IRRIGATION SCHEDULING METHODS FOR POTATOES IN THE NORTHERN GREAT PLAINS

J. B. Shae, D. D. Steele, B. L. Gregor

ABSTRACT. *The successful irrigation of potatoes requires a knowledge of both irrigation application and scheduling methods. A four-year field study of four irrigation scheduling and application methods for Russet Burbank potatoes was undertaken on a sandy loam soil near Oakes, North Dakota. A randomized complete block statistical design was used to assess the influence of irrigation treatments on total yield, no. 1 grade yield, specific gravity, and total irrigation applied. For the reference treatment, above-ground drip irrigation (AGDI) was used to apply irrigations based on 40% depletion of root zone available water on an area basis. The other treatments were: (1) AGDI, basing scheduling on a crop water stress index (CWSI) of 0.2; (2) subsurface drip irrigation (SDI), basing scheduling on measured soil matric potentials (SMPs) of 30 kPa using a feedback and control system to automate irrigation applications; and (3) AGDI, basing scheduling on SUBSTOR-Potatoes (SUBSTOR) growth model estimates of water use. Because of high relative humidity and intermittent cloudiness, irrigations for the CWSI treatment were also scheduled based on SMP of 30 kPa at 0.3-m depth. Averages for yield (39.7 Mg ha^{-1}), percentage no. 1 grade (76.1%), and specific gravity (1.086) did not differ between treatments. The reference treatment required an average of 220 mm irrigation water each year, significantly higher than the 167 mm for CWSI , the 129 mm for SDI, and the 149 mm for SUBSTOR. Improved irrigation methods can save water without compromising potato yield or quality. Tensiometer-based methods were preferred, while SUBSTOR has limited practicality for irrigation scheduling.*

Keywords. *Growth model, Plant temperature, Soil moisture, Water use efficiency, Drip irrigation.*

Potato production in North Dakota, which was once limited to a narrow band of counties lying inside the fertile Red River Valley, is increasing. The soils in the northern Great Plains outside of the Red River Valley are often sandy with low water storage capacity. Potatoes are a shallow-rooted crop in comparison with many conventional crops of the area (corn and small grains). These facts, coupled with unpredictable and often insufficient rainfall, can result in low amounts of available water for potato use. In order to attain stable potato yields and quality in the northern Great Plains, irrigation is often necessary.

Irrigation scheduling is defined as deciding when to irrigate and how much water to apply. Several types of irrigation scheduling have been documented. Martin et al. (1990) classified methods of irrigation scheduling as belonging to one of two broad groups: soil water balance computations, and soil and/or crop monitoring techniques.

Use of the soil water balance equation for irrigation scheduling has been documented by Stegman (1980), Gardner (1983), Martin et al. (1990), and Heermann et al. (1990). Soil water storage is commonly computed daily using estimates of daily evapotranspiration (ET), percolation, and runoff, and recorded values for precipitation and irrigation. Water balance or *checkbook* methods of irrigation scheduling for potatoes and other crops were presented by Lundstrom and Stegman (1988) for North Dakota, Wright and Bergsrud (1991) for Minnesota, and Werner (1996) for South Dakota. Curwen and Massie (1984), Vitosh (1984), and Larsen (1984) illustrated water balance-based irrigation scheduling techniques for potatoes, each proposing different values of soil moisture depletion at which irrigation should be scheduled.

Crop growth models such as SUBSTOR (Magnusson et al., 1987) have been used to schedule irrigations for potatoes. Perillo et al. (1993) concluded that SUBSTOR could be used in a qualitative sense to predict yield and nitrogen leaching in central Minnesota, but needed “fine tuning” before it could be used quantitatively. Mahdian and Gallichand (1995) in eastern Canada found that SUBSTOR underestimated crop ET during the middle of the growing season and was highly sensitive to all parameters related to soil water retention, including the drained upper limit of plant extractable water, lower limit of plant extractable water, and saturation. Trooien and Heermann (1988), studying SUBSTOR as a potato irrigation scheduling device in Colorado, found inconsistencies between actual and predicted ETs, leaf area indices, and growth stages, and did not recommend the model as a scheduling tool. We are aware of no studies that used SUBSTOR predictions of

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soil moisture content for real-time irrigation scheduling in the northern Great Plains.

Soil monitoring methods usually include placing sensors at several locations in a field to measure soil water content or matric potential. Tensiometers were used in studies by Lynch et al. (1995) in southern Alberta, and Singh et al. (1989) and Bourgoin (1984) in Maine. Neutron attenuation was used to determine soil moisture levels in the potato crop by Singh et al. (1989), Stockle and Hiller (1994), and Lynch et al. (1995).

Plant-based methods of irrigation scheduling attempt to define a measurable plant parameter which can be used to determine when to apply irrigation water. For example, the use of infrared thermometry to determine canopy temperature defines a crop water stress index (CWSI) as the basis for scheduling. It is based on the assumption that as water becomes limiting, transpiration is reduced and plant temperature rises. Idso et al. (1981) presented a simple empirical method for determining the CWSI for particular crops using the equation:

$$\mathrm{CWSI}\big|_{\mathrm{VPD}} = \frac{(T_c - T_a) - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}} \qquad (1)$$

in which VPD is the vapor pressure deficit (kPa) at which CWSI is computed; T_c and T_a are canopy and air temperatures, respectively (°C); and the subscripts LL and UL represent lower and upper limits or baselines of crop water stress, respectively. The lower limit represents the condition of a well-watered, nonstressed crop. The upper limit represents the condition of a nontranspiring, severely water-stressed crop. Idso (1982) presented lower limit equations for several crops including the following lower baseline equation for potatoes:

$$(T_c - T_a)_{LL} = -1.83\mathrm{VPD} + 1.17 \qquad (2)$$

where $(T_c - T_a)_{LL}$ is the canopy-air temperature difference (°C) and VPD is the vapor pressure deficit (kPa). Selecting a threshold CWSI value for irrigation has proven to be challenging for drought sensitive crops such as potatoes. McCann et al. (1992) concluded that a range of CWSI values from -0.4 to 0.4 (negative values indicate cases where measured canopy-air temperature differential is below the lower limit) for potatoes in Idaho may indicate a well watered crop, while higher values may indicate periods of plant stress.

Stegman and Nelson (1973) investigated irrigation scheduling methods for production of Russet and Norland potatoes using relative leaf water content and leaf transpiration resistance measurements. More recent studies conducted to compare irrigation scheduling methods in locations outside the northern Great Plains include Stockle and Hiller's (1994) study in Washington to compare CWSI, a computer-assisted scheduling method, and a method based on neutron attenuation to measure soil moisture. Dubetz and Krogman (1973) compared a water budget method to schedule irrigations when 50% of the available water was depleted in a 1.2-m root zone and a tensiometer method that scheduled irrigations when soil water tension reached 40 kPa at the 0.3-m depth on a loam soil in southern Alberta.

Based on the technologies and varieties used in Stegman and Nelson's (1973) study and the more recent studies conducted outside the region, there exists a need to compare current technologies for irrigation scheduling of potatoes via experimentation in the climatic setting of the northern Great Plains and with a more appropriate potato variety. Steele et al. (1996) successfully used subsurface drip irrigation in the northern Great Plains for production of the high value crops sweet corn, winter squash, and cabbage, but subsurface drip irrigation has not been tested for potatoes. Subsurface drip irrigation offers the potential for reduced water applications and may produce a drier crop canopy, the latter helpful for reducing or delaying the onset of diseases in the potato crop. Delaying the first irrigation for potatoes may be another means of reducing seasonal irrigation requirements, reducing the potential for leaching of chemicals to groundwater, and delaying the onset of diseases; hence there is a need to test this irrigation management strategy's effects on potato yield and quality. The dominant potato variety used in the region for French fry production is Russet Burbank (T. Scherer, personal communication with author, 1997).

OBJECTIVE

The purpose of this study was to determine whether "improved" irrigation application and scheduling methods for irrigated Russet Burbank potato production, in the northern Great Plains of the U.S., could reduce irrigation requirements and maintain potato yield and quality as compared with a commonly used water balance technique for irrigation scheduling. The improved techniques included use of infrared canopy temperature sensing, soil moisture sensing using tensiometers, application of irrigations through a subsurface drip irrigation system, delaying the first irrigation of the season, and using a crop growth model to estimate soil moisture content for scheduling irrigations.

MATERIALS AND METHODS

Field plot experiments were conducted from 1992 through 1995 at the Oakes Irrigation Research Station site (lat 46°04′ N, long 98°06′ W, and 401 m elevation above mean sea level; Enz et al., 1995) in southeastern North Dakota. The climate is subhumid and the predominant soil type is Maddock sandy loam.

Individual plots were 5.5 m wide × 12.2 m long. Rows were orientated E-W with a 0.91-m row spacing, resulting in six rows per plot. Plants were spaced 0.30 m apart within rows. Fertilizer application rates and related agronomic activities are summarized in table 1.

Each plot was trickle irrigated with thin-wall drip tape (Chapin Watermatics, Inc., Watertown, N.Y.) placed above or below the soil surface in each row. The tape was rated at 3.1×10^{-3} L s^{-1} m^{-1} (1.5 gpm/100 ft) and had 51-mm emitter spacings. Irrigation water was metered to quantify the actual irrigation application.

WATER MANAGEMENT TREATMENTS

Four irrigation treatments were replicated three times in a randomized block design. The treatments were selected to compare representative, current technologies available for irrigation scheduling to a commonly practiced irrigation

Table 1. Experimental agronomic data

Agronomic Item	Year 1992	 1993	 1994	 1995
Spring soil test N to 0.6 m (kg N ha^{-1})	38	37	21	66
Preplant N (kg N ha^{-1})	50	72	62	4
Planting date	28 April	4 May	4 May	5 May
Variety	Russet Burbank	Russet Burbank	Russet Burbank	Russet Burbank
Plant population	3.6 m^{-2}	3.6 m^{-2}	3.6 m^{-2}	3.6 m^{-2}
Emergence	18 May	27 May	26 May	5 June*
Hilling date & sidedress N (kg N ha^{-1})	4 June 110	14 June 110	14 June 108	20 June 104
Fertigation dates	25-27 June; 17-18 July; 4-6 Aug.	13-15 July; 4-5 Aug.; 18 Aug.	22 June; 9-10 July; 26 July	5 July; 18 July; 8 Aug.
Amount/Fertigation	29 kg N ha^{-1}	29 kg N ha^{-1}	30 kg N ha^{-1}	30 kg N ha^{-1}
Harvest date†	9 Sept.	14 Sept.	12 Sept.	13 Sept.
Cover crop (rye) planting date	15 Sept.	15 Sept.	13 Sept.	13 Sept.

* Emergence was delayed in 1995 by uncharacteristically cool weather in May.

† Harvest dates were set to accommodate the planting of a cover crop by 15 September as per local ASCS regulations.

scheduling method. The methods are described below, following a description of the methods used for soil characterization. The plot layout was blocked to statistically accommodate a north-to-south gradient in the water holding capacity of the soil (E. C. Stegman, personal communication, 1992). A companion study of irrigation treatments for popcorn (Steele et al., 1997) was used in an annual rotation with the potatoes on adjacent plots. That is, plots for potatoes and plots for popcorn were swapped each year of the study. A three- or four-year rotation with potatoes is more common for sustained commercial production in the region, but this experiment was limited in duration and required the use of irrigation research facilities allocated to the plot site.

It is desirable to have simple methods of soil characterization available for producers to use when setting up irrigation scheduling algorithms based on a soil water balance. Steele et al. (1997) described single-measurement procedures to characterize the water holding capacity of the soil for water balance-based irrigation scheduling methods in both studies. Steele et al. (1997) found that plant-available water in the soil profile could be reasonably approximated for irrigation scheduling purposes by halving the field capacity values obtained by neutron attenuation measurements taken one to two days after profile-refilling rainfall events. Using this method, field average water content at field capacity was 70 mm of water in the top 0.30 m of the soil profile and 127 mm of water in the top 0.60 m of the soil profile, with one-half of these values considered available to the plant.

Plots in treatment number one (T1) were irrigated when estimated depletions of available soil water exceeded 40% (denoted by “40% D”). A spreadsheet version of the irrigation scheduling algorithm developed by Stegman and Coe (1984) and their potato crop curve were used, with Jensen and Haise (1963) estimates of reference crop ET. The root zone management depths were 0.3 m from planting through the end of June and 0.6 m for the rest of the growing season. Individual irrigation amounts, applied with aboveground drip tape, were sufficient to refill the soil to field capacity, minus 2.5 to 5 mm storage to accommodate rainfall events. Irrigation volumes are expressed as depth equivalents over the entire plot area. No accounting was made for a smaller application area caused by the drip irrigation compared to rainfall or uniform sprinkler irrigation. Therefore, the 40% depletion level was a conservative irrigation scheduling criterion, i.e., the average soil water depletion level in the root zone near the drip tape was likely lower when irrigations were applied. The 40% D treatment is typical of recommended irrigation management practices in the region. It was intended to be the wettest regime and therefore a reference regime for statistical purposes in this study. Periodic soil moisture measurements were used to correct soil moisture estimates.

Plots in treatment number two (T2) were irrigated based on crop water stress index (CWSI) criteria. The CWSI treatment was characterized by irrigations of 25 mm applied with aboveground drip tape at CWSI values of 0.2 based on equations 1 and 2. The 25-mm application depth is typical of production practices in the region. Because of lack of a locally calibrated CWSI upper baseline for potatoes, a 5°C value determined from previous research at the site for wheat (Stegman and Soderlund, 1992) and corn (Steele et al., 1994) was used. Theoretical estimates of the upper baseline, from energy balance considerations, are generally in the order of 5°C or more (McCann et al., 1992).

One drawback of using CWSI to schedule irrigations is that infrared thermometry readings are inaccurate until the crop reaches full ground cover, since unshaded soil will generally be at a higher temperature than the crop canopy. The result is composite temperature reading of the canopy and soil that registers higher than the true canopy temperature. To compensate for this, tensiometers (Irrometer Company Model S, Riverside, Calif.) installed at 0.3-m depth were used to schedule irrigations at soil matric potential values of 30 kPa before the crop reached full canopy. These tensiometers, read manually because they were not equipped with transducers, were also used as a backup when CWSI data were unreliable because of cloudiness, high relative humidity, and/or low air temperature.

Plots in treatment number three (T3) were irrigated when 0.3-m tensiometer readings exceeded 30 kPa. Subsurface drip irrigation (SDI) was used to apply the irrigation water. Drip tape was buried approximately 0.20 to 0.25 m below the soil surface. Tensiometers (Irrometer Model RSR, Riverside, Calif.) in these plots were equipped with pressure transducers and monitored by a data logger (Campbell Scientific CR10, Logan, Utah). The data logger read the tensiometers (one per plot) three times daily, at 6:00 A.M., 12:00 M. (noon) and 6:00 P.M. and triggered irrigations of 2.5 mm if the transducer reading equaled or exceeded 30 kPa. This limited total daily applications to 7.5 mm. The data logger controlled and monitored the water supply pumping and routing system (groundwater well, flow meter, and solenoid-controlled valves). Prior to data logger installation and operation each season, irrigations were manually applied when tensiometer readings exceeded 30 kPa.

Plots in treatment number four (T4) were irrigated using estimates of crop water use from the SUBSTOR-Potatoes (SUBSTOR) crop growth model. Inputs for the model include climatic data (e.g., solar radiation, daily maximum and minimum temperatures, and rain), crop and cultural practices data (e.g., sowing depth, plant population, fertilization and irrigation dates and amounts, and variety-dependent genetic parameters), and soil data (e.g., initial fertility, upper and lower limits of plant-available water, albedo, and runoff curve number). Model outputs include estimates of yield, biomass, soil water content, phenological development, leaf area index, plant nitrogen uptake, nitrogen stress indices, and water stress indices. In this study, the model's default values for genetic coefficients for Russet Burbank were used. The first irrigation under this treatment was delayed each year until one day after the Jensen–Haise–based soil moisture depletion estimates (see treatment T1 above), averaged across replications, reached 50 to 60%. For example, before irrigation in 1995, the SUBSTOR plots experienced a soil water depletion of 59% as estimated by the 40% D treatment. The delay in the first irrigation tested the hypothesis that irrigation amounts could be reduced compared to the reference treatment without affecting yields or quality. After the first irrigation, irrigations were scheduled based on a 40% available water depletion as predicted by SUBSTOR. The root zone management depth for the growth model was held constant at 0.6 m throughout the season and individual irrigation amounts were 25 mm throughout the season using aboveground drip tape. Soil moisture measurements were used to correct SUBSTOR estimates of soil moisture, forcing the model estimates of plant extractable soil water (PESW) to match corresponding field measurements. When SUBSTOR overestimated ET, the model underestimated PESW, and the estimates were corrected by adding artificial irrigation amounts to the simulation input files (not to the field plots). Thus the 40% D and SUBSTOR methods both used corrections to soil moisture whenever possible. For the 40% D and SUBSTOR methods, an irrigation schedule was developed approximately every week for each plot using methods described by Steele et al. (1997).

MEASUREMENTS

Root zone moisture contents were measured weekly using the neutron attenuation method of soil water measurement. Measurements (Troxler, Model 105A, Lakewood, Colo.; Campbell Pacific Nuclear, Model 503 DR, Pacheco, Calif.) were taken in all plots at depths of 0.15, 0.30, 0.46, 0.61, 0.91, and 1.22 m. No attempt was made in the soil water calculations to account for nonuniform root distributions in the soil because of drip irrigation vs. other methods of water application. Tensiometers were read manually each weekday in treatment T2. One tensiometer per plot was used in treatments T2 and T3. All tensiometers were installed in the second crop row of the plots. Similarly, neutron probe access tubes were installed in the second of six crop rows in each plot. The CWSI values were based on ambient air VPD and canopy-air temperature differences. Crop canopy temperatures were measured using infrared temperature sensors (Everest Interscience Model 4000 and 5000, Tustin, Calif.) using a 15° field of view and assuming a canopy emissivity of 0.98. The canopy temperature sensors were positioned above the crop in a north-south orientation and a 30° angle of depression was used. Incoming solar radiation was measured with a pyranometer (Campbell Scientific Model LI-200S). Ambient temperature and relative humidity were measured with a temperature and humidity probe (Campbell Scientific Model 207). Vapor pressure deficit was estimated from measured relative humidity and the saturation vapor pressure using the polynomial equation presented by Lowe (1977). Meteorological data collection procedures at the site were described in a previous study (Steele et al., 1994).

All meteorological instruments were connected to a data logger (Campbell Scientific Model CR10) which took readings every 30 s and averaged the information over 5 min. The CWSI data recorded by the data logger, from 6:00 A.M. to 6:00 P.M., were downloaded via telephone modem (Campbell Scientific Model DC112) and analyzed daily. Analysis consisted of plotting $T_c - T_a$ versus vapor pressure deficit along with upper and lower baselines using a computer spreadsheet program. The median of the $T_c - T_a$ points corresponding to the highest one-third of the vapor pressure deficits was used to compute the daily CWSI.

Final yield determinations were made by harvesting two 6.1-m rows in the center of each plot. Tubers from the harvest areas were bagged and transported off-site for grading by size. Samples for specific gravity were taken adjacent to and outside of the harvest area. Specific gravity was determined by weighing a sample in air and in water (Dean, 1994).

EVAPOTRANSPIRATION ESTIMATES

ET was estimated for each plot with a water balance equation used by Stegman et al. (1977) to develop ET crop curves for southeastern North Dakota, i.e.:

$$ET_i = -(S_{i+1} - S_i) + P_i + I_i - DP_i \qquad (3)$$

where S is the soil water content in the top 0.6 m of the profile, P is precipitation, I is irrigation, DP is deep percolation past the root zone, the subscript refers to the i*th* time period (approximately one week), and all quantities are expressed as depth equivalents (m). Note that one neutron probe access tube per plot does not allow a detailed study of the spatial variability of soil moisture, the latter being beyond the scope of this study.

Instrumentation was not available to measure DP directly, so DP was estimated on a daily basis, independently from equation 3. Deep percolation for day (j) was estimated as the excess of field capacity with the equation:

$$DP_j = (W_{j-1} + P_j + I_j - K_c ET_r) - W_{FC} \qquad (4)$$

where W_{j-1} is the root zone water content estimate for the previous day; P and I were defined previously; K_c represents a crop curve developed for potatoes at the site by Stegman et al. (1977) and Stegman and Coe (1984); ET_r refers to the Jensen and Haise (1963) reference crop ET equation; and the subscript FC refers to field capacity. If equation 4 produced a negative value, DP_j was set to zero. The sum of the DP_j values between consecutive soil moisture measurements was substituted into equation 3 as DP_i.

Weekly ET values were computed using equation 3 and seasonal ET sums (ΣET) were computed from weekly totals. In some seasons, neutron probe access tubes were installed several days after crop emergence. In these cases, ET before tube installation was estimated using the crop curves of Stegman et al. (1977). Water use efficiencies were calculated for each plot using methods similar to those used previously for dent corn at the site (Steele et al., 1994). A *physiologic water use efficiency* (PWUE) or *ET ratio* (Stanhill, 1986) was defined as:

$$\text{PWUE} = \frac{\text{Yield}}{\Sigma \text{ET}} \quad (5)$$

A *hydrologic water use efficiency* (HWUE) is defined as the fraction of water delivered to or in the root zone that was beneficially used by the crop:

$$\text{HWUE} = \frac{\Sigma \text{ET}}{\Sigma \text{P} + \Sigma \text{I} + \left(\text{S}_o - \text{S}_f\right)} \times 100 \quad (6)$$

where ΣP is the precipitation total, ΣI is the irrigation total, S_o is the initial or start-of-season soil moisture, and S_f is the final or end-of-season soil moisture. For equations 5 and 6, all sums were taken between the times corresponding to S_o and S_f. The PWUE represents the crop response to ET, while the HWUE represents an efficiency of utilization of the water made available to the crop.

Stegman (1982) used the following practical equation to evaluate the efficiency of irrigation management schemes:

$$\text{IE} = \frac{\text{Y}}{\text{I}} \quad (7)$$

where IE is irrigation efficiency, Y is yield per unit area, and I is irrigation depth applied.

Care must be exercised to correctly apply this equation. For example, in a nonirrigated farming situation where no irrigation water is applied, the denominator in equation 7 would be zero and the IE value is undefined. Similarly, a very small irrigation amount may have negligible effect on yield, yet a small denominator in equation 7 would produce a very large irrigation efficiency, perhaps one that is misleading.

ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) was performed on irrigation water amounts, total yields, percent and mass of no. 1 yields, specific gravities, seasonal ETs, PWUEs based on total and no. 1 yields, HWUEs, and IEs for each season. The ANOVA was performed using Duncan's Multiple Range test for a randomized block design (two–way classification) at the $\alpha = 0.05$ level of significance to determine if significant differences existed between treatment means. In order to statistically analyze treatment parameters across the entire four years of the experiment, the data were analyzed as a two-factor factorial design (Montgomery, 1991). Differences in treatments were determined by using Duncan's Multiple Range test contained within SAS version 6.22 software (SAS, 1995) at a significance level of 0.05. It is important to note that the treatments were statistically treated as "packages" of application and scheduling methods. For example, field subplots were not used in treatment T3 to distinguish between the effects of using tensiometers versus water balance methods for irrigation scheduling and the effects of using SDI versus aboveground drip irrigation for application of water. Unless otherwise noted in the remainder of this article, the words "significant", "significantly", etc., are used in their statistical sense, i.e., according to the statistical tests described above.

RESULTS AND DISCUSSION

The following weather summaries correspond to 1 May through 30 September for each year. Seasonal precipitation totals were 128%, 153%, 117%, and 108% of the 1972 through 1991 average at the site for the years 1992, 1993, 1994, and 1995, respectively (table 2). Seasonal ET_r values were 90%, 85%, 102%, and 102% of 1972 through 1991 averages for the years 1992, 1993, 1994, and 1995, respectively (table 2).

Operation of the 40% D and SDI treatments proceeded as planned. Operation of the CWSI treatment was difficult because of intermittent cloudiness, low solar radiation levels, and low average vapor pressure deficits. For these reasons, the backup tensiometers installed at 0.3 m were used to schedule irrigations over 65% of the time for the CWSI treatment.

The SUBSTOR treatment behaved as expected, except for the 1994 crop year. In 1994, by the time irrigation equipment was in place (second week of June), the model had predicted loss of crop because of water stress. Since further irrigations, according to the model, would have been to no avail, the only water applied to this treatment was the water used to apply liquid fertilizer. The treatment essentially behaved as a nonirrigated crop for the 1994 season. The predicted crop loss was an exhibition of SUBSTOR's sensitivity to soil water retention characteristics (drained upper limit of plant extractable water, lower limit of plant extractable water, and saturation), as reported by Mahdian and Gallichand (1995). Statistical analyses are presented later for the entire experiment that include and exclude the 1994 data.

Operationally, SUBSTOR provides no means to directly adjust soil moisture content estimates to measured values at

Table 2. Weather summary for the experimental period

Year	Precipitation* (mm)	Jensen and Haise Reference ET† (mm)
1992	372	627
1993	445	590
1994	340	710
1995	314	708
1992-1995 Average	368	658
1972-1991 Average	291	694

* Long-term average are based on 1 May through 30 September weather records for the site.

† Based on the Jensen and Haise (1963) reference ET_r equation for the period 1 May through 30 September each year.

any time during the season. Adding "artificial" irrigations to the simulations when the model predicted PESW values lower than those measured severely limited the practicality of the model for irrigation scheduling compared to the 40% D treatment.

SUMMARIES FOR EACH YEAR

Yield and Quality. Yield between treatments did not differ significantly for the 1992, 1993 or 1995 seasons (table 3). In 1994, the SUBSTOR treatment had a significantly lower yield than the other treatments because of lack of irrigation. Total average yield was much lower than the goal of 45 Mg ha^{-1} for crop years 1993 and 1995. The overall yield reduction in 1993 was a result of uncharacteristically cool weather and low solar radiation, compounded with heavy precipitation throughout the growing season. Both Dean (1994) and Smith (1977) noted that low amounts of solar radiation can significantly reduce yields of the potato crop. Yield reduction in 1995 was attributed to a short period of unusually hot weather from 14 to 21 June with mean daily maximum temperature of 33.1°C. This period corresponds to 9 to 16 days past emergence. Potato stolons generally begin to appear early in the growth of the plant (7 to 10 days after emergence; Smith, 1977). High temperatures after emergence of the potato crop will delay tuber initiation (Smith, 1977). Delayed initiation can result in a "later" crop than normal and equate to lower yield values at traditional harvest dates. Therefore, the reduced yields in 1995 were probably caused by early heat stress.

Quality results for no. 1 grade yield and percent of total yield which was of no. 1 grade are presented in table 4, while specific gravity results are summarized in table 5. Total yield and percentage of no. 1 grade potatoes did not differ among treatments for 1992 or 1993. In 1994, the SUBSTOR treatment was significantly lower than the 40% D and CWSI treatments in no. 1 grade yield and the SDI treatment was significantly lower than all other treatments in percent of no. 1 grade potatoes. In 1995, the SDI treatment was higher than the 40% D and SUBSTOR treatments in percent of no. 1 grade potatoes. The reason for the SDI treatment producing the lowest percent no. 1 in 1994 and the highest percent no. 1 in 1995 is unknown. Specific gravity across treatments was not significantly different in 1992 through 1994. In 1995, the SDI treatment exhibited the highest specific gravity.

Table 3. Treatment averages and comparison of treatment means for total potato yields

Scheduling Method	Total Yield (Mg ha^{-1}) 1992	1993	1994	1995
40% D	50.3a*	37.0a	46.6a	33.4a
CWSI	48.5a	33.9a	43.7a	31.7a
SDI	48.7a	35.7a	43.7a	33.0a
SUBSTOR	50.1a	37.3a	28.2b	32.9a
Average	49.4	36.0	40.6	32.9

* Amounts in each column with the same letter are not significantly different at the α = 0.05 level.

Table 4. Treatment averages and comparison of treatment means for no. 1 potatoes

Year	1992		1993		1994		1995	
Trt.	No. 1 Yield (Mg ha^{-1})	Percent No. 1 (%)	No. 1 Yield (Mg ha^{-1})	Percent No. 1 (%)	No. 1 Yield (Mg ha^{-1})	Percent No. 1 (%)	No. 1 Yield (Mg ha^{-1})	Percent No. 1 (%)
40% D	41.6a*	82.5a	29.2a	78.8a	34.2a	73.6a	24.1a	72.0b
CWSI	40.2a	82.6a	26.6a	78.4a	31.2a	71.3a	24.3a	76.6ab
SDI	41.8a	85.7a	26.9a	75.2a	27.9ab	63.7b	26.6a	80.3a
SUBSTOR	39.8a	79.2a	26.1a	70.3a	21.4b	76.0a	23.6a	71.1b

* Amounts in each column with the same letter are not significantly different at the α = 0.05 level.

Table 5. Treatment averages and comparison of treatment means for specific gravity

Scheduling Method	Specific Gravity (dimensionless) 1992	1993	1994	1995
40% D	1.092a*	1.095a	1.086a	1.078b
CWSI	1.092a	1.093a	1.086a	1.080b
SDI	1.094a	1.096a	1.082a	1.085a
SUBSTOR	1.092a	1.103a	1.084a	1.076b
Average	1. 092	1.097	1.085	1.080

* Amounts in each column with the same letter are not significantly different at the α = 0.05 level.

Irrigation and Evapotranspiration. Total irrigation amounts were variable across treatments (table 6). The 40% D treatment was in the statistically highest grouping for 1992, 1993, and 1994. The SDI treatment was in the statistically lowest grouping for all seasons, except the 1994 SUBSTOR treatment. The SDI treatment required significantly less irrigation than the 40% D treatment for all years.

The SUBSTOR treatment showed the most variability in irrigation amount across seasons. The highest irrigation amount was applied with the growth model in 1993 and 1995, but the lowest irrigation amount was applied with the growth model in 1994 and 1992. SUBSTOR may lack sensitivity to weather variables, as indicated by its call for the highest irrigation amounts in 1993 and 1995 (table 6), despite the depressed yields for all treatments in 1993 and 1995 (table 3). However, the fact that SUBSTOR was in the highest yield grouping for 1992, 1993, and 1995 suggests delaying the first irrigation may be a viable irrigation management strategy for potatoes. Further research should be done to examine the first-irrigation delay more closely. Such studies should base irrigation decisions directly on soil moisture measurements or on models less sensitive to early-season drought stresses.

For ET, the 40% D treatment fell within the statistically highest grouping for each of the four years of the study (table 7). The SDI treatment showed reduced ETs in 1994 and 1995. The SUBSTOR model produced a significantly lower mean ET in 1994 because of water stress induced by the near nonirrigated condition.

Table 6. Treatment averages and comparison of treatment means for seasonal irrigation water amounts

Scheduling Method	Irrigation Water Amount (mm) 1992	1993	1994	1995
40% D	217a*	178a	289a	199b
CWSI	173b	118ab	227b	152c
SDI	175b	74b	138c	128c
SUBSTOR	146b	178a	38d	236a
Average	178	137	173	179

* Amounts in each column with the same letter are not significantly different at the α = 0.05 level.

Table 7. Treatment averages and comparison of treatment means for seasonal ET totals

Scheduling Method	Seasonal ET Total (mm)			
	1992	1993	1994	1995
40% D	416a*	341a	388a	333a
CWSI	395b	337a	363a	338a
SDI	426a	316a	296b	270b
SUBSTOR	426b	346a	245c	357a
Average	416	335	323	325

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level.

Physiologic Water Use Efficiency. The SDI treatment showed the most variability with respect to PWUE (table 8). The PWUE of the SDI treatment was significantly lower than all other treatments for the 1992 season but significantly higher than all other treatments in 1995. The SDI treatment exhibited the highest PWUE for years 1993 to 1995. The 40% D, CWSI, and SUBSTOR treatments did not significantly differ from each other during the study.

The 1994 unirrigated SUBSTOR treatment was statistically the same as all treatments except the SDI treatment. Yield and ET dropped off at essentially linear rates, resulting in a PWUE statistically identical to other treatments. This supports the linear relationship between yield and ET for the potato crop—for a given irrigation method—as presented by Stegman and Nelson (1973).

PWUEs and corresponding statistical results considering only no. 1 yield as the economic yield are presented in table 9. PWUEs for no. 1 yields were not significantly different across treatments in 1992 through 1994. In 1995, the SDI treatment exhibited a higher no. 1 yield PWUE, because of significantly lower seasonal ET values.

Wright and Stark (1990) summarized yield and PWUE results of sprinkler irrigated potatoes from several studies. The yields listed were generally the maximum yields found in each study so the corresponding PWUEs would be near the optimum value for the region. Their data are shown along with the four-season mean results from this study in table 10. The study at Oakes, North Dakota, exhibited lower yields, the lowest water use, and some of the highest PWUEs when compared with the studies listed by Wright and Stark (1990). This study supports the work of Tanner (1981) who found PWUEs to be higher in more humid zones because of lower saturation vapor pressure deficit, while yields were lower because of other climatological limitations. An exception is the study done by Hill et al. (1985) in Kimberly, Idaho, an arid region. Their study reported high PWUEs (106 to 120 kg ha^{-1} mm^{-1}) and high yields (56 to 68 Mg ha^{-1}).

PWUEs for the study in Oakes, North Dakota, were among the highest in the summary (111 to 125 kg ha^{-1} mm^{-1}). We attribute the higher PWUE values to the VPD values being closer to zero than for other regions. That is, the VPDs typical of the subhumid climate at Oakes, North Dakota, are smaller in magnitude than for other regions in the summary. The PWUE of 125 kg ha^{-1} mm^{-1} exhibited by the SDI treatment is the highest in the summary. Below-surface application of water with the SDI treatment is expected to reduce ET by reducing surface evaporation compared to methods using aboveground drip irrigation, sprinkle irrigation, or surface irrigation.

Hydrologic Water Use Efficiency. Hydrologic water use efficiency, as defined herein, may be considered a measurement of drainage. It may be used as an indicator of potential nutrient leaching past the root zone and an indicator of how well the irrigation scheduling method matches the region's climate. A high HWUE means that rainfall and irrigation are being used efficiently, with drainage and surface runoff minimized. Table 11 lists the hydrologic water use efficiencies for this study and the results of the statistical analysis.

The highest HWUE values occurred in 1995 (average of 93.4% across all treatments) and the lowest values occurred

Table 8. Treatment averages and comparison of treatment means for physiologic water use efficiencies based on total yield

Scheduling Method	Physiologic Water Use Efficiency (kg ha^{-1} mm^{-1})			
	1992	1993	1994	1995
40% D	121.2a*	108.4a	120.2ab	100.2b
CWSI	122.8a	101.3a	121.3ab	93.4b
SDI	113.9b	113.2a	148.0a	123.3a
SUBSTOR	126.5a	107.9a	115.0b	92.7b
Average	121.1	107.7	126.1	102.4

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level.

Table 9. Treatment averages and comparison of treatment means for physiologic water use efficiencies based on no. 1 yield

Scheduling Method	Physiologic Water Use Efficiency (kg ha^{-1} mm^{-1})			
	1992	1993	1994	1995
40% D	100.0a*	85.5a	88.4a	72.4b
CWSI	101.5a	79.1a	87.1a	71.6b
SDI	98.2a	85.1a	94.4a	99.6a
SUBSTOR	100.4a	75.5a	87.4a	65.9b
Average	100.0	81.3	89.3	77.4

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level.

Table 10. Summary of seasonal physiologic water use efficiencies (PWUEs) of potato based on fresh tuber yields and seasonal water use for several locations*

Study	Location	Soil†	Culti-vars‡	Water Use (mm)	Yield (Mg ha^{-1})		PWUE (kg ha^{-1} mm^{-1})	
					Total	No. 1	Total	No. 1
Hane and Pumphrey, 1984	Hermiston, OR	ls	R.B.	640	—	42	—	66
Hang and Miller, 1986	Patterson, WA	ls	R.B.	700	70	60	100	86
Hill et al., 1985	Kaysville, UT	l	R.B.	650	51	19	79	29
Hill et al., 1985	Kaysville, UT	l	L.R.	700	51	43	73	62
Hill et al., 1985	Kaysville, UT	l	Ken.	640	57	43	89	68
Hill et al., 1985	Kimberly, ID	sl	R.B.	527	63	46	120	88
Hill et al., 1985	Kimberly, ID	sl	L.R.	532	56	45	106	84
Hill et al., 1985	Kimberly, ID	sl	Ken.	585	68	60	116	103
Hill et al., 1985	Logan, UT	sl	R.B.	548	53	32	97	59
Hill et al., 1985	Logan, UT	sl	L.R.	550	47	41	86	75
Hill et al., 1985	Logan, UT	sl	Ken.	555	56	52	101	94
Sammis, 1980	Las Cruces, NM	cl	Ken.	606	33	—	54	—
Shalhevet et al., 1983	Negev, Israel	T.C.	Des.	800	72	62	85	78
Tanner 1981	Wisconsin	ls	R.B.	450	50	—	111	—
J.L. Wright, 1972	Kimberly, ID	sl	R.B.	604	62	50	102	83
Wolfe et al., 1983	Davis, CA	l	Ken.	610	—	36	—	59
Wolfe et al., 1983	Davis, CA	l	W.R.	630	—	34	—	54
This Study 40% D	Oakes, ND	sl	R.B.	369	42	32	112	87
This Study CWSI	Oakes, ND	sl	R.B.	358	39	31	110	85
This Study SDI	Oakes, ND	sl	R.B.	327	40	31	125	94
This Study SUBSTOR	Oakes, ND	sl	R.B.	336	37	28	111	82

* Permission to use this table was granted by American Society of Agronomy – Crop Science Society of America – Soil Science Society of America, 677 South Sego Rd, Madison, Wisconsin.

† Soil type abbreviations: ls = loamy sand; l = loam; sl = sandy loam; cl = clay loam; T.C. = Typic Camborthid.

‡ R.B. = Russet Burbank; L.R. = Lemhi Russet; Ken. = Kennebec; Des. = Desiree; W.R. = White Rose.

Table 11. Treatment averages and comparison of treatment means for hydrologic water use efficiencies

Scheduling Method	Hydrologic Water Use Efficiency (%)			
	1992	1993	1994	1995
40% D	78.0b*	64.0b	71.0b	93.1a
CWSI	76.4b	71.1a	75.1a	95.9a
SDI	85.3a	72.6a	76.2a	93.1a
SUBSTOR	81.0ab	64.1b	77.3a	91.3a
Average	80.2	68.0	74.9	93.4

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level.

Table 12. Treatment averages and comparison of treatment means for irrigation efficiencies (Yield/I)

Scheduling Method	Irrigation Efficiency (kg ha^{-1} mm^{-1})			
	1992	1993	1994	1995
40% D	231.4c*	207.2b	168.1b	172.5b
CWSI	279.4b	329.1b	205.0b	189.2b
SDI	277.2b	486.6a	357.7b	262.7a
SUBSTOR	345.0a	209.4b	1333.6a	142.6a
Average	283.3	308.1	516.1	191.8

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level.

in 1993 (average of 68.0%). The highest HWUE coincided with the season with the lowest precipitation and the lowest HWUE coincided with the season of highest precipitation. The SDI treatment was always in the statistically highest grouping, and the 40% D treatment was always in the lowest. The CWSI and SUBSTOR treatments showed the most variability in HWUE. The CWSI treatment was in the highest statistical grouping in 1993 but the lowest in 1992. The opposite is true for the SUBSTOR treatment; it was in the highest grouping in 1992 but in the lowest grouping in 1993.

Note the small differences in HWUE between the CWSI, SDI, and SUBSTOR treatments in 1994. Even though the SUBSTOR treatment was essentially a nonirrigated treatment in 1994, the mean HWUE values between the three treatments did not differ significantly. It would seem reasonable that a treatment where no water was applied, other than rainfall, would exhibit HWUE values in a significantly higher range than treatments in which irrigation water was applied. In this case, however, precipitation occurred in high enough volumes and at the proper timing to eliminate differences in HWUE between these three treatments. This indicates that no matter how carefully a management scheme is carried out, natural weather conditions can still override the effects of irrigation management.

Irrigation Efficiency. The irrigation efficiency of the 40% D treatment was in the statistically lowest category in each of the four years (table 12). The irrigation efficiency of the SUBSTOR treatment was in the highest statistical grouping for 1992, 1994, and 1995. The SDI treatment was in the highest irrigation efficiency grouping for 1993 and 1995 and exhibited higher efficiency than the 40% D and CWSI treatments in 1994.

The irrigation efficiency of 1334 for the SUBSTOR treatment in 1994 (table 12) illustrates one of the inadequacies of using IE to compare treatments. Applying equation 7 to a nonirrigated treatment would produce an undefined efficiency since the denominator would be zero. A more practical application of the irrigation efficiency comparison is to limit its application to treatments with statistically similar yields.

SUMMARIES FOR THE FOUR-YEAR EXPERIMENT

Each of the items discussed previously were analyzed for the entire four-year experiment in an attempt to determine the best treatment. Since the unirrigated 1994 SUBSTOR treatment could be viewed as an aberration in the data, identical statistical tests were compiled using only 1992, 1993, and 1995 data. Results of the four-year and the three-year statistics are given in table 13.

No differences occurred in total yield, no. 1 yield, percent of no. 1 yield or specific gravity of the potato tubers between any of the treatments in the four-year analysis. The SUBSTOR treatment was in a statistically lower grouping for percent of no. 1 yield than the SDI treatment in the three-year analysis. There were no differences between treatments for total yield, no. 1 yield or specific gravity in the three-year analysis. Thus, the hypothesis that potato yield and quality can be maintained under improved irrigation treatments was supported by this study.

Irrigation amounts for the 40% D treatment were significantly higher than all other treatments in the four-year analysis and in the highest grouping of the three-year

Table 13. Four- and three-year statistical summaries

Treat.	Years*	Yield (Mg ha^{-1})	No. 1 Yield (Mg ha^{-1})	No. 1s (%)	Specific Gravity	Irrigation (mm)	ET (mm)	PWUE†	No. 1 PWUE	Irr. Eff.	HWUE (%)
								(kg ha^{-1} mm^{-1})			
40% D	4	41.8a‡	32.3a	76.7a	1.078a	220a	369a	112ab	87a	195b	76.6a
CWSI	4	39.4a	30.6a	77.2a	1.088a	167b	358a	110b	85a	251ab	79.6a
SDI	4	40.3a	30.8a	76.2a	1.089a	129b	327a	125a	94a	347ab	82.1a
SUBSTOR	4	37.2a	27.7a	74.2a	1.089a	149b	336a	111ab	82a	509a	78.1a
Average		39.7	30.3	76.1	1.086	166	348	115	87	326	79.1
40% D	3	40.2a	31.6a	77.8ab	1.088a	197a	363a	110a	86a	204b	78.4a
CWSI	3	38.0a	30.3a	79.2ab	1.088a	148bc	359a	106a	84a	266ab	81.1a
SDI	3	39.2a	31.8a	80.4a	1.092a	126c	337a	117a	94a	343a	83.7a
SUBSTOR	3	40.2a	29.8a	73.5b	1.090a	186ab	366a	109a	85a	233b	78.8a
Average		39.4	30.9	77.7	1.090	164	356	111	87	262	80.5

* A “4” indicates statistics for 1992 through 1995 data; a “3” indicates statistics for 1992,1993, and 1995 data only.

† Abbreviations: PWUE is physiologic water use efficiency, HWUE is hydrologic water use efficiency.

‡ Amounts within each category with the same letter are not significantly different at the $\alpha = 0.05$ level.

analysis. The 40% D treatment is commonly recommended to local producers and was expected to be the most heavily irrigated treatment. The irrigation amounts for the CWSI, SDI and SUBSTOR treatments were not significantly different in the four-year analysis. The CWSI and SDI treatments were statistically in the lowest irrigation amount grouping for the three-year analysis.

Because plots for the CWSI treatment were frequently scheduled based on tensiometer information, it is useful to compare the irrigation requirements of the CWSI and SDI plots. The CWSI and SDI methods were not statistically different from each other in average irrigation amounts for the four-year and the three-year analyses, but the SDI treatment had a smaller average in each case. We attribute the smaller irrigation requirement for the SDI treatment to more frequent soil moisture monitoring, smaller irrigation applications at each irrigation event, and reduced water evaporation at the soil surface because of buried placement of the drip tape with the SDI treatment. Similar to the results for potato yield and quality, the hypothesis that total (seasonal) irrigation amounts can be reduced under improved irrigation application and scheduling methods was supported by this study.

Results for ET, no. 1 PWUE, and HWUE were not significantly different based on the statistical tests performed for either the four-year or the three-year analyses. The PWUE for the CWSI treatment was found to be statistically lower than the PWUE for the SDI treatment in the four-year analysis. Since the CWSI was scheduled primarily with tensiometers, the difference in efficiency would be because of either the high frequency applications and/or the buried placement of the drip tubing. PWUEs were not significantly different for any of the treatments in the three-year analysis.

The irrigation efficiency for the SDI treatment was statistically higher than the 40% D and SUBSTOR treatments in the three-year analysis because the SDI treatment had significantly lower water application amounts in 1993 and 1995.

CONCLUSIONS

This four-year study of potatoes indicates that in the northern Great Plains of the U.S., improved irrigation treatments can achieve statistically significant irrigation water savings compared to a reference treatment, generally without significant reductions in yields or quality. The improved treatments require careful attention to soil hydraulic properties and intensive soil moisture or plant monitoring.

The tensiometer-based methods of irrigation scheduling were preferred because of their ability to produce yields and quality equivalent to those from the reference treatment with significant savings in seasonal irrigation totals. The SUBSTOR treatment was sensitive to early-season drought stress and has limited capability to accommodate in-season corrections to soil moisture estimates. The SUBSTOR treatment was less practical than the other methods for irrigation scheduling. However, delays in the first irrigation should be investigated more closely in terms of their effects on potato yield, quality, and seasonal irrigation requirements.

Further study is needed to assess the influence of improved irrigation scheduling methods and water application methods on energy savings and ground water quality in the northern Great Plains of the U.S.

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