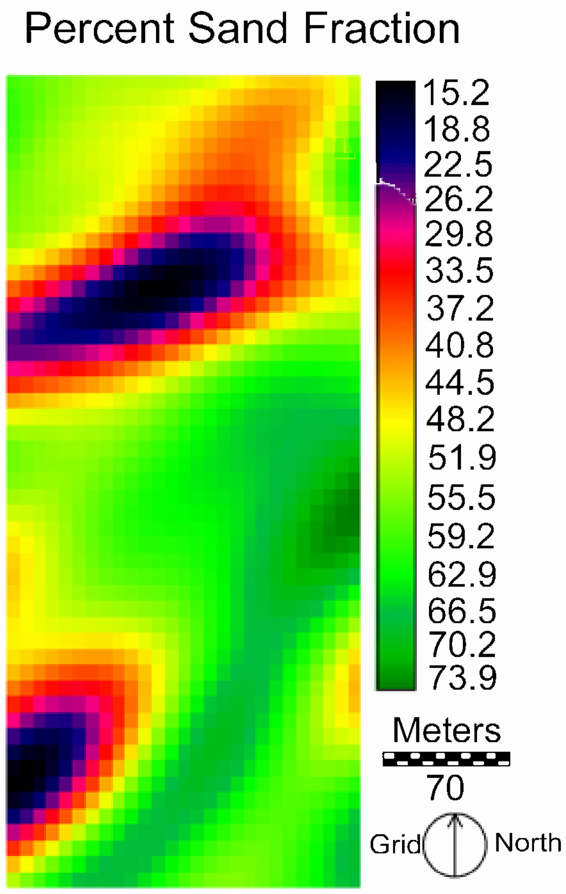

Figure 1. Modeled spatial distribution of soil sand fraction percentage across study field site.

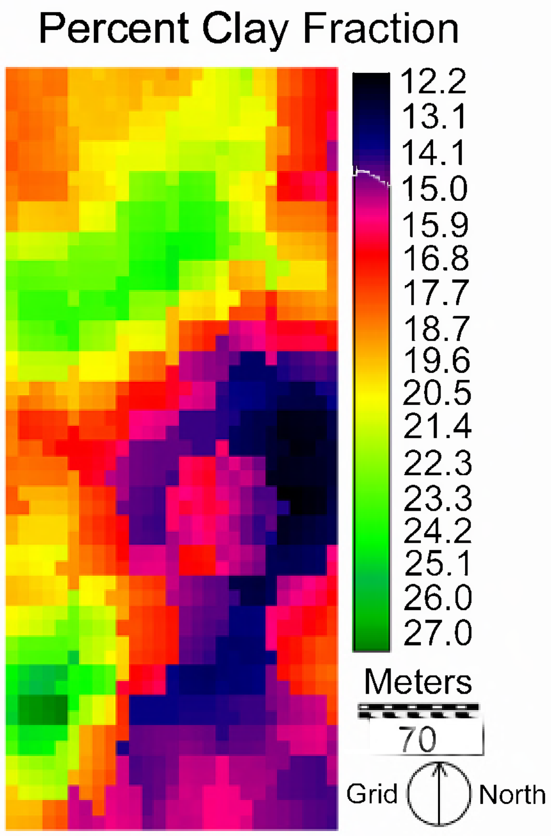

Figure 2. Modeled spatial distribution of soil clay fraction percentage across study field site.

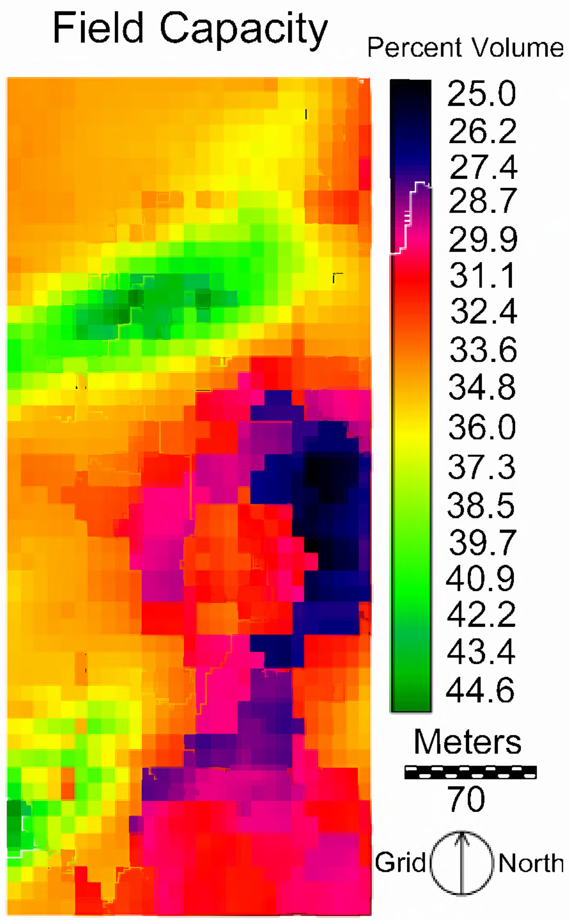

Figure 3. Modeled spatial distribution of soil water content at field capacity (FC) across study field site.

The spatial distribution in volumetric soil water content at field capacity (FC) for the study site was estimated based on a derived relationship between soil particle fractions (sand, clay) and *in-situ* FC tests (Cassel and Nielsen, 1986) across the field site. The *in-situ* FC tests involved building a berm around a 1- × 1-m (3.3- × 3.3-ft) soil area and ponding water to a depth of at least 20 cm (8 in.) inside the bermed area. The bermed area was then covered with white plastic to eliminate surface evaporation. After 48 hours the white plastic was removed and the volumetric water content of the top 30 cm (12 in.) measured with a CS615 soil moisture sensor (Campbell Scientific, Logan, Utah). Six soil water content measurements were taken within the bermed soil area and averaged to represent FC at that location. *In-situ* FC tests were conducted at 12 grid point locations across the field site where soil particle fractions were measured. The test locations were selected to span the ranges in soil particle fractions measured across the study site. The relationship between measured soil particle fractions and FC was modeled with a multiple linear equation using percent sand and clay soil particle fractions. The resulting equation with an R^2 of 0.88 is:

$$FC = -18.08 - 0.87 \times sand + 7.87 \times clay + 0.008 \times sand^2 - 0.20\ clay^2 \quad (1)$$

where FC is the volumetric soil water content in percent, sand is the soil particle sand fraction in percent, and clay is the soil particle clay fraction in percent. The spatial distribution of FC based on equation 1 is shown in figure 3. The range in estimated FC is 25% to 44.6%.

Selection of the CS615 soil moisture sensor for use in this study was based on a comparison of CS615 measurements with Time Domain Reflectometry (TDR) measurements using a Trace System 1 (Soil Moisture Equipment Corp., Santa Barbara, Calif.). Soil water content measurements in the top 30 cm (12 in.) of the soil profile were taken at each of the 88 grid point locations where soil samples were collected. Soil water content measurements with both sensors were taken 3 m (10 ft) in each principle direction from the grid point. The four measurements at each location were averaged and the linear relationship between the average values was determined. Measured TDR volumetric soil water contents ranged from 13.7% to 28.7%. The linear regression relationship between TDR and CS615 measurements was $Y = 0.54 + 0.98 \times X$ with an R^2 of 0.92. The slope of the regression equation was not significantly different ($p \leq 0.01$) from 1.0. Based on this result, the CS615 was judged as a good sensor for measuring soil water contents at this study site. Use of the CS615 sensor in the *in-situ* FC measurements provided a sensor specific calibration of FC values for the study site. The CS615 sensor used to develop the soil water content relationships was considered to be representative of CS615 sensor response.

The spatial distribution of volumetric soil water content at permanent wilting point (PWP) for the study site was estimated based on percent sand and clay fractions in the soil using the general relationships of Rawls et al. (1982). Potatoes are a relatively water sensitive crop which generally require soil water contents above 65% AWHC for maximum yield and quality. Corresponding critical soil water potentials generally range from -75 to -25 kPa (-0.75 to -0.25 bar) as soil texture ranges from silty clay to sand, respectively (King and Stark, 1997). Thus, soil water potentials under well-managed irrigated conditions are normally above -75 kPa (-0.75 bar) during the active growing period for potatoes. The general shape of a soil water release curve with the characteristic rapid decline in soil water content at soil water potentials that plants can readily use occurs above soil water potentials of -200 kPa (-2 bar). Consequently, actual soil water content at PWP [-1500 kPa (-15 bar)] has little influence on soil water potentials above -100 kPa (-1 bar). This is well demonstrated in the equations presented by Rawls et al. (1982), which found that percent sand and clay fractions and organic matter explained 87% of the variability in soil water content at soil water potentials of -33, -60, and -100 kPa (-0.33, -0.60, and -1.0 bar). This, plus the cost and measurement uncertainty associated with laboratory determination of PWP soil water content of small soil cores was the reason for using estimates of PWP soil water contents based on regression equations developed by Rawls et al. (1982). The resulting spatial distribution of PWP is shown in figure 4 and ranges from 10% to 18.4% soil water content by volume.

The spatial distribution of AWHC based on FC and PWP (figs. 3 and 4) is shown in figure 5. The range in AWHC is 13.9 to 28.4 cm/m (1.67 to 3.4 in/ft). Thus, AWHC varies by factor of two over the study field. The irrigation system pivot point is located in the area of lowest AWHC. The first span of the center pivot was not used in this study due to the small area of coverage. Thus the soil with the lowest AWHC was not included in the study.

In each study year, one 2.9-ha (7.1-acre) quadrant of the center pivot irrigation system was divided into 18 arbitrary irrigation management zones (fig. 6). Different quadrants were used each year. The 18 arbitrary irrigation management zones were paired according to the most similar soil texture in the top 0.3-m (1-ft) soil profile as shown in figure 6 to provide nine experimental blocks. Irrigation treatments of SSIM and CUIM were randomly assigned to the two experimental units in each block (paired treatment comparison). The resulting experimental design is a randomized complete block with two treatments and nine replications. Layout of the experimental design in the two quadrants is shown in figure 6.

An experimental plot measuring 6.5 m (7 rows) × 10 m (21 × 33 ft) was established in each experimental unit located approximately three-quarters of the radial span length outward from the pivot point under a particular span. The minimum distance between the boundary of the experimental plot and the boundary of the irrigation management zone (fig. 6) was 7.6 m (25 ft) and the wetted radius of the sprinklers was 6.4 m (21 ft), which allowed the desired water application to the experimental plot to be attained. A custom data logger (King et al., 2005) recorded soil water content at two depths and water application using a tipping bucket rain gage at 30-min intervals. The opening of the tipping bucket rain gage was approximately 0.76 m (30 in.) above ground level. The instrumentation was installed immediately following crop emergence. Soil water content was measured using the CS615 sensors. The CS615 sensors measure average soil water content of a cylindrical volume about 5 cm (2 in.) in diameter and 30 cm (12 in.) in length. The sensors were installed in the crop row at 45° inclines to measure soil water content at depths of 2 to 23 cm (1 to 9 in.) and 20 to 41 cm (8 to 16 in.). The soil water sensors were placed about 5 cm (2 in.) offset of the crop row and adjacent to an actively growing potato plant. An installation jig was used to ensure that the sensors were installed at identical depths and orientation in all experimental plots. The location of the center of each experimental plot was recorded using GPS. The soil particle fractions FC, PWP, and AWHC based on GPS locations of each plot are listed in table 1.

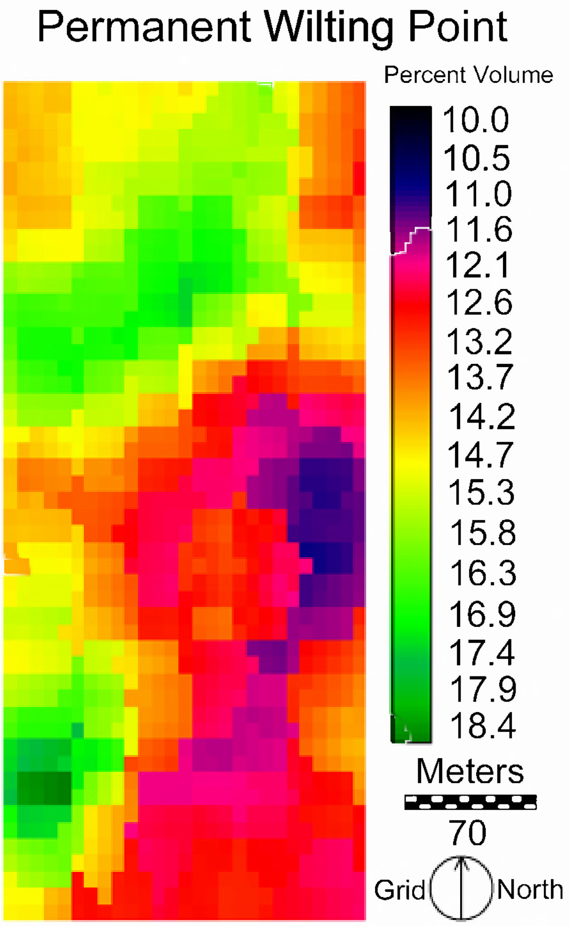

Figure 4. Modeled spatial distribution of soil water content at permanent wilting point (PWP) across study field site.

A site-specific irrigation decision support model was used to determine the irrigation requirement of each irrigation treatment in each experimental unit. The irrigation decision model used a conventional soil water balance in combination with estimated potato evapotranspiration (ET) to compute the minimum irrigation amount needed to maintain 65% available soil moisture (ASM) in the 41-cm (16-in.) soil profile until the next scheduled irrigation. Potato ET was obtained from published regional values of daily crop evapotranspiration (USBR, 2004). Daily potato ET was computed as potential ET for an alfalfa reference crop based on climatic parameters from a network of weather stations

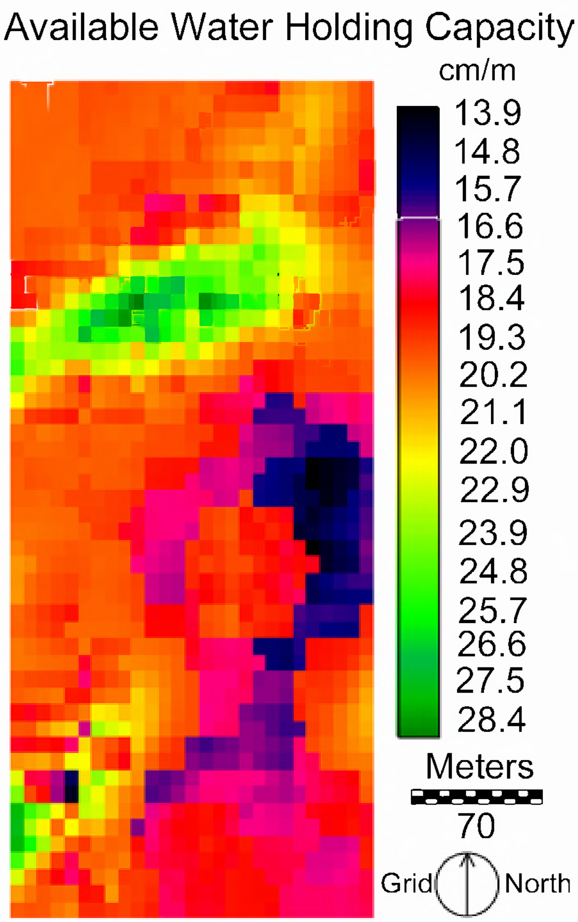

Figure 5. Modeled spatial distribution of available water holding capacity (AWHC) in cm/m across study field site.

using a modified Penman equation (Wright, 1982) multiplied by a potato crop coefficient. Climatic data was from a weather station located within 1.6 km (1 mile) of the field site. The soil water balance was used to account for actual potato ET being less that estimated potato ET due to site-specific factors. For example, assume estimated ET is 7 mm/day (0.28 in./day) or 14 mm (0.55 in.) for two days until the next scheduled irrigation. Thus, without site-specific information on soil water content, the irrigation depth would need to be 14 mm. However, if soil water data shows that 9 mm (0.35 in.) is available above the lower limit (65% ASM), then only 5 mm (0.2 in.) needs to be applied to sustain 65% ASM until the next scheduled irrigation. Applying this soil water balance throughout the season allows irrigation to follow actual crop ET without actually knowing the value of crop ET while assuring that sufficient water is available until the next irrigation event. However, this approach requires soil water content measurements that are representative to true field conditions. If they are biased or incorrect, excess or deficit soil water conditions will prevail. Irrigation frequency was once or twice weekly at the beginning and end of the growing season and three times weekly from mid-June through mid-August.

The overall objective of this study was to investigate the increase in gross return from SSIM relative to CUIM (marginal gross return) for irrigated potato production in Idaho. A true evaluation of marginal gross return requires that the CUIM treatment be optimized for maximum gross return in order to obtain the true marginal economic return from SSIM. The simulation studies of Nijbroek et al. (2003) and Oliveira et al. (2005) found no significant differences ($p \le 0.05$) in economic return between SSIM and a CUIM strategy based on area weighted AWHC or largest area AWHC. The CUIM strategies evaluated included irrigation scheduling based on area weighted AWHC, soil with minimum AWHC and soil with highest yield. The CUIM strategy that resulted in the highest yield was irrigation scheduling based on the soil with minimum AWHC. However, the yield model used by Oliveira et al. (2005) did not account for a yield reduction due to over-irrigation. Russet Burbank potatoes exhibit a pronounced decrease in yield under over-irrigation (Wright and Stark, 1990; King and Stark, 1997). This decreased yield response is attributed to poor soil aeration, leaching of mobile nutrients from the root zone, and increased disease incidence. Excessively wet soil conditions in potatoes substantially increase the incidence of potato diseases such as Early Die, Early Blight, Late Blight, White Mold, and Pink Rot all of which adversely affect yield, and in some cases, especially with Pink Rot, can lead to serious storage problems and losses from secondary bacterial infection (Nolte et al., 2003). For these reasons, irrigation scheduling for the soil with the minimum AWHC (earliest stress) is not a common practice in irrigated potato production due to the greater potential loss from maintenance of excessively wet soil conditions than localized areas of water stress. For this reason, the CUIM strategy used in this study was to base irrigation depth on the average irrigation requirement for the study field. The

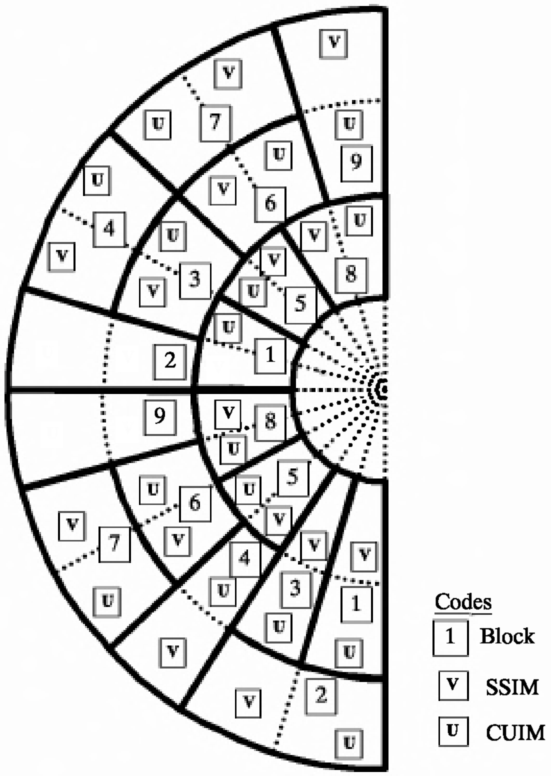

Figure 6. Diagram of experimental design for two quadrants used in two-year potato irrigation management field study comparing conventional uniform irrigation management (CUIM) and site-specific irrigation management (SSIM). The heavy lines show blocks in experimental design and dashed lines separate treatments.

Table 1. Soil physical properties in each experimental unit of each pair-wise treatment comparison (block) of site-specific irrigation management (SSIM) and conventional uniform irrigation management (CUIM) in the two-year field study.

	SSIM					CUIM				
Block	Sand (%)	Clay (%)%	PWP (%)	FC (%)	AWHC (cm/m)	Sand (%)	Clay (%)	PWP (%)	FC (%)	AWHC (cm/m)
2001 Study										
1	50.7	17.0	13.5	33.2	19.7	53.6	15.5	12.7	31.0	18.3
2	58.0	15.3	12.6	30.6	18.0	62.3	14.7	12.3	29.8	17.4
3	63.5	15.8	12.9	31.8	18.9	61.7	14.0	12.0	28.3	16.3
4	68.4	14.2	12.1	29.6	17.5	67.7	14.5	12.2	30.1	17.8
5	68.1	13.1	11.5	26.9	17.2	67.7	15.3	12.6	31.6	18.9
6	55.4	15.3	12.6	30.6	18.0	57.3	15.7	12.8	31.3	18.4
7	42.4	21.6	15.8	34.9	19.1	40.8	19.8	14.9	36.1	21.3
8	57.3	15.7	13.3	32.9	19.6	63.6	16.6	12.8	31.7	18.9
9	60.6	14.7	12.3	29.6	17.3	52.9	20.0	15.0	34.3	19.3
2002 Study										
1	63.5	15.5	12.7	31.3	18.6	62.3	15.1	12.5	30.5	18.0
2	53.9	17.9	13.9	33.7	19.8	46.4	17.7	13.8	34.3	20.5
3	42.5	20.6	15.3	35.5	20.2	20.2	24.3	17.1	39.8	22.7
4	19.2	22.3	16.1	43.4	27.3	37.1	21.0	15.5	36.7	21.2
5	59.5	15.0	14.0	33.8	19.9	53.0	18.0	12.5	30.1	17.7
6	19.2	24.0	17.0	40.9	23.9	32.6	20.9	15.4	38.3	22.8
7	41.9	20.7	15.3	35.6	20.3	41.2	22.6	16.3	34.1	17.9
8	50.8	18.6	14.3	34.3	20.3	47.7	20.0	15.0	34.8	19.8
9	43.6	18.4	14.2	35.3	21.1	45.2	16.7	13.3	33.6	20.3

irrigation amount applied to the CUIM treatment was computed as the average irrigation requirement from the irrigation decision model for the nine experimental units assigned to this irrigation treatment. The travel speed of the center pivot was set as that needed to apply the required irrigation depth to the CUIM treatment using the 2X application rate. This approach allowed less or more water to be applied to the SSIM treatments using 0X, 1X, or 3X application rates as well as the same amount using the 2X application rate. For example, if the CUIM treatment required a 15.2-mm (0.6-in.) irrigation application, then the available application depths for the SSIM treatments were 0, 7.6, 15.2, and 22.6 mm (0, 0.3, 0.6, and 0.9 in.). The actual depth applied to the SSIM treatment was rounded to the nearest available application depth determined from the irrigation decision model.

For this field study, the irrigation requirement in each experimental unit was needed prior to irrigation to calculate the average irrigation depth for the CUIM treatment. To accomplish this, the center pivot system was run dry over the field site to upload data from the soil moisture sensors using the RF communication link with the pivot DCADAS network. The time required to pass over the field and upload the data was 3 to 4 h. The soil moisture data was stored at DCADAS network node located at the pivot point. This data was downloaded to a personal computer and used with the irrigation decision support model to compute the irrigation requirement for each experimental unit. The mean irrigation requirement for the CUIM treatment was then calculated. The computed irrigation requirements were then used to develop a water control map for irrigation to each treatment of each experimental unit. The resulting map was downloaded to the center pivot control computer and irrigation completed.

Russet Burbank potato was planted on 9 May 2001, and 1 May 2002, with a seed piece spacing of 30 cm (12 in.) and row spacing of 91 cm (36 in.). Basin tillage prior to irrigation was used to create small water storage basins in the furrow between crop rows to eliminate water movement down slope. Fertilizer, herbicide, and fungicide applications were applied following University of Idaho potato production guidelines (Stark and Love, 2003). All chemical applications through the irrigation system were done uniformly using the 3X application rate with the minimum required water application according to label guidelines. The crop was harvested on 5 October 2001, and 10 October 2002. Tuber samples from each experimental plot consisted of 9.1-m (30-ft) sections of three crop rows. Tuber samples were weighed, sized, and graded within 30 days of harvest. Specific gravity was determined with the standard weight-in-air/weight-in-water method using a sub sample of U.S. No. 1 grade tubers weighing 170 to 283 g (6 to 10 oz).

The GLM and MIXED procedures of SAS (SAS Institute Inc., 2003) were used for analysis of measured yield parameters. The MIXED procedure was used to accommodate the potential presence of a random effects parameter and residual errors that are not independent with zero mean. When the random effects parameter and residual errors are normally distributed with zero mean, the MIXED statistical model reduces to the traditional linear model with fixed effects (i.e. GLM). The numerical results of the GLM and MIXED procedures were identical indicating that the effects parameter and residual error were normally distributed with zero mean.

RESULTS AND DISCUSSION

Seasonal water application to the CUIM treatment for the 2001 and 2002 growing seasons in relation to estimated seasonal ET (USBR, 2004) is shown in figure 7. Seasonal estimates of potato ET were 648 mm (25.5 in.) in 2001 and 598 mm (23.6 in.) in 2002. Irrigation occurred in both years prior to crop emergence to meet pre-emergence herbicide application requirements. Equal irrigation amounts were applied to both irrigation treatments prior to the first week of July in both years. It takes about a month of crop growth to accumulate spatial differences in available soil water of sufficient magnitude to warrant site-specific irrigation management. Seasonal water application began to diverge from estimated potato ET (fig. 7) in mid-August because actual crop coefficients were less than those used to estimate potato ET.

Seasonal irrigation amounts applied to the two irrigation treatments of each pair-wise comparison in order of increasing average AHWC are shown in figures 8 and 9 for 2001 and 2002, respectively. In 2001, the average seasonal irrigation depth for the SSIM treatment was 503 mm (19.8 in.) which is essentially equivalent to the 503 mm (19.7 in.) applied to the CUIM treatment. The minimum seasonal irrigation depth under the SSIM treatment was 437 mm (17.2 in.) and the maximum depth was 597 mm (23.5 in.). In 2002, the average seasonal irrigation depth for the SSIM treatment was 445 mm (17.5 in.), which is 3% less than the 432 mm (17.8 in.) applied to the CUIM treatment. The minimum seasonal irrigation depth applied under the SSIM treatment was 372 mm (14.6 in.) and the maximum depth was 498 mm (19.6 in.). Variations in SSIM treatment irrigation depths of 86% to 119% of the average depth in 2001 and of 82% to 110% of the average depth in 2002 are within the 61% to

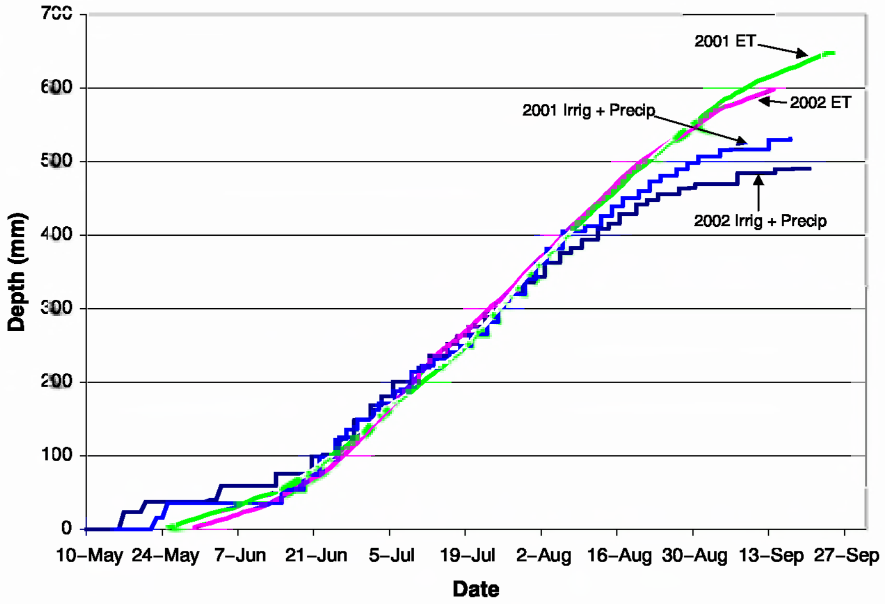

Figure 7. Cumulative estimated potato ET compared to cumulative irrigation plus precipitation under conventional uniform irrigation (CUIM) for both study years.

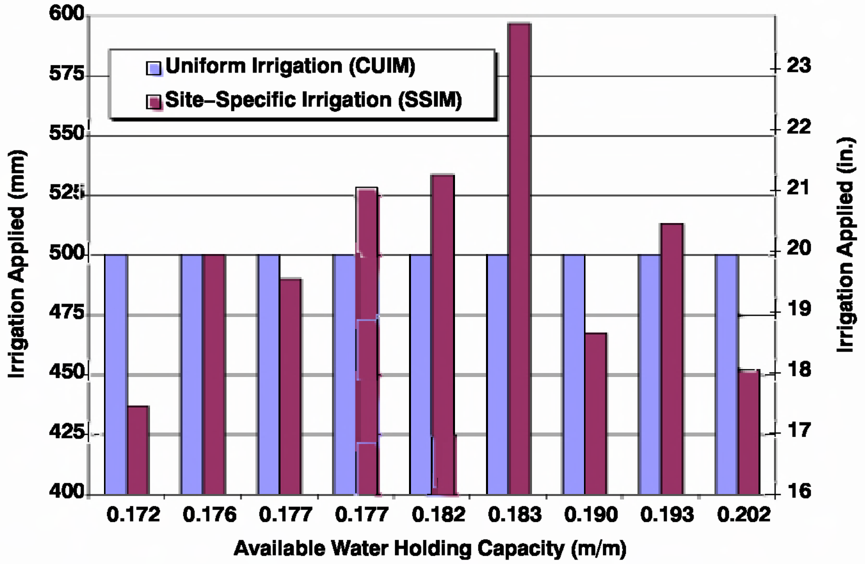

Figure 8. Seasonal irrigation applied to each pair-wise comparison arranged in order of increasing average available water holding capacity for the irrigation management study in 2001.

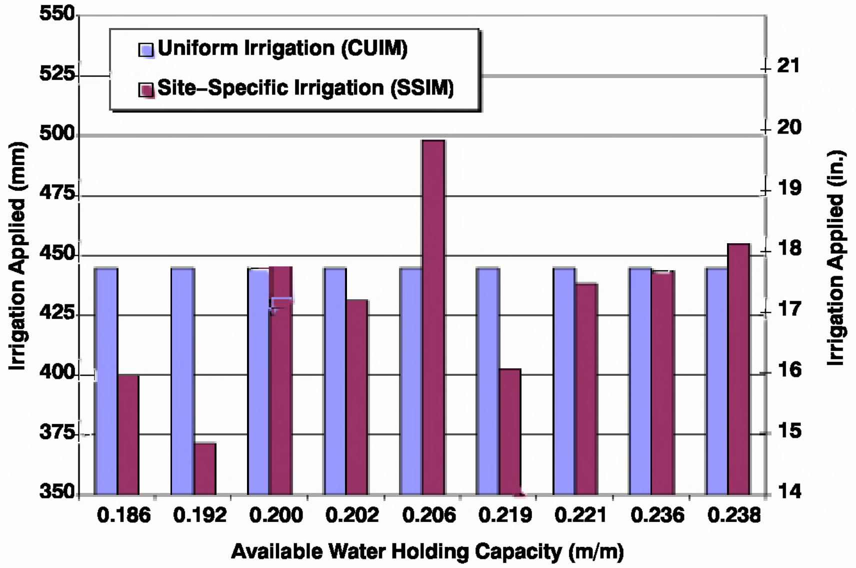

Figure 9. Seasonal irrigation applied to each pair-wise comparison arranged in order of increasing average available water holding capacity for the irrigation management study in 2002.

120% range in optimal water application depth reported by Sadler et al. (2002) for corn over 12 soil map units in South Carolina. The correlation coefficient between pair-wise comparison average AWHC and irrigation application depth was -0.11 in 2001 and 0.40 in 2002. The differences in irrigation depth under the SSIM treatment were largely in response to differences in crop vigor during August and September. Field areas that emerged first were the first to reach canopy closure and the first to begin senescence. Over the length of the growing season, differences in growth rates resulted in about 20- to 25-day difference in time of crop senescence across the study site.

Irrigation treatment effects on potato yield distributions are shown in tables 2 and 3 for 2001 and 2002, respectively. In general, tuber yield distributions were greater for the SSIM treatment in both years, but none were significantly different at the 5% confidence level. Irrigation water use efficiency calculated as total yield divided by seasonal irrigation depth plus precipitation was 0.070 and 0.073 Mg/ha-mm (15.9 and 16.6 cwt/acre-in.) for CUIM and SSIM treatments, respectively, in 2001. It was nearly the same in 2002 at 0.068 and 0.071 Mg/ha-mm (15.3 and 16.2 cwt/acre-in.) for CUIM and SSIM treatments, respectively. Irrigation water use efficiency was not significantly different ($p \leq 0.05$) in either year of the study. However, irrigation water use efficiency averaged over both study years trended 5% higher under the SSIM treatment.

Table 2. Effect of site-specific irrigation management (SSIM) and conventional uniform irrigation management (CUIM) treatments on potato tuber yield distributions in 2001.

	Tuber Yield (Mg/ha)						
Treatment	<114g	114–170 g	170–284 g	>284 g	U.S. No. 1	Mal–formed	Total
CUIM	3.90	6.45	12.25	9.81	28.44	4.99	37.40
SSIM	3.79	7.26	12.63	9.48	29.34	5.64	38.97

Table 3. Effect of site-specific irrigation management (SSIM) and conventional uniform irrigation management (CUIM) treatments on potato tuber yield distributions in 2002.

	Tuber Yield (Mg/ha)						
Treatment	<114g	114–170 g	170–284 g	>284 g	U.S. No. 1	Mal–formed	Total
CUIM	2.38	2.93	7.34	7.59	17.9	12.79	33.14
SSIM	2.82	3.20	9.54	8.73	21.5	9.92	34.26

Total tuber yields for each pair-wise treatment comparison in order of increasing average AWHC in 2001 and 2002 are shown in figures 10 and 11, respectively. In 2001, total tuber yield was greater under the SSIM treatment in six of the nine comparisons. Only for one comparison was total tuber yield substantially greater (9%) under the CUIM treatment. In 2002, total tuber yield was again greater under the SSIM treatment in six of the nine comparisons. Total tuber yield under the CUIM treatment at the two lowest AWHC values was substantially greater (15% and 37%, respectively). Instances where yield under the CUIM treatment was greater than yield under the SSIM treatment in the same comparison could be due to soil water data unrepresentative of actual field conditions or factors unrelated to soil water holding capacity. The CS615 soil water content sensors have a minute sample volume in relation to the size of the experimental plot. The sample volume is also small in relation to the root volume of a single potato plant. This is true for most soil water content sensors. It is quite possible that placement of the soil water sensor was such that it did not represent of the soil water status in the experimental plot. This was apparently the case for the SSIM treatment at 0.192-m/m AWHC during 2002 as the crop visually appeared water stressed in late July, yet measured soil water content remained within the optimum range based on established PWP and FC values. This problem was corrected but not before water stress adversely impacted yield. Eliminating the comparison at 0.192 AWHC from the study analysis does not make the yield distributions statistically significant ($p \leq 0.05$). However, it does make the results very similar to those of 2001 in terms of total yield treatment differences. Correlation coefficients between pair-wise comparison average AWHC and total yield was -0.88 for SSIM and -0.26 for CUIM in 2001 and was 0.51 for SSIM and 0.09 for CUIM in 2002, showing no consistent relationship over the two-year study. Maximum

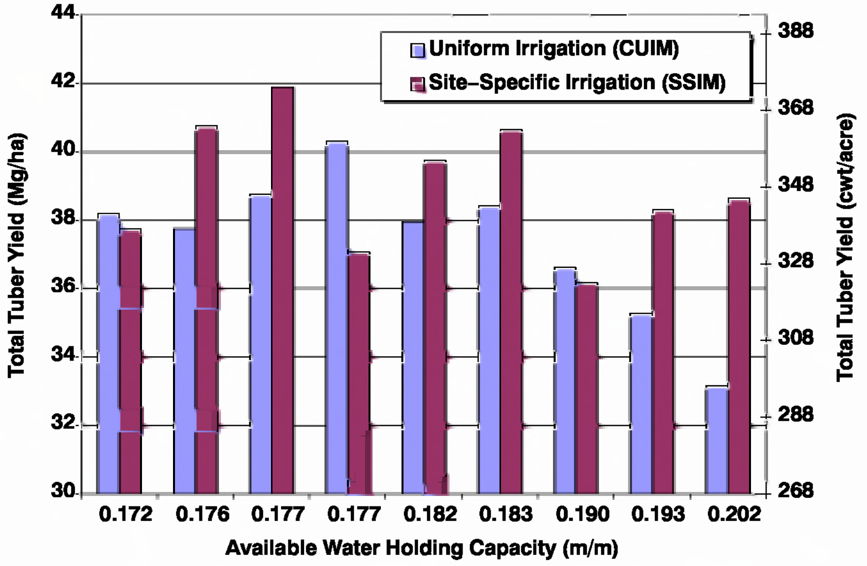

Figure 10. Total tuber yield in each pair-wise comparison arranged in order of increasing average available water holding capacity for the irrigation management study in 2001.

cumulative ET over the 2- or 3-day (weekend) irrigation interval was less than the 35% AWHC water stress limit for potatoes. Thus, there was no water stress due to irrigation interval length in this study and the lack of any consistent relationship between AWHC and total yield is not unexpected. The experimental design was based on the fact that AWHC is a primary factor in irrigation management, consequently the experimental plots were paired based on most similar soil texture. It is quite possible that under near optimum water management, other non-measured factors unrelated to soil texture had a predominate effect on tuber yield. The results of Sadler et al. (2002) suggest that this can easily occur as they found significant differences in corn yield response to irrigation between adjacent blocks within soil map units. Possible sources of spatial variability in potato yield in this field study include spatial variability in disease incidence, nutrient availability, soil temperature, infiltration rate, and irrigation efficiency. The field was treated uniformly in regards to fertilizer application and chemical control of pests. There were likely spatial differences in residual N and N mineralization for the study site. High N availability prior to tuber initiation is known to reduce potato yield because it promotes vegetative growth at the expense of tuber set (Westermann et al., 1988; Errebhi et al., 1998). Redulla et al. (2002) found a negative correlation between potato yield and preplant NO_3N in a uniformly fertilized potato field. They also found a negative correlation between soil pH and potato yield which was attributed to the effect that pH has on soil P availability. The field site used in this study has varying degrees of free lime, which influences soil pH and also influences soil crusting from sprinkler droplet impact. With conventional potato hilling, water that does not immediately infiltrate runs off the potato hill into the furrow between potato rows. The water then infiltrates under ponded conditions. The water has to move laterally and upward into the potato hill where the highest densities of roots are present.

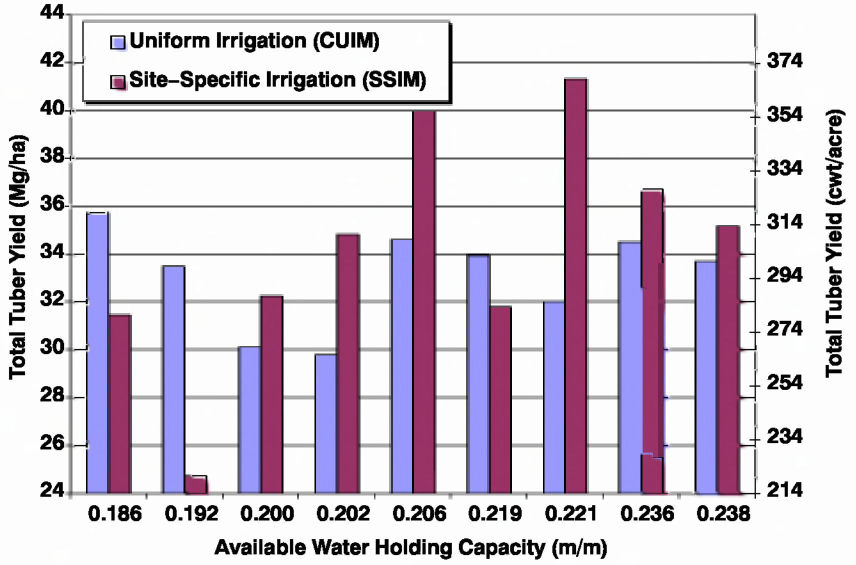

Figure 11. Total tuber yield in each pair-wise comparison arranged in order of increasing average available water holding capacity for the irrigation management study in 2002.

Thus, the more water ponded in the furrow, the more water that moves downward by gravity passing the potato root system. Thus, irrigation efficiency likely varied across the field site. The presence of free lime also influences the color of the soil with areas high in free lime appearing white in color. Thus, the reflectance of solar radiation from the soil surface varies across the field site, leading to spatial variability in soil temperature, especially early in the season. This is likely one reason for the spatial variability in plant emergence across the field site with the darker soil areas having earliest plant emergence. While irrigation and AWHC were controlled in the experimental design, there were other sources of spatial variability present that could affect potato yield.

Gross income under both irrigation management treatments was calculated using the tuber yield distributions shown in tables 2 and 3 and a local tuber quality incentive-based potato processing contract price structure. In 2001, gross income averaged across the field site was \$3690/ha (\$1494/acre) for the CUIM treatment and \$3856/ha (\$1561/acre) for the SSIM treatment, resulting in a trend difference of \$165/ha (\$67/acre) greater under SSIM. In 2002, gross income averaged across the field site was \$3283/ha (\$1329/acre) for the CUIM treatment and \$3435/ha (\$1391/acre) for the SSIM treatment, a trend difference of \$152/ha (\$62/acre) greater under SSIM. Given the high degree of short range spatial variability in yield response to water demonstrated by Sadler et al. (2002) and apparent in figures 10 and 11 from this study highlights the difficulty that can be expected in measuring a significant response in crop yield due to water management alone. The high degree of short range spatial variability in yield response to water highlights the need for a greater understanding of the factors responsible. This understanding will play a significant role identifying water management zones needed to achieve economically viable SSIM.

The \$159/ha (\$65/acre) average increase in gross receipts alone is not sufficient to warrant commercialization of site-specific irrigation technology. The \$159/ha (\$65/acre) is likely about half the retail cost of a commercial system. The required 3- to 5-year crop rotation for potato disease management means that either the site-specific irrigation system needs to be mobile or that an economic benefit must also be realized from other crops in the rotation. In eastern Idaho, possible rotation crops are small grains, sugar beets, and alfalfa, all of which are relatively insensitive to soil water availability compared to potatoes and have deeper root zones allowing greater spatial differences in soil water availability without adverse effects. Site-specific irrigation also increases management costs due to increased data requirements and maintenance of added components to the irrigation system. The results of this study suggest that water savings will be minimal as nearly the same field average amount of water was applied under site-specific irrigation management, only the timing and location was modified.

The results of this field study are consistent with results of other studies of SSIM. Simulation studies of SSIM (Ritchie and Amato, 1990; Nijbroek et al., 2003; Oliveira et al., 2005) found that SSIM tended to increase yield and decrease water use but yield and water use were not significantly different ($p \le 0.05$) from CUIM. In this study yield differences under CUIM ranged from 88% to 108% of average and from 73% to 120% of average under SSIM. The field study of Redulla et al. (2002) found only 30% to 41% of the variability in yield of potatoes in center pivot irrigated fields was explained by measured soil chemical and physical parameters. Sadler et al. (2003) found a 61% to 120% variation in the optimal irrigation amount for corn in southeastern United States. Collectively, these studies suggest that factors other than AWHC can have a substantial effect on yield.

SUMMARY AND CONCLUSIONS

SSIM was compared with CUIM based on near-real time soil moisture monitoring of both management treatments. Field average seasonal water application was nearly equal under both irrigation management treatments. Site-specific seasonal water application varied from 82% to 119% of field average site-specific seasonal water application. In both study years, six of the nine pair-wise treatment comparisons between SSIM and CUIM had higher total yield with SSIM. In both study years, tuber yield distributions trended greater under SSIM but were not significantly different ($p \le 0.05$). Based on a local tuber quality adjusted potato processing contract price structure, the trend in gross income averaged across the field site was \$159/ha (\$65/acre) greater under site-specific irrigation management.

Results from this study and others collectively suggest that AWHC may not be the best or only parameter to consider in delineating irrigation management zones. A systems approach to SSIM will likely be required that takes into account all known factors affecting yield and include them in delineating irrigation management zones and making SSIM decisions.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Cooperative State Research, Education and Extension Service, U.S. Department of Agriculture, under Agreement No. 99-35102-8575.

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