AN ABSTRACT OF THE THESIS OF

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Potato (*Solanum tuberosum* L. 'Russet Burbank') tuber quality response to a transient water stress was evaluated by withholding irrigation until the soil dried to pre-assigned treatment soil water potentials. Treatments were -25, -44, -66, -82, -101, and -120 kPa soil water potential replicated seven times in a randomized block design. A solid-set sprinkler system was used to irrigate the entire experiment uniformly before June 21 and after July 18, in 1988 and 1989. During the transient stress period, portable plot sprinklers were used to irrigate individual plots 13.7 m long by 4.6 m wide at treatment stress levels.

Soil water potential was measured with two granular matrix sensors (GMS) per plot. Tensiometer water potential defined GMS readings by the relationship: $y = -6.45 - 0.753x$, where y = tensiometer kPa, and x = GMS

reading, with $r^2 = 0.89$. Leaf water status was measured with a hydraulic leaf press when each plot reached the pre-assigned soil water potential. The relationship between leaf press and pressure chamber readings using paired pinnae was: $y = -0.403e^{-0.848x}$, where y = leaf press MPa, and x = pressure chamber MPa, with $r^2 = 0.85$.

Tubers were sampled four times for reducing sugar determinations: before the transient stress period; at maximum stress; two weeks after stress relief; and after harvest in late September. Increased stem end reducing sugar was not observed until September harvest. Reducing sugar concentrations increased with increased stress below -80 kPa. Dark end tubers corresponding to USDA #3 and #4 fry colors resulted when soil water potential fell below -80 kPa in 1988 and below -69 kPa in 1989. Dark stem ends were associated with increased reducing sugar and decreased total solids.

Increased stress decreased tuber grade and size, without yield reduction. The incidence of jelly-end rot, a severe symptom associated with dark end, increased when stress exceeded -68 kPa soil water potential. Tuber appearance was adversely affected by water stress as shown by a decrease in USDA number one tubers and an increase in USDA number two tubers when transient stress exceeded -49 kPa.

Potato (*Solanum tuberosum* L.) Tuber Quality Response to a Transient Water Stress

by

Eric P. Eldredge

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CONTRIBUTION OF AUTHORS

Dr. Clint Shock, my co-major professor, and the Superintendent of Oregon State University Malheur Experiment Station (MES), is a co-author on each of the four journal articles in this thesis. Dr. Shock's contributions to the research included, but were by no means limited to, finding funding for my graduate research and providing intellectual support for planning and implementing the research reported here. Clint's patient guidance throughout the research helped me to complete each of the four journal articles that resulted. Dr. Al Mosley, my co-major professor, was instrumental in deciding upon methods to produce stressed tubers in field conditions and to examine them to learn the tuber quality response. His understanding of potato crop physiology led to the tuber quality response research reported in the last chapter.

Dr. Zoe Ann Holmes is a co-author of the article reporting the tuber quality response. The reducing sugars concentrations analyses were performed in her lab on campus, and she collaborated on the research from the beginning, often driving the 640 km to MES to help sample.

Tim Stieber, Senior Research Associate at MES, is a co-author because he was closely involved in the day-to-day conduct of the experiments, including many insightful contributions in data management. Tim also fried the tuber stem end samples in the Potato Quality Lab at MES.

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Introduction

Oregon growers are utilizing new opportunities to market value-added agricultural commodities overseas. An expanded export market is particularly important to Oregon's rural economy with its increasing constraints on logging and ranching. Potato is the leading value-added crop produced in Oregon.

In the irrigated Treasure Valley production region of eastern Oregon's Malheur County, growers face a special irrigation management problem in potato production. In some years, apparently associated with hot weather in June, a high incidence of dark end syndrome or, popularly, "sugar end", is found in harvested tubers in Malheur County. Dark end is a mild expression of the more severe conditions referred to as translucent (glassy) end and jelly end rot. Tubers with sugar end may look normal, or may have pointed stem ends. The stem ends may be quite firm to the touch, yet fry dark and have high concentrations of reducing sugars. Dark end is associated with heat and water stress that can be modified by irrigation.

Dark end is undesirable because frozen french fries darken at the stem end during frying. Large fast food chains, the principal consumers of Oregon's frozen french fries, have progressively reduced tolerances for dark ends. When contracted tubers are delivered to a processor, a sample is fried and the grower is penalized according to the percent of tubers that fried dark, if the contract contained a dark end penalty clause.

The water stress that occurred in furrow irrigated fields was thought to be responsible for the dark end syndrome, and sprinkler irrigation seemed to alleviate the problem. Since this research began in 1987, many Treasure Valley potato growers have converted from furrow irrigation to sprinklers. One advantage of sprinkler irrigation for relieving stress during hot weather is flexibility in scheduling. Furrow irrigation systems may not allow a grower to uniformly irrigate a field frequently enough to avoid stress on all portions of the field during hot weather. Research to determine the effect of transient stress in sprinkler irrigated fields had never been conducted using replicated field plots. The Oregon Potato Commission funded research to learn more about the dark end syndrome, particularly the response of Russet Burbank to transient stress. This research tested the hypothesis that a transient soil water stress early in tuber bulking could result in dark stem end fry color at harvest, and quantified the stress response.

Review of Literature

Dark end is a condition associated with higher concentrations of reducing sugar (glucose, fructose, etc.) in the basal (stem) end of the tuber (Iritani and Weller, 1973b,c). Iritani and Weller (1980) described three forms of dark end corresponding to: low starch and high sugars in the stem end and a normal apical end resulting from stress during early tuber development; high sugars and low starch in the apical end and a normal basal end resulting from stress during late tuber development; and high starch and high sugars in the stem end with low starch and sugars in the apical end found in overmature tubers caused by early death of the foliage. Their use of the term "dark end" was confined to the french fry produced from the tuber displaying the "sugar end" syndrome. We have applied the term "dark end" to the tuber affected with the syndrome because the grower is paid on the basis of fry color in a sample from the delivered tubers. Dark end is the appropriate term to use until research fully elucidates the true relationship between stress, increased reducing sugars, and dark fry color.

Potato leaf canopy temperature change in response to stress was investigated by Stark and Wright (1985). They reported that elevated canopy temperature with respect to air temperature did not occur until soil water potential fell below -65 kPa. They said canopy temperature measurement would not be useful in scheduling irrigation since potato is generally irrigated to relieve stress at a soil water potential wetter than -65 kPa. Leaf water potential, however, declined linearly with soil water potential and showed good predictive value as a measure of potato stress.

Dwelle, et al., (1981), observed a decline in photosynthetic rate associated with stomatal closure as stress increased. Levy (1983) also measured the relative turgor of potato leaves with stomatal fluctuations in response to stress and found that the degree of osmotic regulation was related to the maintenance of turgor. Measures of turgidity and leaf water potential are good indicators of potato plant water status.

Several hypotheses have recently been published regarding the carbohydrate metabolism of potato following a symposium on the subject held by the Potato Association of America at Quebec City, Canada on July 23, 1990 (Hiller, 1990). The symposium authors discussed several topics regarding the present lack of clear understanding of potato starch and sugar interconversions.

The first major problem in resolving the biochemistry of potato carbohydrate metabolism is understanding the cellular compartmentalization of the relevant constituents (ap Rees and Morrell, 1990). If an enzyme is located inside the amyloplast the activity of the enzyme in starch degradation may be profoundly different from the activity of the same enzyme located outside the amyloplast. Second, the relevant measurements of carbohydrate metabolism have been made for plants like beet and corn, and when measurements have been made for potato tuber, thin slices have been used which are known to metabolize carbohydrate very differently than intact tubers. An example of this problem is the intriguing report of Wright and Oparka (1989) that in actively growing potato tuber cells, the intake of sucrose is very sensitive to turgor. Wright and Oparka (1989) did not examine the situation in intact growing tubers, so the question remains: What is the relation of turgor to sucrose metabolism in developing tubers in the field?

Potato has been shown to be a water stress sensitive crop (Epstein and Grant, 1973), and the literature covering stress response and water requirements for potato production was reviewed by Singh (1969), and more recently by Stark and Wright (1990). Stress response has been measured in outdoor pot experiments (Levy, 1985) and in the field under shade cloth and full sunlight (Sale, 1973).

The water requirement for potato production has been measured by means of weighing lysimeters and by neutron probe studies of soil water content through the growing season. Wright and Stark (1990) tabulated the results of 17 studies reported from 10 locations and showed that potato uses between 450 and 700 mm of applied water during the growing season.

Studies of tuber bulking response to water stress in the field have been based on severe stress that reduced foliage (Hang and Miller, 1986), and resulted in reduced yield (Miller and Martin, 1987; Moorby and Milthorpe, 1975). The problem examined in this research was transient stress, similar to the situation encountered by a conscientious grower, with good irrigation management, who sometimes completes the season with dark end potatoes even though he never missed a scheduled irrigation. Such short duration, or transient, stresses in field-grown sprinkler irrigated Russet Burbank potato had not been studied or reported in the literature. It seems likely that the dearth of reports of studies using realistic transient stress as a factor in field research was due to the lack of a practical method to conduct such research.

Plot Sprinklers for Irrigation Research

E.P. Eldredge, C.C. Shock, and T.D. Stieber

Abstract

Research on crop response to soil moisture deficits may require irrigation of plots at different intensities, frequencies or durations. Portable plot sprinklers were developed that allowed for irrigation of individual plots independently of other plots. Each plot sprinkler consisted of three rotary pendulum, square-pattern sprinkler heads mounted on a PVC pipe frame. Plot sprinklers applied water at 0.9 m^3 h^{-1}, in an area 13.7 m long by 4.6 m wide, when operated at 86 kPa. Plot sprinklers were used to manage six levels of transient soil moisture deficit in a randomized block design to measure potato (*Solanum tuberosum* L. 'Russet Burbank') response during early tuber bulking. Plot sprinkler pattern uniformity (C_u = 76%) was adequate to manage soil moisture deficit in 20 kPa increments in June and July. Yield of USDA number one tubers decreased and yield of USDA number two tubers increased with increasing severity of transient soil moisture stress in both years. Plot sprinklers would also be useful for rainfall simulation, chemigation, or other research where irrigation levels are varied as independent, randomly assigned treatments.

Introduction

Field research to investigate the physiological responses of crop plants to irrigation often requires variable rates and frequencies of water application. Sprinklers are desirable for irrigation research because they provide versatility of water delivery in a pressurized system, flexibility of field layouts and absence of ditches, and good uniformity of delivery. The choice of research irrigation system is particularly important when, as is the case with potato, crop quality is sensitive to small variations in soil moisture.

Line-source sprinkler systems provide a continuous gradient of water application decreasing with distance from a single sprinkler line (Hanks, et al., 1976). Application frequency with a line-source system cannot be varied, unless individual plots are tarped, or sections of the line-source system are operated at different times relative to other sections. Because the different levels of water application under a line-source system cannot be randomized, Hanks, et al. (1980) pointed out that the influence of irrigation level on any crop parameter cannot be assigned a probability in such studies. Bresler, et al. (1982) provided a statistical method for separating the components of yield variability in a line-source experiment. Magnusson, et al. (1988) used intersecting line-source systems to apply continuous gradients of two variables, N-level and salinity. Senthong and Pandey (1989) used a line-source sprinkler system to compare responses of five legumes to a soil moisture stress gradient imposed during the pod-filling period.

Standard agricultural sprinklers could be used for randomized treatments in irrigation research; however, plot size would be large, with border areas, and treatment effects would be difficult to measure if wind distorted application patterns. The use of standard agricultural sprinkler systems for irrigation frequency research could result in large equipment and crop expenses and unwieldy field layouts.

Other methods for applying sprinkler irrigation to research plots have been described. Heatherly and Ginn (1980) described a mobile, tractor-mounted tank, pump, and water distribution framework for irrigating plots one at a time. Application rate was varied by adjusting the pressure, and plots longer than the framework could be irrigated by moving forward after irrigating the first section of a plot.

Adjustable part-circle sprinkler heads have been used to apply pre-plant herbicides to soil for research plots (Ogg, 1980). A pair of sprinkler heads were set to irrigate one-quarter of a 24 m diameter circle and a wind screen was used during the application. Plots were located in an area 6 m wide between 3 and 9 m from the sprinklers. Within the plot area, application rate decreased with distance away from the sprinklers. Application uniformity was inadequate for research closer than 3 m and farther than 9 m from the sprinkler heads and resulted in excess border area.

Individual field plots have been irrigated using a single lawn sprinkler in each plot for each irrigation (Larry Hiller, 1987, Washington State University, personal communication). Application uniformity of most stationary lawn sprinklers is less than desirable for irrigation crop response research. Kerr, et al. (1980) tested six types of lawn sprinklers and found that some pattern overlap between adjacent sprinklers was necessary for adequate water distribution uniformity. Required overlap ranged from one-quarter overlap for an impact sprinkler head to three-quarter overlap for a revolving arm impulse sprinkler. Pattern uniformity was deemed adequate when the data from a catchcan test yielded a Christiansen Coefficient of Uniformity (C_u) of 70% or larger.

Uniformity of application of sprinkler irrigation water to plots is an important factor in the design of field experiments to measure crop responses to water stress. If overall yield per plot is the parameter response being measured, treatment effects may be confounded by crop response to non-uniform water application (Solomon, 1984). Potato tuber shape, for example, is responsive to soil moisture deficit (Robins and Domingo, 1956). Decreased application uniformity increases the variance of any plant response to soil moisture. However, if the scale of non-uniformity of irrigation water application is smaller than the horizontal extent of the root system, crop plants tend to integrate variations in water availability (Seginer, 1979, Letey, 1985). Cogels (1983) derived a uniformity function based on the scale of a plant root zone to determine the effect of measurement scale on the variability of water distribution by sprinklers.

Cogels (1983) devised a scalogram for describing effective uniformity when the scale of influence is equal to the scale of observation. Cogels's assertion, that the effective uniformity of a given irrigation distribution is dependent on the availability of water to the plant, was echoed by Solomon (1984), who stressed that the consequences of irrigation application uniformity should be quantified in order to measure irrigation system application efficiency. Letey (1985) pointed out that "Matching the scale of measurement to root zone scale is conceptually important but has not been properly verified."

Zoldoske and Solomon (1988) said that C_u, although the most widely used measure of sprinkler uniformity, cannot be used to distinguish between sprinkler application patterns that may be very different at the scale of crop root zones. They also pointed out that no method of depicting sprinkler application uniformity takes into account the relative position of high and low water values in a catchcan grid, or the benefit that may be derived from high catchcan values in a pattern being located adjacent to low catchcan values.

Integration of differences in catchcan grid data at the scale of crop root systems would differ depending on the mechanism chosen for integration. If the differences are to be integrated by mathematical manipulation, such as Cogels's (1983) scalogram, Seginer's (1979) harmonic analysis, or Zoldoske and Solomon's (1988) sliding window, the resulting pattern may still not depict the water distribution resulting from an application to a given crop or soil system. None of these mathematical integrations account for factors such as splash, canopy interception, and stemflow that result in non-uniform infiltration into the soil. Sinai and Zaslavsky (1977) suggested the highly variable soil moisture in the root zone after uniform irrigation could be explained by unequal lateral conductivity through soil layers resulting in lateral redistribution.

Letey (1985) suggested using infiltrometers the size of the horizontal extent of the root zone of the crop in question to integrate the differences in sprinkler application uniformity. That suggestion, he recognized, neglected the possibility of differences in vertical root penetration, but would also, we suggest, neglect differences in infiltration rate of the soil inside the infiltrometer, water droplet interaction with crop canopy, and root growth into variably wetted soils that exist in field plantings. Saffigna, et al. (1976) used rhodamine WT water-soluble dye to study the soil distribution of sprinkler water application to Russet Burbank potato. They found that water ran down the stems of plants and down the sides of the potato hills, resulting in a very non-uniform distribution of water in the soil. Water infiltrated deeper below the plants and below the bottom of the furrows than in other portions of the hills.

The plot sprinklers described in this article allowed irrigation frequency to be varied in a randomized block design to evaluate potato tuber quality response to a transient soil water deficit.

Materials and Methods

Potato (*Solanum tuberosum* L. 'Russet Burbank') was planted at the Oregon State University Malheur Experiment Station in adjoining fields on Owyhee silt loam (course-silty, mixed, mesic Xerollic Camborthid) in 1988 and 1989. Irrigations before and after the transient stress period were applied both years with a solid-set sprinkler system consisting of three laterals equipped with impact sprinkler heads (Nelson model F32, Nelson Irrigation Corp., Walla Walla, WA 99362) with 3.2 mm nozzles operated at 407 kPa. Sprinkler heads were mounted on 71 cm vertical risers. Sprinkler heads were spaced 12.2 m apart on laterals by 15.2 m between the laterals. After June 21 the two outside laterals were temporarily dismantled, and the center lateral was modified to supply water to plot sprinklers.

During the transient stress period, from June 21 to July 19 in 1988 and from June 21 to July 18 in 1989, plots 13.7 m long by 4.6 m wide (5 row) were irrigated individually using 15 portable plot sprinklers. Plots were allowed to dry by evapotranspiration until each plot reached a pre-assigned level of soil water potential as measured by the average of the readings of two electrical resistance granular matrix sensors (GMS) per plot (Watermark Soil Moisture Sensor model 200x, read with meter model 30KTC, Irrometer Company, Riverside, CA 92516).

Each plot sprinkler consisted of three Rainjet 836C rotary pendulum, square-pattern sprinkler heads (James Hardie Irrigation, Laguna Niguel, CA 92677) mounted on 46 cm tall polyethylene risers spaced 4.57 m apart on a frame of Schedule 40 polyvinylchloride pipe (Fig. 1, and Table 1). Components for each plot sprinkler cost about $35 in 1988. The frame of the plot sprinkler rested on the potato vines in the center row of the five-row plot and was held upright by legs extending to the top of the rows on each side. The center row was a buffer row between two sample rows and the outside two rows of each plot were borders.

Application uniformity of the 836C sprinkler head distribution pattern was tested indoors with a square grid of 100 catchcans, spaced 50 cm apart with a single sprinkler head in the center (ASAE Standards, 1987). Catchcans were 9.3 cm inside diameter, made by cutting the rim from plastic drinking cups to leave a sharp edge (Kerr, et al, 1980). Clean tap water was delivered to the sprinkler through a garden hose 18 m long by 1.6 cm inside diameter. Pressure at the inlet of the hose was maintained at 86 kPa by a diaphragm pressure regulator. Sprinkler output in a 1 h test was measured with an in-line totalizing flowmeter, water caught in each catchcan was measured with a graduated cylinder, and the pattern uniformity test was repeated.

The treatments were six soil moisture levels, in 25 kPa increments, from -25 to -150 kPa as indicated by the GMS meter. The six treatments were replicated seven times in a randomized complete block design in 1988 and again in 1989. Soil water potential was measured daily as the average reading of two GMS, buried 6 m apart, 25 cm deep, in the center row of each plot. During the stress period, when GMS indicated the soil water potential of a plot had reached the designated treatment level, water was applied using a plot sprinkler.

The GMS and meter were calibrated in 1988 and 1989 by comparison to tensiometers in a potato row beside the experimental area. Installations consisting of tensiometers at 30 and 60 cm depth with GMS 30 and 60 cm depth were replicated 10 times in 1988 and pairs of tensiometers at 46 cm depth with pairs of GMS at 46 cm depth were replicated 10 times in 1989. Readings were taken about every 3 days as soil dried from saturation following an irrigation to approximately -100 kPa. Data from all installations and depths for both years were combined and analyzed by regression.

During the transient stress period, garden hose faucets were mounted in pairs in pipe tees installed in place of the impact sprinkler heads on the risers of the center lateral of the solid-set system to temporarily modify it to supply water to plot sprinklers. Each faucet was drilled and tapped downstream of the valve seat and a Schrader-type tank valve was installed to serve as a port for pressure measurement. Plot sprinklers were carried into plots scheduled for irrigation and connected to a riser of the solid-set system lateral with a garden hose 1.6 cm inside diameter by 18 m long. At each irrigation, water pressure into the garden hose feeding a plot sprinkler was manually adjusted to 86 kPa reading on a pressure gauge with an air chuck on the tank valve. After the initial pressure was set, final pressure adjustments were made by fine tuning the pressure of each faucet upward until all plot sprinklers were operating at a steady 86 kPa. Final pressures could be achieved in less than 10 min by two persons.

All tubers from 12 m of row 2 of each plot were harvested and graded into USDA number one tubers, undersize tubers, USDA number two tubers, and decayed tubers. Data were analyzed by regression procedures for a randomized block design.

Results and Discussion

Individual 836C sprinklers applied less water near the sprinkler head, more around the perimeter, and decreasing amounts again at the outer edge, with a resulting C_u = 76%, (Fig. 2). The rotary pendulum operation of the 836C sprinkler head produced a square pattern adequate to design the plot sprinkler without overlap, based on the criterion followed by Kerr, et al. (1980), of C_u = 70% being the minimum acceptable coefficient of uniformity for turf sprinkler systems designed without overlap. The grid spacing selected for monitoring distribution, 50 cm, provided enough catchcans to adequately quantify the distribution pattern of the 836C sprinkler head (ASAE, 1987). The 50 cm grid spacing was small enough to represent the horizontal extent of the potato root system since, if the catchcan grid were superimposed on the potato rows, there would have been two rows of catchcans per row of crop.

The distinct margin of the spray pattern allowed potato plots to be established with a minimum of border area. The water pressure used, 86 kPa measured at the inlet of the 18 m long garden hose, resulted in 0.3 m^3 h^{-1} output from each sprinkler head and produced a pattern 4.6 m wide by 13.7 m long when the three-head plot sprinkler was connected through the garden hose. The low pressure used produced large droplets with a low angle of trajectory, limiting wind distortion of the wetted pattern. Since plot sprinkler output, 1.4 cm h^{-1}, exceeded the infiltration rate of the soil, irrigation sets were 1 h in duration.

One method for assessing the distribution uniformity of a given sprinkler system for a given crop on a given field conformation could be to measure some crop or soil parameter sensitive to variations in water application. If, at the scale of the plots sampled, differences in the crop parameter response to treatments were small within plots compared to between treatments, the sprinkler irrigation uniformity was probably adequate for the crop and experiment conducted. Such parameters might include, but not be limited to, plant water potential, plant relative water content, leaf permeability, plant canopy temperature, soil water potential, or soil gravimetric water content. Shimshi, et al. (1983) reported potato response to irrigation treatments imposed with drip, standard sprinkler, and line-source sprinkler irrigation systems. They measured leaf permeability, leaf and tuber water potential, and rate of photosynthesis, and concluded that leaf permeability is a more useful index of water stress in potato.

Plot sprinklers provided a method for irrigating a field crop physiology experiment using different levels of soil water potential as independent treatments in a randomized block design. Treatment levels, after calibration of Watermark readings in the field against tensiometers, were 19 kPa increments of soil water potential (Table 2). The relationship between tensiometer readings (y) and Watermark sensor readings (x) in the root zone of a potato crop grown in Owyhee silt loam, was: $y = -6.45 - 0.753x$, with $r^2 = 0.89$.

Yield and grade of Russet Burbank tubers responded to transient water stress treatments imposed during early tuber bulking. Plot sprinklers applied water uniformly so that tuber grade response to soil moisture deficit during the transient stress period could be measured (Table 2). Total yield of USDA number two tubers increased while total yield of USDA number one tubers decreased with increasing levels of stress. In both years, increasing levels of stress resulted in increases in undersized tubers. Most of the decayed tubers in both years were affected by jelly-end rot, especially in the most stressed treatments (Nielson and Sparks, 1953).

Soil moisture sensors were situated in the center row, where the drier region in the center of each 836C sprinkler head pattern was located. The amount of water applied to plants in row 2, the sample row, may have slightly exceeded the amount of water applied to the center row, where GMS were buried. Treatment differences in potato tuber quality were detectable in this experiment because the effects of plot sprinkler pattern deficiencies and soil moisture sensor placement were smaller than treatment influences.

Uniformity of water application with these plot sprinklers may be inadequate for closely-spaced plants with small root systems, season-long irrigation of crops, or research on soils with very high or very low infiltration rates. The area of plots from which samples are taken should be aligned with the area of most uniform water application as shown by the catchcan test. Designing the plot sprinklers with partial overlap of the patterns from adjacent 836C sprinkler heads, or increasing the pressure, or both, might improve application uniformity. Plot sprinklers such as the ones described in this paper are ideally suited to automated control and could also be used to investigate fertilizer or pesticide applications in field research.

Table 1. Components of plot sprinklers.

<u>COMPONENTS FOR ONE PLOT SPRINKLER SYSTEM</u>
(4.6 x 13.7 m pattern)

qty	
3	836C square-pattern sprinkler head
3	1/2 inch[†] x 18 inch polyethylene riser
2	3/4 inch x 1/2 inch SxT PVC elbow
2	3/4 inch x 3/4 inch x 1/2 SxSxT PVC tee
2	3/4 inch SxSxSxS PVC cross
4	3/4 inch PVC cap
4	3/4 inch x 89 inch schedule 40 PVC pipe
4	3/4 inch x 41 inch schedule 40 PVC pipe
1	3/4 inch x 6 inch schedule 40 PVC pipe
1	1/2 inch x close polyethylene nipple
1	1/2 inch x 3/4 inch FPT x hose swivel

<u>COMPONENTS FOR CONNECTING TO SOLID-SET RISER</u>
(solid-set sprinkler head removed)

1	3/4 inch galvanized nipple
1	3/4 inch galvanized tee
2	3/4 inch garden hose brass faucet
2	1/8 inch tank valve
1	5/8 inch i.d. x 60 ft garden hose
1	0-30 psi, 1/4 inch bottom mount gauge
1	1/4 inch air chuck

[†]English units identify U.S. standard plumbing parts.

Table 2. Yield and grade after transient stress. Tubers were from Russet Burbank plants subjected to soil moisture stress during early tuber bulking in 1988 and 1989.

Stress Criterion	Soil Water Potential†	U.S. No.1	U.S. No.2	Undersize	Rot	Total Yield
			1988			
	-kPa	-----------	-----------	Mg ha^{-1}	-----------	-----------
25	32	18.3	19.7	15.5	0.2	53.7
50	48	19.3	21.8	16.3	0.1	57.5
75	63	17.6	23.2	17.1	0.0	58.0
100	81	16.5	24.9	18.7	0.0	60.1
125	104	6.4	28.3	21.7	0.9	57.3
150	105	5.4	33.9	19.0	0.5	58.8
Mean		13.9	25.3	18.1	0.3	57.6
Slope		-0.17	0.14	0.06	0.0	0.04
r^2		0.50***	0.38***	0.22***	0.10NS	0.04NS
			1989			
25	32	42.5	9.6	11.8	0.8	64.7
50	50	44.6	9.0	10.8	0.6	65.1
75	69	40.0	11.1	11.5	0.6	63.2
100	93	36.6	16.7	11.4	1.8	66.4
125	100	28.1	21.6	15.4	2.8	68.0
150	107	22.7	23.7	18.7	4.9	70.0
Mean		35.7	15.3	13.3	1.9	66.2
Slope		-0.21	0.18	0.04	0.04	0.47
r^2		0.43***	0.61***	0.11*	0.30***	0.11*
			Both Years			
25	32	30.4	14.7	13.6	0.5	59.2
50	49	32.0	15.4	13.6	0.4	61.3
75	68	28.8	17.1	14.3	0.3	60.6
100	87	26.6	20.8	15.0	0.9	63.3
125	102	17.2	25.0	18.6	1.8	62.6
150	106	14.1	28.9	18.6	2.7	64.1
Mean		24.9	20.3	15.6	1.1	61.9
Slope		-0.19	0.16	0.54	0.02	0.04
r^2		0.13***	0.28***	0.10***	0.16***	0.05*
Slope		22.32	70.45	-5.01	1.59	8.42
R^2tm + yr		0.80***	0.68***	0.39***	0.39***	0.47***

†Soil water potential values are average maximum sensor values for each treatment, converted by $y = -6.45 + -0.75x$, where y = -kPa and x = Watermark reading.

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

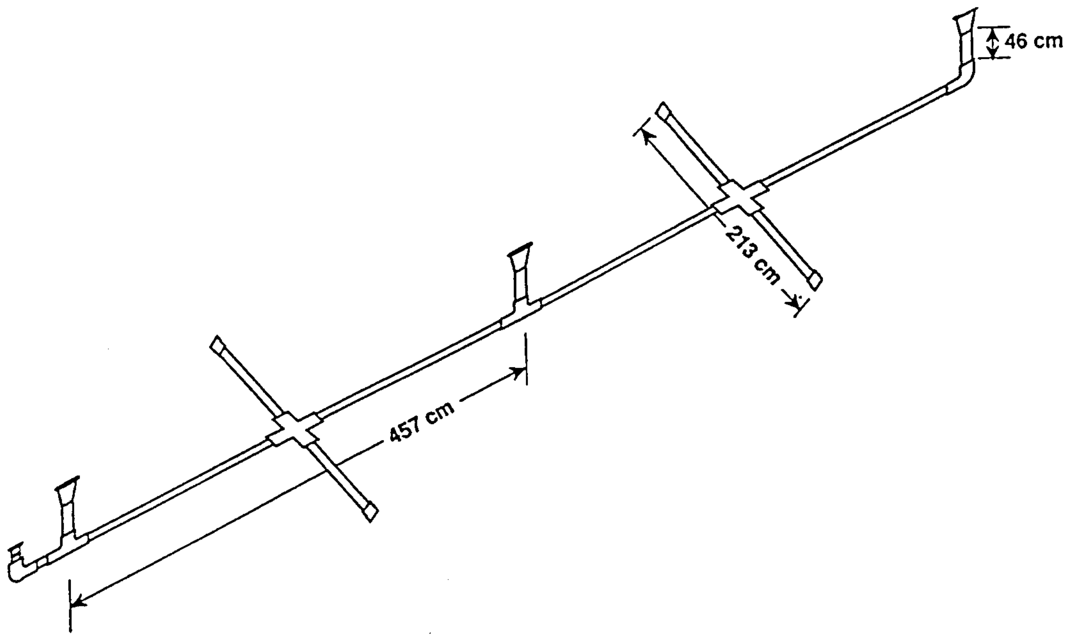

Figure 1. Assembled plot sprinkler apparatus. The schematic view of an assembled portable plot sprinkler shows the relationships among the components listed on Table 1.

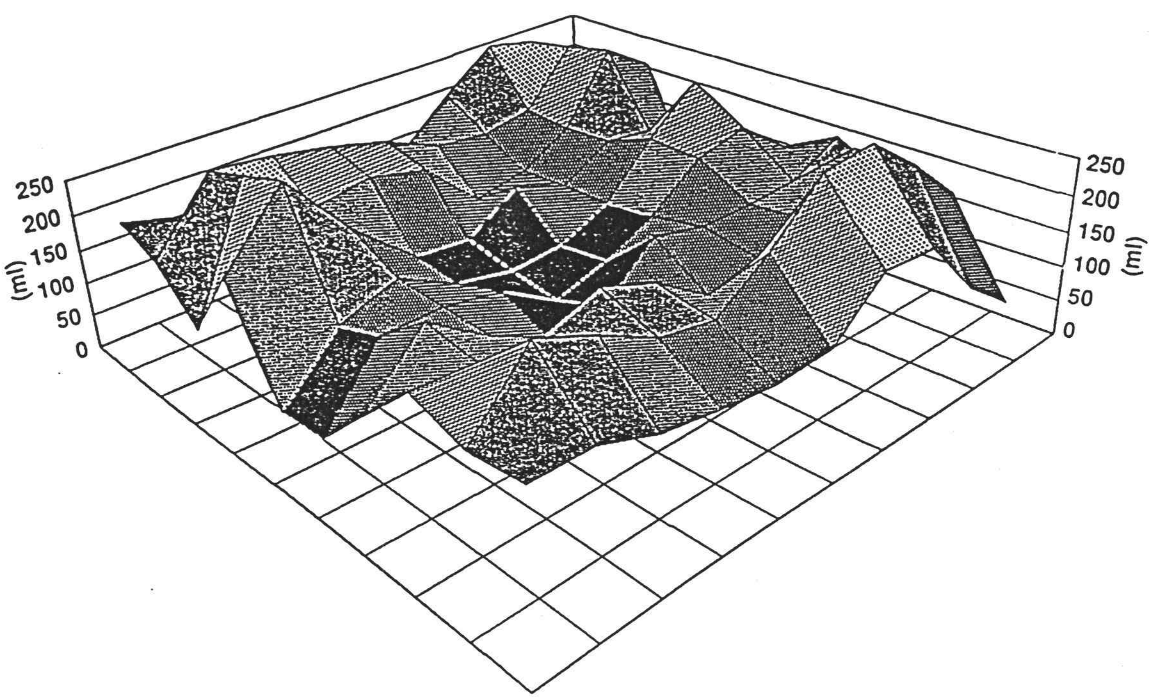

Figure 2. 836C distribution pattern. Water distribution from a single 836C square-pattern sprinkler head located in the center of a grid of 100 catchcans. Each square in the diagram represents a catchcan, darker shading indicates less water.

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Calibration of Granular Matrix Sensors for Irrigation Management

Eldredge, Eric P., Clinton C. Shock, and Timothy D. Stieber

Abstract

Granular matrix sensors (GMS) for measuring soil water potential were tested by drying them to measure changes in electrical resistance with decreasing moisture. GMS resistance response to drying in air in an oven was virtually identical (t = -0.87, 134 d.f.) to that for drying in a field soil, with a response curve that suggested GMS could be used to measure soil water potential. GMS were compared to tensiometer, neutron probe, and gravimetric estimates of moisture in the root zone of potato (*Solanum tuberosum* L. 'Russet Burbank') grown in silt loam soil. GMS readings were more closely related to tensiometer readings than to gravimetric or neutron probe readings. The GMS calibration equation was y = -6.45 -0.753x; where y = tensiometer kPa soil water potential and x = GMS resistance meter 30KTC reading, with $r^2=0.89$. GMS were used to monitor transient soil water stress level treatments in an

experiment to determine potato response to moisture stress. Single episode transient soil water stress treatments in 20 kPa increments of soil water potential were managed according to mean readings of two GMS per plot.

Introduction

Profitable irrigation of moisture-sensitive crops requires some system of irrigation scheduling to manage irrigation decisions. In simplest terms, once an irrigation system and application rate are chosen, the two basic questions every manager must answer to schedule each irrigation are: 1. "When do I turn the water on?" and 2. "When do I turn the water off?" The answers to those questions determine irrigation frequency and duration. Information to answer those questions may include atmospherically-based, plant-based, or soil-based data (Heerman, et al., 1990). Examples of atmospheric scheduling information are weather forecasts and pan evaporation measurements, plant data may include canopy temperature and visible wilting, and soil-based data may include soil water content and soil water potential. In practice, plant, soil, and atmospheric data are often used concurrently, especially when changes in irrigation scheduling are required to adjust for changes in crop water use.

Soil-based irrigation scheduling data acquisition methods range from the simple "feel" method to such technologically advanced methods as the neutron probe and time-domain reflectometry (Campbell and Mulla, 1990). Tensiometers and gypsum blocks provide technology and cost between these extremes, but they have limitations for practical use by growers to schedule irrigations. Tensiometers require continual service, a high level of skill in installation and management, and are only accurate in the 0 to -70 kPa range of soil water potential with a reduced range in light-textured soils (Cassel and Klute, 1986). Gypsum blocks are manufactured at different sensitivities by mixing the plaster to obtain different ranges of pore sizes (Campbell and Gee, 1986). The water content of gypsum blocks, or any porous absorber placed in firm contact with soil, depends on the soil water potential and not the water content of the soil (Gardner, 1986). The blocks will eventually dissolve, lose firm contact with the soil, and respond inconsistently to soil moisture changes. Because of these limitations, tensiometers and gypsum blocks have not gained widespread acceptance for irrigation management.

A granular matrix sensor (GMS) for electronically measuring soil moisture has been patented (Larson, 1985). GMS technology reduces the problems, inherent in gypsum blocks, of restricted pore size distribution and loss of contact with the soil, by use of an insoluble granular fill material held in a fabric tube supported in a metal or plastic screen. GMS operate on the same electrical resistance principle as gypsum blocks and contain a wafer of gypsum imbedded in the granular matrix below a pair of coiled wire electrodes. The electrodes inside the GMS are imbedded in the granular fill material above the gypsum wafer. The gypsum wafer slowly dissolves to buffer the effect of salinity of the soil solution on electrical resistance between the GMS electrodes. According to Larson (1985), particle size of the granular fill material and its compression determines the pore size distribution in the GMS and its response characteristics.

GMS calibration using pressure plate apparatus was described by Thomson and Armstrong, (1986), and by Wang and McCann, (1988). GMS were shown to respond in the -10 to -100 kPa range of soil water potential; however, the published reports are not in agreement on the resulting calibration equation. Thomson and Armstrong (1986) presented the equation:

$$S = \frac{R}{0.01306\,[1.062\,(34.21 - T + 0.01060\,T^2) - R]}$$

where R = sensor resistance, kohm; S = soil water potential, kPa; and T = temperature, °C. Wang and McCann (1988), published a different calibration of GMS described by the equation: $S = -57.976 + 4.4753R + 2.5225T$ where R = sensor resistance, kohm; S = soil water potential, kPa; T = temperature, °C.

This paper reports GMS responses and GMS application to irrigation management. The water retention characteristic of GMS was measured in drying experiments in an oven and field soil. GMS were calibrated in the field against tensiometers, a neutron probe, and gravimetric soil water determinations. This paper also presents results of the use of GMS for managing a replicated field trial where treatments were increments of transient soil moisture stress in sprinkler-irrigated potato.

Materials and Methods

An oven drying study was conducted in 1987 to measure the relationship between GMS (marketed as "Watermark" by Irrometer Co., Box 2424, Riverside, CA 92516) resistance measured with a model 30KTC meter (Irrometer Co.) and GMS gravimetric water content. The 30KTC meter is a manually adjustable parallel bridge with an audible reference buzzer to indicate the balance resistance. The value of a reading when the buzzer sounds is indicated by the pointer location over a scale printed on the case of the instrument. A switch allows readings to be made in either of two ranges, from 0 to -100 kPa and from -100 to -200 kPa. An adjustment knob permits temperature compensation of approximately 0.55 percent of the range per degree C.

Five GMS were selected at random from 1987 production and labeled 1 through 5. Saturated electrical resistance readings of the set of GMS were obtained as follows: GMS were soaked for 1 h in de-ionized water, removed and drained for 10 min, blotted with paper towel to remove surface moisture, and quickly weighed to the nearest 0.01 g. Resistance values were measured with the 30KTC meter. GMS were then placed on a tray in a forced-air drying oven at 38 °C for 1 h, removed from the oven, weighed, tested for resistance values and returned to the oven. GMS electrical resistance and weight were measured hourly for the first 4 h, every 0.5 h for 4.5 h, then left 36 h after which oven dry weight and resistance readings were recorded.

A study was conducted in 1989 to measure the response of GMS to a drying cycle in Nyssa silt loam (coarse-silty, mixed mesic Xerollic Durorthid). Fifty-two GMS were repeatedly soaked in water and air dried, then oven dried for 72 h at 44 °C and weighed. GMS were then soaked for 2 h and saturated weights were recorded. A uniform field area 15 m long left fallow for 150 days after it was rototilled to 30 cm was irrigated to saturation with a soaker hose for 4 h. After allowing the soil to drain for 16 h, 26 pairs of GMS were installed 20 cm deep at sites 0.5 m apart on the center of the wetted strip on August 15. After 24 h, and on day 5, 6, 7, 9, 23, 24, 27, 40, and 44 thereafter, two or four sites were selected at random, measured using meter 30KTC, and the GMS were removed for determining gravimetric water content. The soil dried by evaporation because of the absence of plants in the rototilled strip.

GMS were compared to tensiometers, neutron probe, and gravimetric sampling for estimating moisture levels in the root zone of a potato crop grown on Owyhee silt loam (coarse-silty, mixed, mesic Xerollic Camborthid). Ten replicate soil moisture measurement comparison stations were established in the root zone of a uniformly-irrigated potato row. Each station consisted of tensiometer, GMS, and a neutron probe access tube with 3 m spacing between stations. Data were collected from all stations seven times from July 6 to July 31, 1989. Data were initially collected the day after an irrigation, after which the potato crop was intentionally stressed beyond normal irrigation criteria to increase the range of readings taken with the four methods.

GMS were used to manage field trials in 1988 and 1989 to investigate potato response to transient soil moisture stress during early tuber bulking. Six levels of soil moisture were imposed as treatments, replicated seven times in a randomized block design. Plots were five rows wide (4.6 m) by 13.7 m long. Transient stress treatment levels, as measured by GMS 30KTC meter readings, were imposed by withholding irrigation until individual plot mean GMS readings indicated the assigned treatment stress level had been reached.

Two GMS were installed in the center row of each plot, 25 cm deep and 6 m apart. Each GMS was attached to 18 m of 18 gauge speaker wire leading into each plot from a plastic spool outside the border rows of the experimental area. More wire was unwound from spools for GMS in plots near the center of the experiment, and less from spools for GMS near the outside edges. Spade tongue lugs were soldered onto the ends of wires from the spools and fastened to a 12-terminal Jones-type terminal strip mounted atop a cross-piece on a wooden stake. The six readings from GMS in three plots could be taken at each stake. A row of seven stakes down each side of the research area permitted data to be quickly taken daily. The GMS meter 30KTC leads were modified by fastening the alligator clips to an insulating PVC block at spacing matching the terminals. Bare spade tongue lugs were fastened under each screw on the terminal strip opposite the GMS wires. The paired alligator clips could be depressed in unison, placed on a pair of lugs, the 30KTC reading recorded, and the procedure repeated.

The experiment was sprinkler irrigated uniformly until June 21 both years, and plots were then allowed to dry by evapotranspiration. GMS readings were taken daily, and each plot was individually irrigated using a plot sprinkler when it reached the predetermined soil water potential (Eldredge, et al., 1991). Immediately before the irrigation ending the transient stress was initiated, a gravimetric soil sample consisting of 10 soil probe cores from the 20 to 25 cm depth was taken from the center row of the plot, and leaf water potential was estimated on 10 leaflets from plants in the third row of the plot using a leaf press (Eldredge and Shock, 1990).

After the transient stress episode, the entire experiment was uniformly sprinkler irrigated for the rest of the growing season with irrigations scheduled to prevent plant stress.

Data from studies of GMS response to oven-drying, a soil drying cycle, comparison to other soil moisture measurement devices, and field trials of GMS management of replicated irrigation treatments were analyzed using regression methods.

Results and Discussion

GMS meter 30KTC data from the oven drying trial of five GMS were curvilinear when plotted against percent water content (Fig. 3). Regression analysis for the best fit line produced the equation $y = 349.3\ e^{-0.851x}$; where y = meter model 30KTC reading and x = percent water in GMS, and $r^2 = 0.94$. Data from the drying cycle test conducted in a field soil yielded a similar regression curve equation $y = 382.2\ e^{-0.820x}$; where y = meter model 30KTC reading and x = percent water in GMS, and $r^2 = 0.94$ (Fig. 4). The uniform response curves resulting from regression analysis of data from the different drying environments of an oven and field soil showed inherent uniformity of GMS electrical resistance to drying. The curves were compared using a paired-t test, finding $t = -0.87$, 134 d.f. The change in measured resistance over the range of water contents demonstrated that a range of pore sizes existed within the granular matrix. GMS construction controls the particle size of the granular fill material and its compression, thereby determining the pore size distribution in the GMS and its response characteristics (Larson, 1985).

Comparison of GMS to tensiometers in the root zone of a potato crop resulted in a scatter diagram and linear equation of least squares line $y = -6.45 - 0.753x$; where y = tensiometer kPa and x = GMS meter model 30KTC reading, with $r^2 = 0.89$ (Fig. 5). The relationship was linear, over the range 0 to -100 kPa. Soil water content and soil water potential are related, since as soil water content increases, soil water potential increases, until the soil is saturated. As soil water content diminishes soil water potential decreases, but the rates of decline are not necessarily identical, depending on the pore size distribution in the soil. Neutron probe and gravimetric measurements of soil water content were less closely related to each other than they were to GMS or tensiometer measurements of soil water potential (Table 3). GMS 30KTC readings were more highly correlated to tensiometer readings than measurements taken with other devices, indicating inherent reliability of GMS. The devices that measured soil water potential, GMS and tensiometers, were more closely in agreement than any other pair of measurements.

GMS were used to monitor soil water potential during drying by evapotranspiration of individual plots in a potato experiment. In this experiment, the mean duration of stress to achieve a soil water potential of -100 kPa was 12 d, since plant water uptake and transpiration diminished as the soil became progressively drier. The plots assigned higher values of soil water potential reached their treatment level sooner and received a stress relief irrigation. To prevent any further stress on potato plants that had reached their treatment soil water potential, whenever the daily average GMS reading was drier than the treatment level a plot received an additional irrigation. In this sense the experiment was "sensor-driven".

GMS averages of Replicate V of 1988 during the transient stress are shown in Fig. 6. GMS readings started uniformly wet at day 175, and increased steadily in treatments that were not being irrigated, treatments 5 and 6, for example. GMS readings were related to leaf water potential estimated with a leaf press with $r^2 = 0.49$ (Fig. 7), and leaf press estimates were correlated to soil water content determined gravimetrically with $r^2 = 0.75$ (Fig. 8). Leaf press and gravimetric measures may be more highly correlated because they are based on 10 subsamples taken down the length of the plot, while GMS figures are based on only two locations 3 m apart in the center row of the plot. Leaf press and gravimetric measures spanned more spatial variability in each plot. Further research should be done to clarify how leaf press measures of plant water status physically relate to leaf anatomy, plant water status, soil water potential, and soil water content.

The good fit of the linear model and the strong correlation found in field comparison of tensiometers with GMS indicates GMS can be used to measure soil water potential to indicate when an irrigation should be started. GMS can be substituted for tensiometers in irrigation management after calibration to tensiometers when irrigation criteria based on soil water potential have been established. The GMS calibration results in this report may not apply to crops growing on soil textures other than silt loam. GMS should be calibrated against tensiometers in the root zone of a growing crop. The tensiometers used should be new or freshly reconditioned and calibrated.

GMS are ideally suited for sensing soil moisture to automatically start an irrigation, such as the system described by Shull and Dylla (1980). GMS have advantages of low unit cost, and simple installation procedures similar to those used for tensiometers. Once they have been installed, however, GMS have advantages over tensiometers. GMS data acquisition can be remote from the measurement site by use of long electrical wires, so the plants and soil at the measurement site remain undisturbed. Modification of the meter to permit rapid electrical connections enabled a researcher to record the daily readings from 84 GMS in less than 0.5 h.

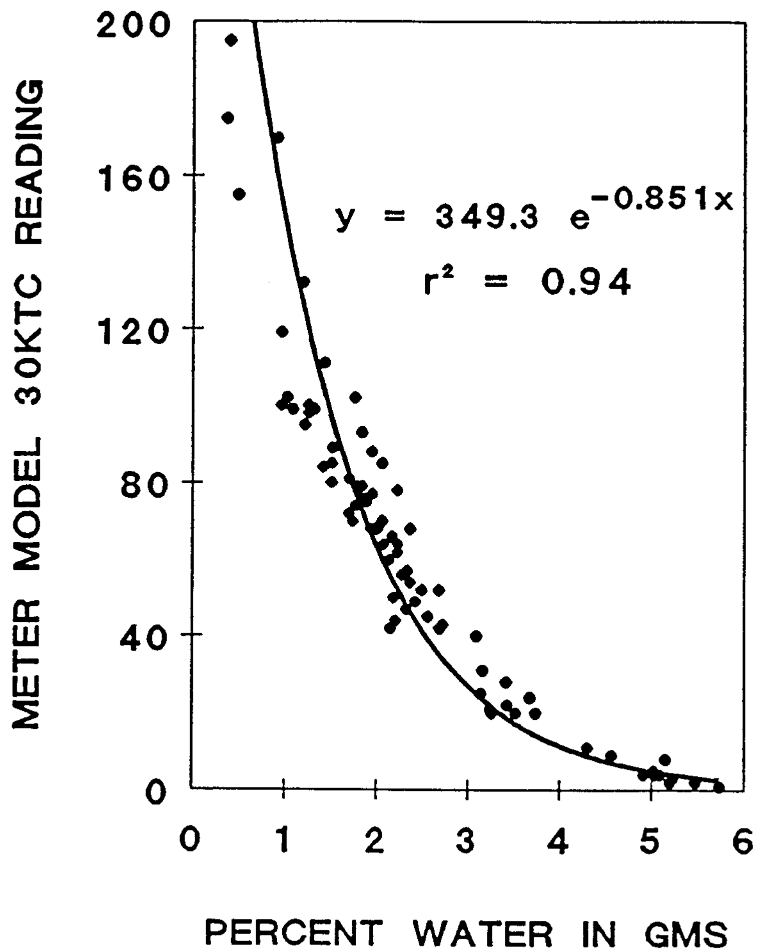

Figure 3. Oven drying GMS. Relationship of GMS resistance recorded with meter model 30KTC to percent water in GMS during an oven drying cycle.

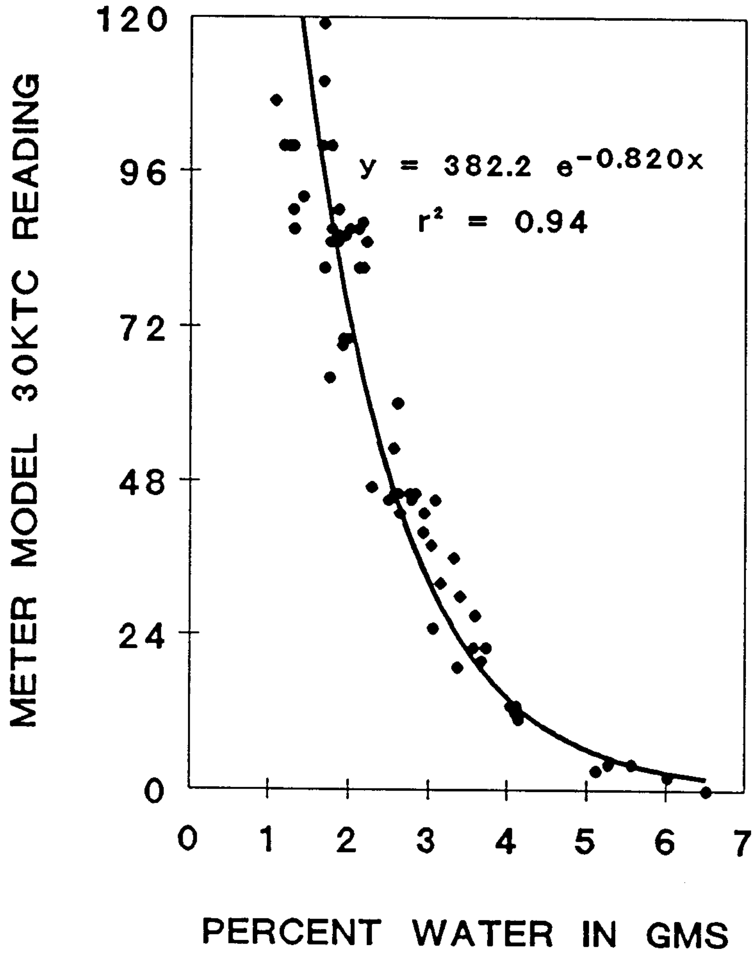

Figure 4. Soil drying GMS. Relationship of GMS resistance recorded with meter model 30KTC to percent water in GMS during a drying cycle in field soil.

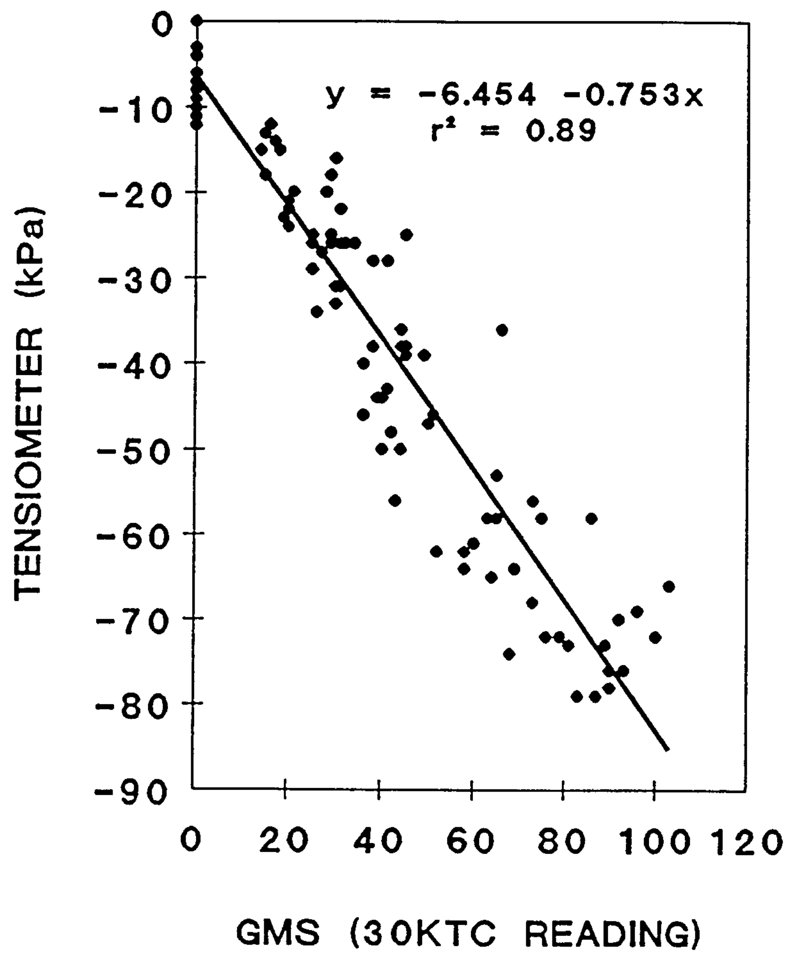

Figure 5. GMS compared to tensiometers. Relationship of GMS meter model 30KTC readings to tensiometer readings from devices installed 15 cm apart in the root zone of potato grown in a silt loam.

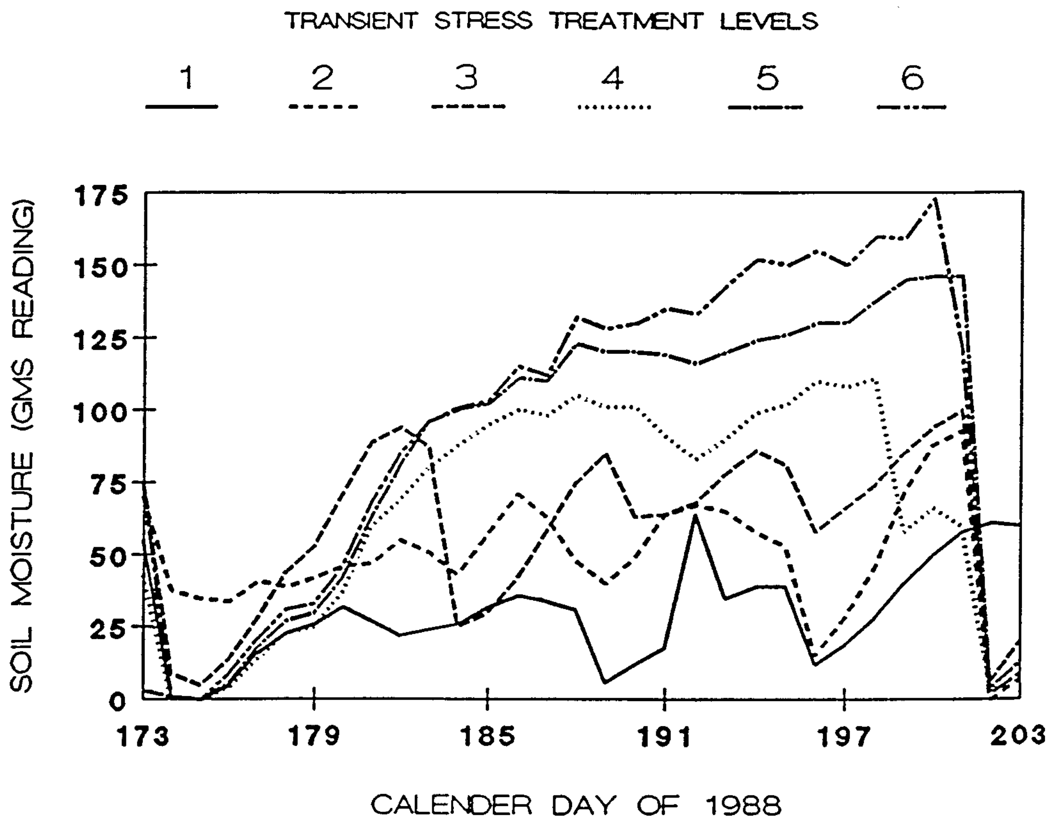

Figure 6. Soil moisture levels. Soil moisture levels of field plots of potato managed by daily GMS readings of soil moisture during a transient stress period.

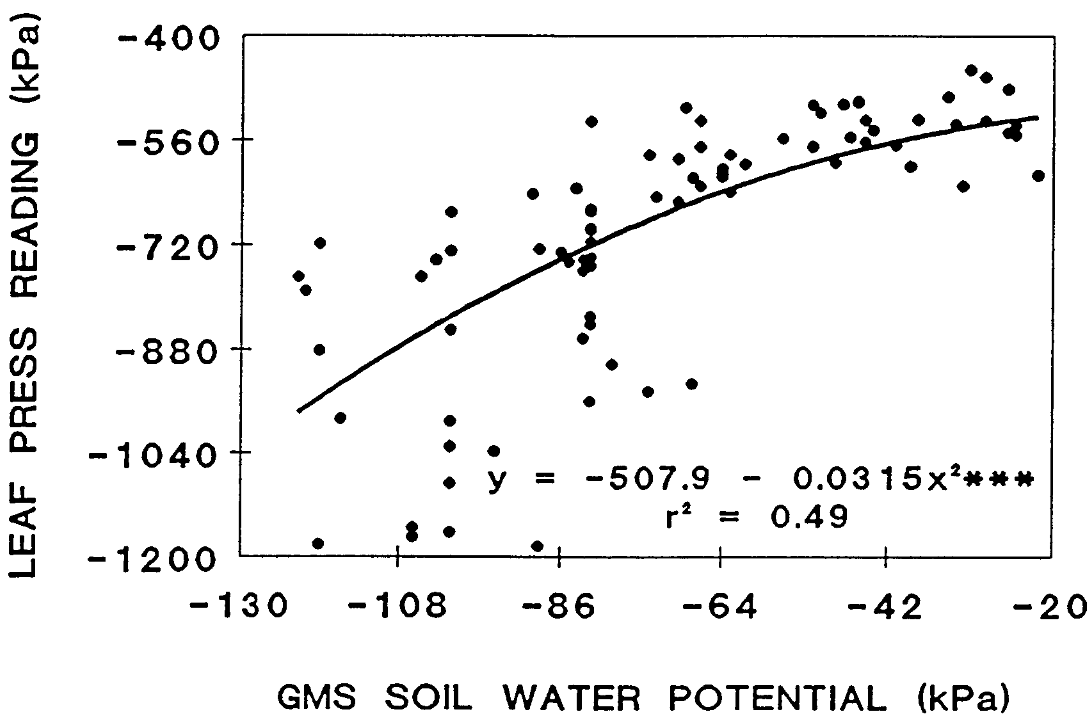

Figure 7. Leaf press and GMS. Relationship of leaf press estimates of potato water status to GMS readings of soil water potential.

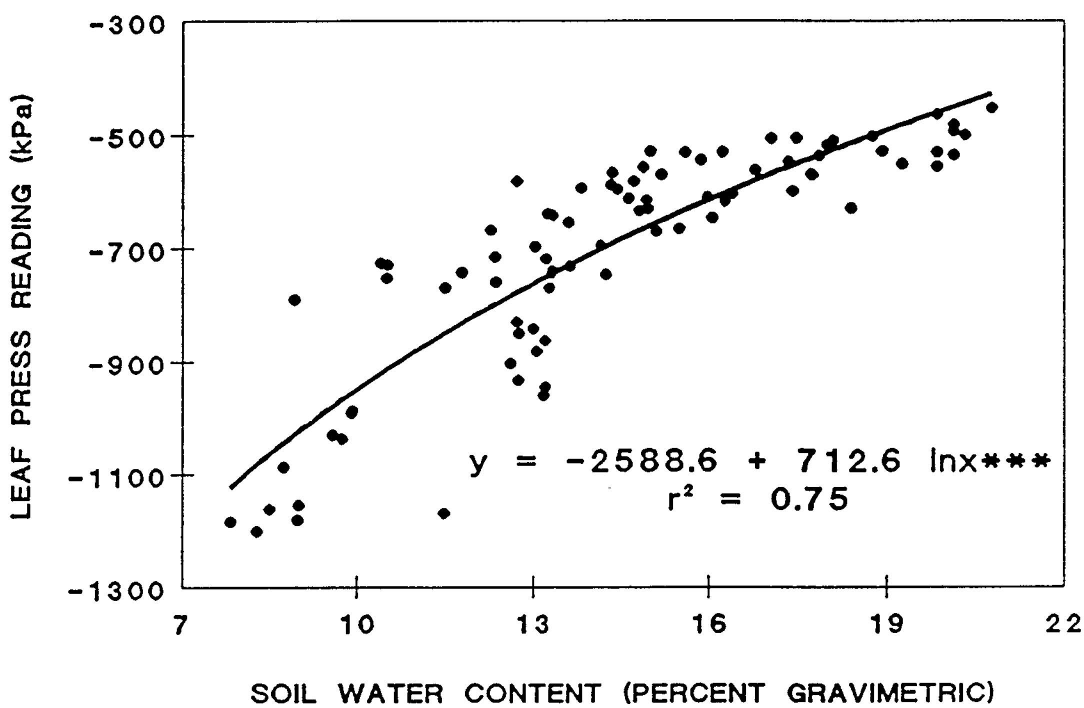

Figure 8. Leaf press and gravimetric. Relationship of leaf press estimates of potato water status to gravimetric soil water percentage.

Table 3. Four soil water monitoring devices. Relationships among four water monitoring devices for estimating soil water in the root zone of a potato crop.

y	equation	*x*	r^2
tensiometer kPa	$y = -6.45 - 0.753x$***	GMS 30KTC reading	0.89
tensiometer kPa	$y = -145 + 5.70x$***	gravimetric percent	0.57
tensiometer kPa	$y = -185 + 49.2x$***	neutron probe in/ft	0.66
neutron probe in/ft	$y = 3.45 - 0.0107x$***	GMS 30KTC reading	0.79
gravimetric percent	$y = 22.3 - 0.0763x$***	GMS 30KTC reading	0.71
gravimetric percent	$y = 0.398 + 6.17x$***	neutron probe in/ft	0.67

*** correlation significant at P = 0.001

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Comparison of Hydraulic Press and Pressure Chamber Estimates of Potato Leaf Water Potential

Eric P. Eldredge and Clinton C. Shock

Abstract

Leaf water potential was estimated in field-grown potato (*Solanum tuberosum* L. cv Russet Burbank) with a pressure chamber and a leaf press to assess the usefulness of the leaf press for evaluation of potato leaf water status. Paired leaflets were used for leaf water potential estimation with both instruments. Leaflets were taken from potato plants exposed to excessive soil moisture and high relative humidity, from plants with adequate soil moisture, and from plants under severe water stress. Over the range from -0.28 to -1.61 MPa, for 124 leaflet pairs, the leaf press estimates of leaf water potential were exponentially related (r^2 = 0.85) to pressure chamber estimates. The leaf press compared well with the pressure chamber in the range from -0.6 to -1.2 MPa.

Introduction

Leaf water potential in potato plants can be used as an indicator of crop response to environmental conditions. This paper compares leaf water potential readings taken with a leaf press to readings taken with a pressure chamber. The pressure chamber estimates the xylem pressure potential of a plant and can provide approximate measurements of leaf water potential if calibrated with a thermocouple psychrometer (Boyer and Ghorashy, 1971, Turner and Long, 1980). The pressure chamber procedure can be impractical for field research (Hicks et al., 1986, Radulovich, et al., 1982, Rajendrudu, et al., 1983, Yegappan and Mainstone, 1981).

Shayo-Ngowi and Campbell (1980) found that, for five species tested, leaf tissue matric potentials measured with the leaf press and pressure chamber were identical when the cell membranes were destroyed by freezing and thawing. Apparently when the apoplast is partially filled with cell sap in thawed tissue, the two devices measure the same thing. In living tissue, where intercellular spaces are filled by the atmosphere, the pressure chamber exerts pressure on all surfaces of cells equally (Turner and Long, 1980), while the leaf press exerts mechanical pressure, which varies with leaf anatomy (Hunt, et al., 1984, Yegappan and Mainstone, 1981).

The theoretical basis for estimating leaf water potential with the leaf press is still lacking (Hunt, et al., 1984, Shayo-Ngowi and Campbell, 1980), and leaf press estimates should be calibrated to pressure chamber estimates. No report was found in the literature of the leaf press being calibrated to the pressure chamber for estimating potato leaf water potential, although calibration experiments have been performed with 26 other species (Bristow, et al. 1981, Grant, et al., 1981, Hicks, et al., 1986, ,Hunt, et al., 1984, Jones and Carabaly, 1980, Markhart and Smit-Spinks, 1984, Radulovich, et al., 1982, Rajendrudu, et al., 1983, Renard and Ndayishimie, 1982, Sojka, et al., 1987, Yegappan and Mainstone, 1981). A good correlation between estimates of leaf water potential using the pressure chamber and leaf press would suggest that the leaf press may be useful for field research on potato response to water stress.

Materials and Methods

Leaf water potentials were estimated in August 1988 on furrow-irrigated potato grown in field plots on Owyhee silt loam at Oregon State University, Malheur Experiment Station at Ontario, Oregon. A Scholander pressure chamber (PMS Instruments Company, Corvallis, Oregon, 97330) and a Campbell-Brewster J14 leaf press (Decagon Devices, Incorporated, Pullman, Washington, 99163) were used as estimating devices. Opposite pinnae (leaflets) were cut from a rachis, the second leaflet immediately after the first, using a sharp blade. The petiolule (stem) of a leaflet was inserted into a 5 cm length of 2 mm inside-diameter clear plastic tubing held in a slit in the center of a rubber plug 4 mm thick cut from a #6 rubber stopper. When the end of the stem inside the plastic tubing emerged through the rubber plug, the plastic tubing was withdrawn, leaving the stem protruding from the rubber plug. The rubber plug was then inserted into the recess in the lid of the pressure chamber with the cut end of the leaflet stem protruding through the hole in the lid, and the lid was fastened onto the pressure chamber. Nitrogen gas was metered into the pressure chamber at 0.01 MPa/sec while the cut stem surface was viewed with a magnifying lens. When fluid appeared at the cut surface, the flow of nitrogen to the chamber was stopped and the pressure reading on the gauge was recorded.

When it was cut from the rachis the other leaflet was placed underside-up on the membrane of the leaf press and the viewing window was fastened over it. Immediately after the pressure chamber reading was completed for the first leaflet, the leaf press reading was begun on the second leaflet. The handle of the leaf press was rapidly pumped a few strokes, until the gauge showed an increase in pressure, and then slowly pumped to increase the pressure 0.01 MPa/sec until the surface of the leaflet against the window became uniformly dark green and moisture flowed between the surface of the leaflet and the window. The pressure reading on the gauge was recorded at that point. After the water potential estimates for both devices were recorded for a leaflet pair, another leaflet pair was cut from a rachis and the procedure was repeated.

Plants chosen for leaf water potential estimation represented a range of water status. Plants deprived of irrigation were used for data in the more negative water potential range. Less negative leaf water potentials were provided by irrigating at dusk and covering the plants with clear plastic overnight. Leaf water potentials were estimated the next morning on leaflets taken from under the plastic. Leaf water potentials for plants between dry and wet extremes were from irrigated plants. Regression analysis, with the pressure chamber observation as the independent variable and the leaf press observation as the dependent variable, was performed on 124 pairs of observations using the exponential model $y = ae^{bx}$.

Errors in estimation of leaf water potential were measured on potato leaflet pairs using the pressure chamber alone or the leaf press alone as described above. The pressure chamber was tested on 28 leaflet pairs with estimated leaf water potential ranging from -0.95 to -1.67 MPa and the leaf press was tested on 68 leaflet pairs ranging from -0.61 to -1.64 MPa. Paired leaflet data from each device were analyzed using the paired *t*-test.

Results and Discussion

Leaf water potential estimates ranged from -0.38 to -1.72 MPa with the leaf press and from -0.28 to -1.61 MPa with the pressure chamber. Regression analysis resulted in a best-fit curve $y = -0.403e^{-0.848x}$ with a coefficient of simple determination $r^2 = 0.85$ (Fig. 9).

Other researchers (Bristow, et al., 1981, Grant, et al., 1981, Hicks, et al., 1986, Hunt, et al., 1984, Jones and Carabaly, 1980, Markhart and Smit-Spinks, 1984, Radulovich, et al., 1982, Rajendrudu, et al., 1983, Renard and Ndayishimie, 1982, Sojka, et al., 1987, Yegappan and Mainstone, 1981) who calibrated the leaf press against the pressure chamber for 26 species reported correlations of leaf press to pressure chamber readings ranging from $r^2 = 0.45$ in tomato (*Lycopersicon esculentum* Mill.) reported by Markhart and Smit-Spinks (1984) to $r^2 = 0.96$ in sugar maple (*Acer saccharum* L.) reported by Hunt, et al. (1984). The lowest correlation, reported by Markhart and Smit-Spinks (1984) for greenhouse-grown tomato, was based on 29 leaf water potentials estimated with a pressure chamber ranging from -0.11 to -0.4 MPa. The sugar maple correlation reported by Hunt, et al. (1984) represented 30 pressure chamber readings from -0.2 to -1.7 MPa.

Several researchers reported comparison tests for grasses only (Bristow, et al., 1981, Hicks, et al., 1986, Jones and Carabaly, 1980), and others reported comparison data for tree species (Hunt, et al., 1984, Renard and Ndayishimie, 1982). Since Gandar and Tanner (1975, 1976a, 1976b) stressed the importance of plant-soil water relations in potato production, implications of leaf water potential estimates with the leaf press compared to the pressure chamber should be clarified.

Factors influencing the reliability of estimation of leaf water potential using the pressure chamber include the time elapsed between excision and estimation, leaf wrapping, and the rate at which the chamber is pressurized (Gandar and Tanner, 1976a, Turner and Long, 1980, Wenkert, et al., 1978). Pressurization causes heating inside the chamber, drying unwrapped leaves, causing underestimation of leaf water potential. Turner and Long (1980) found underestimation from any of these causes is exaggerated in leaves at high leaf water potential. Potato leaflets were not wrapped in this study analogous to the procedure of other studies comparing the two devices where leaves were not wrapped (Bristow, et al., 1981, Grant, et al., 1981, Hicks, et al., 1986, Hunt, et al., 1984, Jones and Carabaly, 1980, Markhart and Smit-Spinks, 1984, Radulovich, et al., 1982, Rajendrudu, et al., 1983, Renard and Ndayishimie, 1982, Yegappan and Mainstone, 1981). Leaf water potential will be underestimated with the pressure chamber if the time between excision and estimation is too long, or if the leaf is not wrapped. Gandar and Tanner (1976a) noted that if the pressurization rate is too rapid, the endpoint may be exceeded.

No firm theoretical foundation exists for leaf press estimation of leaf water potential, because the leaf press squeezes the leaf tissue mechanically (Hunt, et al., 1984, Shayo-Ngowie and Campbell, 1980). Leaf press readings are erratic for plants with thick, rigid leaf structure (Hunt, et al., 1984, Markhart and Smit-Spinks, 1984, Yegappan and Mainstone, 1981), apparently because the flexible membrane over the oil must exert force against cell wall structure without proportional force distribution inward on individual cell membranes.

In a study of diurnal fluctuation of leaf water potential in wheat (*Triticum aestivum* L.), Bristow, et al. (1981) reported the leaf press data coefficient of variation was more consistent than pressure chamber data coefficient of variation, and did not exhibit diurnal fluctuation. Errors of water potential estimation on potato leaflet pairs in this study were lower for the pressure chamber (t = 0.076, d.f. = 27) than for the leaf press (t = 0.65, d.f. = 67). Leaf press estimates of leaf water potential have not been compared to soil water potential. In a study comparing three different leaf press endpoints to each other, to pressure chamber estimates, and to a crop stress index, Sojka, et al. (1987), concluded leaf press parameters did not relate to other stress parameters. Hunt, et al. (1984) reported leaves with lower specific leaf area have greater structural rigidity and cause the leaf press to be less sensitive to changes in water potential.

The potato leaflet data (Fig. 1) suggest that the leaf press did not accurately estimate differences in leaf water potential above -0.6 MPa. Leaf tissue of plants at higher water potential resists the force applied by the leaf press. This could explain why reports of leaf press calibration to the pressure chamber show a weak relationship when measurements are made only in the high range of leaf water potential (Markhart and Smit-Spinks, 1984, Yegappan and Mainstone, 1981). Reported discrepancies in the relationship of the two devices for various plant species may be related to drying of uncovered leaves, especially at high water potentials (Wenkert, et al., 1978), or the choice of endpoint used for the leaf press, especially with thick or rigid leaves (Sojka, et al., 1987). In the range of potato leaf water potential from -0.6 to -1.2 MPa, where irrigation decisions would be made, the leaf press provided a useful estimate of leaf water potential when calibrated against the pressure chamber.

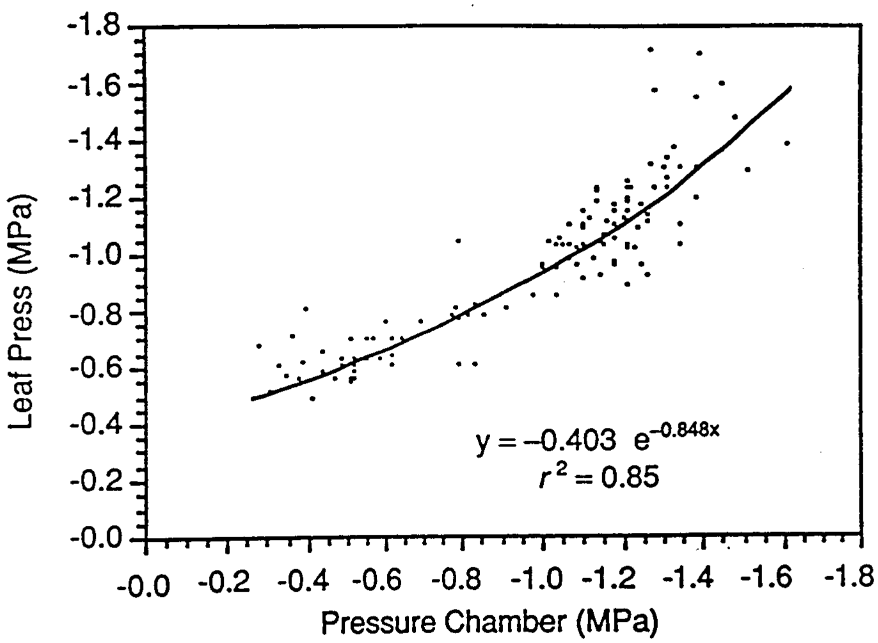

Figure 9. Leaf press and pressure chamber. Relationship of leaf press and pressure chamber estimates of leaf water potential for 124 potato leaflet pairs.

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Potato Tuber Stem End Reducing Sugar and Fry Color Response to Transient Water Stress

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Abstract

Russet Burbank potatoes grown for french fry processing in irrigated regions of the Pacific Northwest can develop undesirable dark stem end fry color. Hot weather after tuber initiation can promote dark ends. Dark ends are also known as sugar ends because dark fry color is associated with increased levels of reducing sugar in tuber stem ends. Single episodes of transient water stress ranging from -32 to -107 kPa soil water potential were imposed in 1988 and 1989. Tubers were sampled before stress, during maximum stress, after stress was relieved, and at final harvest in September to determine when the increase in reducing sugar occurred. Tubers were also sampled from storage and separated into specific gravity categories. Reducing sugar concentrations increased in tuber stem ends more than two weeks after the stress ended. Increased water stress was associated with increased reducing sugar concentrations and darker stem end fry colors. Dark fry colors were associated with tubers with low solids from highly stressed treatments.

Introduction

Manufacturers of frozen french fries specify standards of product quality in contracts for potatoes (*Solanum tuberosum* L. 'Russet Burbank'). Excess reducing sugars accumulate in the stem ends of tubers when subjected to hot weather hot weather and water stress. French fries prepared from such tubers show dark ends also known as "sugar ends". Growers in eastern Oregon's Treasure Valley have reduced dark end severity by shifting from furrow to sprinkler irrigation. The purpose of the research reported here was to quantify the response of Russet Burbank to short duration, or transient, water stress, similar to a stress event which may conceivably occur in commercial fields, resulting in dark end tubers.

More research has been published on the irrigation requirements for optimum yield than for optimum tuber quality. Hane and Pumphry (1984) reported that Russet Burbank tuber yield increased with increasing irrigation water up to 650 mm applied throughout the growing season in the Columbia Basin region of Oregon. They described K coefficients for weekly potato water use varying from 0.3 at plant emergence to 0.8 at full canopy in a study irrigated three times per week using a line-source sprinkler system on a loamy sand. Season-long water deficit resulted in reduced yield and quality.

Martin and Miller (1983) tested the effect of stress during tuber bulking and maturation by irrigating with solid-set sprinklers until July, when a line-source sprinkler operated daily was used to create a water stress gradient. On a loam soil, any irrigation above 40% of ET had no effect on yield, grade, or specific gravity, leading Martin and Miller (1983) to speculate that the early irrigations with the solid-set sprinkler had applied enough water to the soil to sustain crop growth the remainder of the growing season with only minimal daily water applications.

Miller and Martin (1987) interrupted a schedule of daily irrigations for 10 d in early July and 10 d in late July to investigate effects of transient soil water deficits on Russet Burbank yield and grade. Transient stress at either time significantly reduced overall yield and size of Russet Burbank tubers. None of the cited research reported water potential during stress, or effects on fry color or reducing sugar, and none separated the effect of irrigation frequency from the effect of the soil water deficit severity.

The physiological basis for the accumulation of reducing sugars in the stem end of Russet Burbank tubers exposed to water and heat stress is unknown. Iritani and Weller (1981) determined that water and heat stress during tuber bulking would result in excess sucrose and decreased starch in the tuber stem end at harvest. They speculated that excess sucrose would be converted to reducing sugar during storage. Iritani and Weller (1973b) hypothesized that when water stress during tuber growth is followed by good growing conditions secondary tuber growth partially utilizes stored carbohydrate from the stem ends of the tubers. Iritani and Weller (1973a,c) showed a decline in percent solids in the stem end of Russet Burbank tubers exposed to water stress during tuber bulking. Weaver et al. (1972) tested tubers from lots having dark ends and others without dark ends for reducing sugar, total sugar, and fry color. They found that reducing sugar concentration was associated with dark fry color and that dark end tubers would not re-condition by respiring or converting sugar to starch at warm storage temperature.

Hiller, et al. (1985) described four possible physiological mechanisms, representing disruptions of the source to sink relationship of the plant shoots to the tubers, to account for the observed increase in reducing sugar in dark end tubers. The four possibilities involved (1) translocation of carbohydrate to the foliage for vegetative growth following water stress relief, (2) translocation of carbohydrate from the stem end to the apical end of the tuber following water stress relief, (3) conversion of starch in the stem end to sugar, and (4) failure of sugar translocated to the stem end to be converted to starch. The possible timing of the physiological events required for alternatives (3) and (4), in relation to the water stress episode and the relief of water stress, was not discussed.

This article reports results of research addressing the relationship of Russet Burbank stem end fry color and reducing sugar concentration at different sampling dates to a broad range of transient water stress treatments imposed during early tuber bulking.

Materials and Methods

The research was conducted on Owyhee silt loam (coarse-silty, mixed, mesic Xerollic Camborthid) at the Oregon State University Malheur Experiment Station at Ontario, Oregon in 1988 and 1989. Each year, following harvest of a winter wheat crop, the 31 by 134 m experimental area was fumigated and fall bedded before planting potatoes in the spring. Certified Russet Burbank seed was cut by hand into 60 g seedpieces and treated with the fungicide thiophanate-methyl, {dimethyl[(1,2-phenylene)-bis (iminocarbonothioyl)] bis (carbamate)} sold as Tops, at 24 g ai 100 kg^{-1} cut seed. At planting, the field was sprayed with the herbicides pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzamine], sold as Prowl, plus metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide], sold as Dual, at 1.65 plus 2.2 kg ai ha^{-1} and fertilized according to soil test results with 121 kg N ha^{-1} sidedressed after planting. Plots were planted during the third week of April both years with seedpieces spaced 23 cm apart in rows 91 cm apart.

Plots were irrigated through solid-set sprinkler before and after the transient stress period both years. Sprinkler heads with 3.2 mm nozzles were operated at 407 kPa mounted on 71 cm vertical risers. Heads were spaced

12.2 m apart on laterals separated by 15.2 m. The two outside laterals were temporarily dismantled on June 21, and the center lateral was modified to supply water to plot sprinklers (Eldredge, et al., 1991b).

Six transient water stress levels were assigned randomly to seven replications in a Randomized Block Design. Stress levels assigned were soil water potentials of -25, -44, -66, -82, -101, and -120 kPa. Soil water potentials were estimated by use of two granular matrix sensors (GMS) per plot (Watermark Soil Moisture Sensor model 200x, read with meter model 30KTC, Irrometer Company, Riverside, CA 92516). GMS vary in resistance with soil water potential and were calibrated against tensiometers in the root zone of a potato crop (Eldredge, et al., 1991a).

During the transient stress periods (June 21 to July 19, 1988 and June 21 to July 18, 1989) plots 13.7 m long by 4.6 m wide (5 rows) were individually irrigated using 15 portable plot sprinklers. The soil was allowed to dry by evapotranspiration until each plot reached a pre-assigned level of soil water potential as indicated by the mean reading of two GMS. After each plot reached its pre-assigned soil water potential it was individually irrigated to prevent further water stress (Table 4).

Plant water status and soil water content for each plot were measured the day the assigned soil water potential was achieved according to the GMS. Plant water status was estimated by using a leaf press to measure leaf water potential of the terminal leaflet on the third leaf from the apex of a main stem

(Eldredge and Shock, 1989). Leaf press readings were taken between 0900 h and 1200 h, with most readings occurring between 0900 and 1000 h. Soil samples for gravimetric soil water determinations were taken from 10 locations along the center row, using a soil probe between plants to sample to a depth of 20 to 25 cm, corresponding to seedpiece and GMS placement.

Tuber samples for reducing sugar analysis were removed from five plants per plot three times during the growing season and 25 tubers were sampled per plot after one month of post-harvest storage. Specifically, tuber samples were collected the day the transient stress began, on the day each plot reached its assigned water potential, two weeks after the transient water stress period had been terminated by resuming irrigation, and in mid-October. On each sampling date, french fry strip was cut lengthwise from the center of each tuber and a 1 cm cube of peeled tissue from the stem end of each strip was bulked with other cubes from the same plot and immediately frozen in liquid nitrogen. Samples were then freeze-dried, ground to powder, and analyzed for reducing sugar content.

Total reducing sugar was determined with a modified version of the colorimetric dinitrophenol method of Ross (1959). One gram of homogenized powdered sample was washed with 5 ml of distilled water into a 50 ml conical centrifuge tube, vortexed 45 seconds, and centrifuged at 2000 rpm for 10 minutes. The supernatant was used to determine total reducing sugar as percent dry weight.

A 25 tuber sample was taken from each plot for fry color determination at harvest and after a month of storage at 13 °C and 95 % relative humidity. Stored tubers were sorted into five solids categories of less than 16%, 16 to 18%, 18 to 20 %, 20 to 22%, and greater than 22% by floating tubers in a series of five brine solutions. Each tuber was then sliced longitudinally to obtain a matching pair of center sections. One section was immediately fried in vegetable oil at 191 °C for 150 s. A 1 cm cube of tissue was cut from the stem end of the other section and frozen in liquid nitrogen for subsequent reducing sugar analysis.

Fry color of tuber sections was measured 0.64 cm from the stem end immediately after frying using a Photovolt light reflectance meter (Photovolt, Indianapolis, IN 46206) equipped with a green tristimulus filter. The Photovolt meter was calibrated to read 0 light reflectance from a black 35mm film can used as a black standard (actual reflectance 0.03%); the gain was adjusted to a reflectance reading of 62 for a white enamel standard plate 25-570-59 with a light reflectance of 44.7 percent. Percent light reflectance was recorded and converted to USDA fry color category as follows: USDA #00 = >43.8%, USDA #0 = 43.7 to 36.8%, USDA #1 = 36.7 to 29.7%, USDA #2 = 29.6 to 22.6%, USDA #3 = 22.5 to 15.5%, USDA #4 = <15.4%. Reducing sugar and fry color data were analyzed by regression analysis and ANOVA against other measured variables.

Results and Discussion

Soil water potential levels are presented in Table 4. Calibrated soil water potentials resulting after comparison of GMS to tensiometers in the root zone of potatoes growing in silt loam yielded the equation $y = -6.45 - 0.753x$, where y = tensiometer kPa soil water potential, and x = GMS meter reading, with $r^2 = 0.89$, resulting in treatment levels differing by approximately 19 kPa increments, rather than the 25 kPa increments sought. Because of variability among plots, the average water potential actually measured on the day when stress was relieved varied within as well as among treatments.

Gravimetric soil water content averages for the -101 and -119 kPa treatments in both years did not agree with the soil water contents predicted by the OSU soil physics laboratory. The soil water release curve for Owyhee silt loam predicted water potential on the order of -1000 kPa for soil water content of 9% and -800 kPa for soil water content of 13%. A discrepancy also existed for the differences between the gravimetric soil water content and the recorded GMS soil water potentials in 1988 and 1989. Actual soil water potentials measured with GMS were very similar both years, yet gravimetric soil water contents for the two years showed consistently greater soil water content at each GMS-estimated soil water potential in 1989. Heavy irrigation early in 1988 may have collapsed soil particle structure and reduced water holding capacity.

The actual water potentials reached by the two most stressed levels ranged from -99 to -104 kPa because some plots lost water at an ever decreasing rate. Some plots assigned the lowest water potential did not reach their assigned treatment level both years. After 26 days, the stress episode was ended by sprinkler irrigating all plots with the solid-set system. Leaf water potential responded to the treatments imposed, as did gravimetric soil water content.

Plots assigned the same treatment also varied in the number of days required to reach the assigned water potential. The wetter plots took fewer days to reach assigned soil water potentials in 1989 than in 1988 because residual soil moisture in the experimental area was greater in 1988. The drier treatments required about the same number of days to reach assigned soil water potentials both years.

Tuber stem end reducing sugar concentrations resulting from a single episode of transient soil water stress are presented in Table 5. Sugar concentrations for all sampling dates in 1988 were significantly related to the stress level measured at stress relief. Weak relationships existed for sugar concentrations at maximum plant stress and two weeks after stress in 1989. An r value of 0.35 was calculated for reducing sugar concentrations during maximum stress and after stress in 1988 and post-harvest in 1989. The strongest correlation between stress and sugar concentrations was observed post-harvest in 1988.

These results indicate that in Russet Burbank the increase in stem end reducing sugar in response to water stress did not begin earlier than two weeks after the stress ended. This result suggests that the reducing sugar was not produced by starch degradation to provide carbohydrate energy for vine growth or secondary growth of the apical end of the tuber immediately following the relief of stress. The increase in stem end reducing sugar later than two weeks after stress is consistent with the theories that either (1) sugar translocated to the stem end is not incorporated into starch, or (2) starch in the stem end is degraded and resulting sugars are not translocated, or both.

Table 6 presents the probability of significant correlations among the variables measured concurrently with reducing sugar concentrations. Only those relationships in Table 6 that were significant at the 0.05 level of probability and beyond are presented in Table 7. In 1988 the relationships of reducing sugar concentration at maximum stress to treatment, leaf water potential, soil water content, and soil water potential were significant. The data showed that as stress increased, less reducing sugar was present in tuber stem end tissue at the time of maximum stress. That trend was not observed in 1989 and the relationships from the 1988 data do not conclusively support any of the four dark end theories described by Hiller, et al. (1985).

Leaf press estimates of leaf water potential were made mid-morning, when plant water potential values would have been decreasing in diurnal fluctuation. Pre-dawn estimates of plant water status have been proposed as a measure of plant equilibration with soil water potential, but have not related well to daytime plant stress (Jones, 1990). Stressed and non-stressed potato plants have similar pre-dawn leaf water potential, but stressed plants stay at high water potential a shorter time (Gandar and Tanner, 1976). Leaf press readings were positively related to percent reducing sugar at maximum stress in 1988 and percent reducing sugar two weeks after stress in 1988, and negatively related to percent reducing sugar post-harvest in 1988 and 1989 (Table 7).

Two weeks after stress was relieved on all plots in 1988, reducing sugar concentrations were still significantly lower in the tubers from highly-stressed plots than tubers from the lightly-stressed plots, as measured by soil moisture treatment level, soil water potential, and leaf water potential. Tuber stem end samples taken after harvest in 1988 showed a significant trend toward increased reducing sugar with increased exposure to transient water stress, regardless of whether the indicator of water stress was soil water potential, leaf water potential, or soil water content. Increased reducing sugar levels were related to dark fry color and reduced specific gravity.

Pre-harvest reducing sugar data from the 1989 experiment showed no significant (0.05 level) relationship between percent reducing sugar in tuber stem ends and any of the measured parameters, except samples collected two weeks after stress showed a trend for high reducing sugar in tubers with low specific gravity. After harvest in 1989, stem end reducing sugar levels were related to soil water potential, leaf water potential, soil water content, dark fry color, and percent dark-ends as in 1988.

Fry data collected for tuber stem end pieces at harvest and after post-harvest storage are presented in Table 8. The only significant deviation in fry color response involved stem end light reflectance in 1989. Results from both 1988 and 1989 indicate that the percentage of dark end fries from Russet Burbank tubers is closely, positively related to water stress during early tuber bulking.

Specific gravity of Russet Burbank tubers also responded to transient water stress (Table 9). Overall solids declined with increasing stress both years, and the percent of tubers in each solids group varied according to stress level. Tubers from the least stressed treatments had higher solids.

Treatment effects on USDA fry colors are presented in Table 10. The darkest fry colors, USDA #3 and #4, called dark ends, were predominantly associated with the most stressed treatments in both years. Results from the 1988 experiment showed the Russet Burbank dark end response to stress more distinctly than the 1989 data, perhaps because irrigations before the stress period in 1988 and 1989 allowed luxuriant canopy growth that was more susceptible to the stress imposed. Also, weather differences between the two summers could have accounted for some of the difference between years, as temperatures were lower during the transient stress period in 1989 than in 1988 (Table 11). Daily maximum air temperature reached or exceeded 34 °C on 11 days during the 27 day transient stress period in 1988, but on only 5 days in 1989. Average daily maximum temperature for the transient stress period in 1988 was 32.4 °C compared to 31.2 °C in 1989 during the same time span. The temperature differential between 1988 and 1989 could have altered plant stress through differences in canopy temperature.

The effect of stress during early tuber bulking on reducing sugar levels in Russet Burbank tuber stem ends in 1988 and 1989 is shown in Figure 10. Transient stress tended to cause increased reducing sugar levels after one month of storage at 13 °C and 95 % relative humidity. Reducing sugar levels varied slightly before treatments were imposed. At the time of maximum stress, which varied according to treatment, reducing sugar levels were relatively uniform, averaging about 1% of tuber dry weight. All treatments showed a slight decline in reducing sugars two weeks after stress was relieved by irrigation. Stress-related reducing sugar levels were highest after tubers were stored one month at 13 °C.

Table 4. Variables affecting tuber stress response. Average measured values at maximum stress compared to assigned treatment levels.

Soil Water Potential			Duration of Transient Stress Treatment	Leaf Press Estimate of Leaf Water Potential	Gravimetric Soil Water Content
Assigned	Calibrated†	Actual			
1988					
---------------------- kPa ------------------			--- d ---	--- kPa ---	--- % ---
-25	-25	-32	4.6	-563	17.8
-50	-44	-48	5.4	-556	15.9
-75	-63	-66	7.3	-613	14.2
-100	-82	-80	11.3	-707	12.0
-125	-101	-104	21.3	-990	9.6
-150	-119	-104	24.1	-1080	9.4
1989					
-25	-25	-32	2.7	-503	20.1
-50	-44	-50	4.7	-533	17.4
-75	-63	-69	6.1	-586	16.2
-100	-82	-92	12.7	-687	14.1
-125	-101	-99	21.3	-844	13.3
-150	-119	-107	24.6	-818	13.1

†Assigned treatment after calibration by the equation $y = -6.45 - 0.753x$ where y = tensiometer value and x = granular matrix sensor value for instruments installed in a potato root zone.

Table 5. Stem end reducing sugar. Percent reducing sugar in Russet Burbank tuber stem ends at four sampling times.

Average Soil Water Potential At Stress Relief	Sampling Time			
	Before Stress	Maximum Stress	Two Weeks After Stress	One Month Post-Harvest
		1988		
---- kPa ----	%			
-32	0.956	0.656	0.448	3.556
-48	0.838	0.461	0.806	4.454
-66	1.124	0.561	0.636	4.541
-80	0.580	0.336	0.430	5.599
-104	1.284	0.514	0.283	7.827
-104	0.978	0.338	0.226	7.598
LSD 0.05	NS	0.209	NS	1.763
r	NS	0.35*	0.35*	-0.62***
		1989		
-32		1.199	0.296	3.849
-50	2.31	1.046	0.410	3.186
-69		1.014	0.280	4.671
-92		1.406	0.266	4.750
-99		1.440	0.309	5.767
-107		1.250	0.307	5.190
LSD 0.05		NS	NS	NS
r		NS	NS	-0.35*

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 6. Probability of association with tuber reducing sugars. Probability of association of seven measured variables with reducing sugar concentrations in tuber stem ends at four sampling times.

	Before Stress		Maximum Stress		Two Weeks After Stress		One Month Post-Harvest	
	88	89	88	89	88	89	88	89
	---probability level---							
treatment stress level	0.4280	0.9937	0.0166	0.5479	0.0259	0.6989	0.0000	0.0094
soil water potential	0.3115	0.8383	0.0268	0.7038	0.0239	0.6885	0.0000	0.0238
leaf water potential	0.6061	0.6707	0.0160	0.2483	0.0271	0.9898	0.0001	0.0027
soil water content	0.7164	0.0704	0.0010	0.1454	0.1089	0.7389	0.0001	0.0036
post-harvest fry color†	0.4280	0.7647	0.0905	0.1077	0.0696	0.9569	0.0002	0.0008
post-harvest specific gravity	0.3642	0.5966	0.0971	0.9680	0.1181	0.0212	0.0000	0.2272
percent dark-end tubers	0.1204	0.8841	0.0523	0.0893	0.2522	0.9426	0.0003	0.0035

†Fried 150 s in vegetable oil at 191 °C, percent light reflectance measured with a Photovolt meter equipped with a tristimulus green filter.

Table 7. Regression relationships with tuber reducing sugars. Equations of best-fit regression line for stem-end reducing sugar concentrations versus other measured variables showing statistically significant (P<0.05) treatment effects.

y	equation	*x*	*r*
% reducing sugar at maximum stress 1988	$y = 0.642 + 0.00187x^{*}$	treatment stress level, kPa	0.372
% reducing sugar at maximum stress 1988	$y = 0.668 + 0.00262x^{*}$	soil water potential, kPa	0.346
% reducing sugar at maximum stress 1988	$y = 0.739 + 0.000343x^{*}$	leaf water potential, kPa	0.374
% reducing sugar at maximum stress 1988	$y = -0.0670 + 0.0313x^{**}$	soil water content, %	0.495
% reducing sugar two weeks after stress 1988	$y = 0.784 + 0.00350x^{*}$	treatment stress level, kPa	0.348
% reducing sugar two weeks after stress 1988	$y = 0.869 + 0.00537x^{*}$	soil water potential, kPa	0.352
% reducing sugar two weeks after stress 1988	$y = 0.952 + 0.000637x^{*}$	leaf water potential, kPa	0.345
% reducing sugar post-harvest 1988	$y = 2.67 - 0.0316x^{***}$	treatment stress level, kPa	-0.635
% reducing sugar post-harvest 1988	$y = 2.22 - 0.0432x^{***}$	soil water potential, kPa	-0.616
% reducing sugar post-harvest 1988	$y = 0.727 - 0.00639x^{***}$	leaf water potential, kPa	-0.612
% reducing sugar post-harvest 1988	$y = 10.4 - 0.381x^{***}$	soil water content, %	-0.598
% reducing sugar post-harvest 1988	$y = 18.4 - 0.374x^{***}$	post-harvest reflectance%†	-0.581
% reducing sugar post-harvest 1988	$y = 334 - 304x^{***}$	post-harvest specific gravity	-0.695
% reducing sugar post-harvest 1988	$y = 3.23 + 0.222x^{***}$	dark-end tubers, %	0.581
% reducing sugar post-harvest 1989	$y = 3.12 - 0.0167x^{**}$	treatment stress level, kPa	-0.396
% reducing sugar post-harvest 1989	$y = 2.98 - 0.0211x^{*}$	soil water potential, kPa	-0.348
% reducing sugar post-harvest 1989	$y = 0.883 - 0.00557x^{**}$	leaf water potential, kPa	-0.451
% reducing sugar post-harvest 1989	$y = 9.27 - 0.299x^{**}$	soil water content, %	-0.439
% reducing sugar post-harvest 1989	$y = 12.7 - 0.259x^{***}$	post-harvest reflectance%†	-0.497
% reducing sugar post-harvest 1989	$y = 3.42 + 0.0509x^{**}$	dark-end tubers, %	0.451

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†Fried 150 s in vegetable oil at 191 °C, percent light reflectance measured with a Photovolt meter equipped with a tristimulus green filter.

Table 8. Fry color responses. Treatment differences in fry color response to transient water stress at harvest and after a month of storage.

Average Soil Water Potential At Stress Relief	Average Stem-end Light Reflectance			USDA #3 and #4 Dark-ends		
	harvest	post-harvest	difference	harvest	post-harvest	difference
			1988			
------kPa------	----------	----------	---------- %	----------	----------	----------
-32	38	34	-3.9	7.6	3.5	4.1
-48	38	32	-5.3	6.9	4.2	2.6
-66	37	34	-3.6	5.2	3.7	1.5
-80	35	31	-4.3	9.8	6.6	3.2
-104	30	29	-1.4	23.0	26.9	-3.9
-104	27	27	-0.7	34.0	25.4	8.6
LSD 0.05	3.2	2.5	NS	14.0	10.1	NS
r	-0.62***	-0.61***	-0.27	0.43**	0.61***	-0.12
			1989			
-32	35	32	-3.6	11.4	23.2	-11.7
-50	34	31	-2.9	10.0	24.2	-14.2
-69	32	33	+0.7	12.1	29.3	-17.1
-92	30	32	+2.2	26.5	29.4	-2.8
-99	29	30	+0.7	34.8	40.8	-5.9
-107	28	31	+2.9	40.2	48.7	-8.5
LSD 0.05	2.8	NS	NS	12.1	17.2	NS
r	0.61***	-0.063	-0.36*	0.54***	0.32*	0.18

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 9. Solids responses. Response of tuber solids to a transient water stress.

Average Soil Water Potential At Stress Relief	Overall Solids	Solids Distribution				
		<16%	16-18%	18-20%	20-22%	>22%
		1988				
------kPa------	----------	----------	----------	%	----------	----------
-32	21.8	0	0.8	2.7	47.9	48.7
-48	21.9	0	0	5.4	34.8	59.8
-66	21.4	0	0.5	8.4	53.1	38.1
-80	21.1	0	1.3	12.5	63.7	22.5
-104	19.6	2.9	5.9	41.8	44.1	5.2
-104	19.4	1.5	4.5	47.0	42.4	4.5
LSD 0.05	0.7	NS	3.1	9.7	11.9	12.4
r	-0.75***	0.31*	0.51***	0.76***	0.09	-0.79***
		1989				
-32	20.6	1.5	11.1	26.4	29.4	31.5
-50	21.3	0.6	2.3	22.7	28.0	46.4
-69	20.4	1.2	9.7	31.6	33.0	24.4
-92	20.7	0	10.6	24.3	36.5	28.6
-99	20.4	0.5	21.3	24.2	23.2	30.7
-107	20.2	5.3	12.6	24.8	33.4	23.8
LSD 0.05	0.6	NS	7.4	NS	NS	11.5
r	-0.26	0.02	0.32*	0.01	0.08	-0.30

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 10. Fry color distribution. Fry color distribution in response to a transient water stress.

Average Soil Water Potential At Stress Relief	Average Stem-end Light Reflectance	Stem-end Fry Color Distribution					
		USDA Fry Color					
		00	0	1	2	3	4
				1988			
------kPa------	%						
-32	47	18	36	23	12	8	0
-48	45	17	35	24	17	7	0
-66	47	16	40	24	11	5	0
-80	43	13	33	24	19	9	1
-104	40	9	12	18	36	22	1
-104	37	4	11	20	31	31	3
LSD 0.05	3.4	9.1	11.3	NS	11.5	12.8	NS
r	-0.61***	-0.40***	-0.62***	-0.16***	0.59***	0.44***	0.21
				1989			
-32	44	17	24	28	17	11	0
-50	43	11	18	31	28	10	0
-69	46	9	19	31	28	9	4
-92	45	11	11	22	26	21	6
-99	41	9	15	20	20	26	9
-107	43	13	12	18	18	26	14
LSD 0.05	NS	NS	8.9	11.6	11.3	11.2	5.9
r	-0.063	-0.23	-0.43***	-0.28***	0.054***	0.45***	0.46***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 11. Air Temperature. USDA weather station maximum daily air temperatures recorded at the Malheur Experiment Station during the transient stress period in 1988 and 1989.

Day of Year	Maximum °C	
	1988	1989
173	31.7	28.9
174	35.0	24.4
175	35.0	27.8
176	35.6	30.0
177	35.0	31.7
178	31.1	31.7
179	30.0	30.6
180	32.2	30.6
181	30.0	32.2
182	28.3	30.0
183	30.6	29.4
184	32.2	32.2
185	33.3	32.2
186	33.9	33.3
187	32.8	33.9
188	30.0	33.3
189	30.6	32.8
190	31.7	32.2
191	32.8	31.7
192	33.9	32.2
193	35.0	33.3
194	31.1	34.4
195	32.2	32.8
196	33.9	31.7
197	32.2	29.4
198	33.3	28.9
199	33.3	31.7

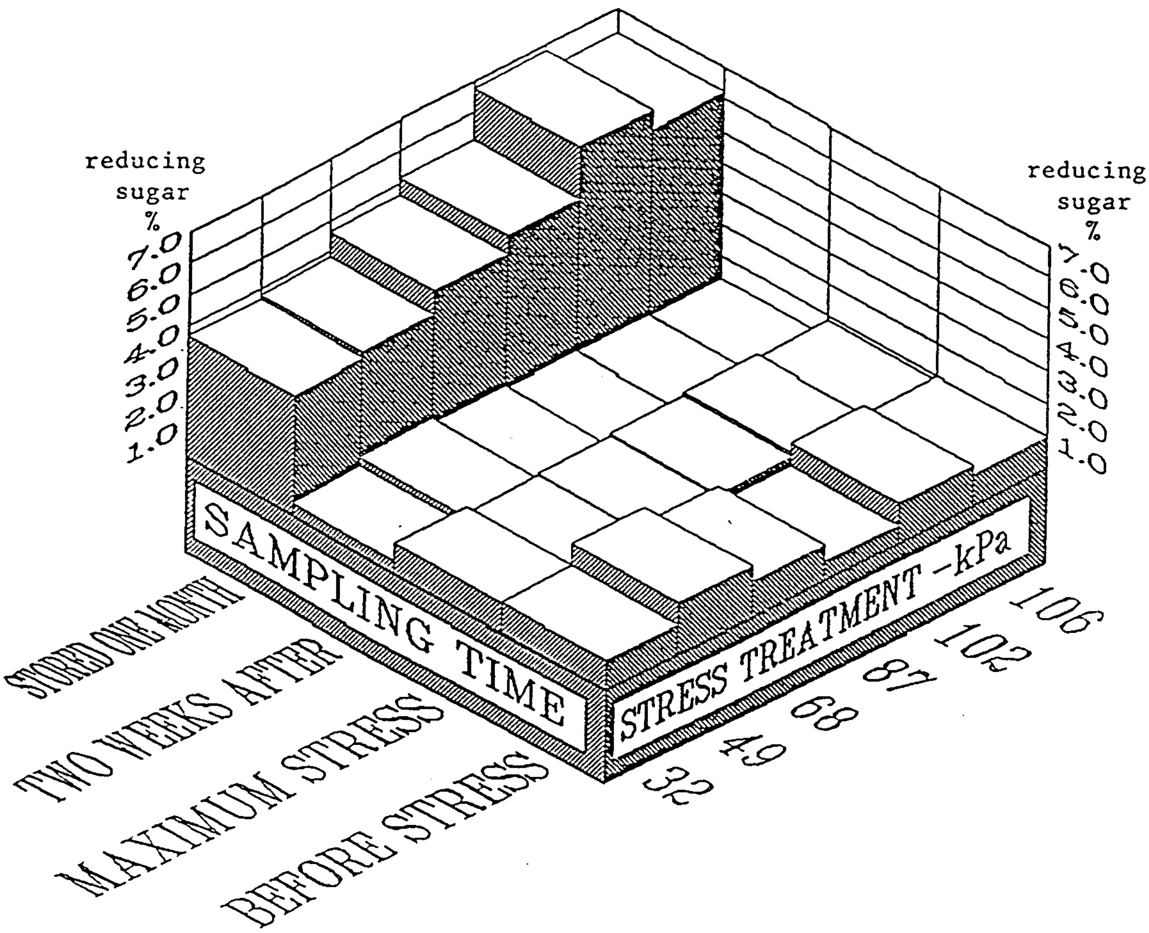

Figure 10. Seasonal changes in reducing sugar levels. Averaged data from 1988 and 1989 showing percent by dry weight of reducing sugar in tuber stem ends at four times.

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Summary

The use of irrigation frequency as an experimental variable in a randomized block design enabled us to efficiently manipulate potato stress. We hoped to monitor the potato plant responding to a transient soil moisture stress, given the facts as they were understood at that time. We learned as a major result of our research that the stress-related change in reducing sugar concentrations is measurable only several weeks after the transient stress. This finding indicates it is highly unlikely that dark ends occur because the tubers act as a temporary source of carbohydrate for the foliage during stress or immediately following stress. Reducing sugar concentration increased with additional stress when soil water potential was below -80 kPa during the transient stress. Jelly-end rot, a severe expression of the dark end syndrome, was more prevalent when stress exceeded soil water potential of between -68 and -87 kPa. Sensitivity of tuber grade to water stress was shown by the decrease of USDA number one tubers and increase in number two tubers when the transient stress exceeded -49 kPa. Dark end tubers frying USDA #3 and #4 at harvest resulted when transient stress was between -80 to -104 kPa in 1988 and between -69 and -92 kPa soil water potential in 1989. Specific gravity of tubers was reduced when transient stress exceeded -80 kPa soil water potential. These findings will enable researchers to better determine when to examine tuber tissue to determine differences between stressed and non-stressed tubers.

Fry color was the obvious indicator of the fry color response to stress. Although sugars are known to be a factor in the darkening reaction, the mechanism, and hence, the physiological importance of the sugars remains uncertain. Future research will focus on events leading to sugar formation during crop recovery from stress. The research reported in this thesis will enable future researchers to subject potato to transient water stress leading to dark ends at harvest, and to sample tubers for determining what physiological changes occur during and after recovery from stress.

The plot sprinkler technique is especially promising as a research tool for determining crop water use, since the plot sprinkler technique can provide data similar to that derived from replicated lysimeters. If crop water use efficiency or stress-related phenomena are to be investigated, randomly arranged, individually irrigated plots should be used in preference to the line-source method. Line-source systems typically impose two major constraints on detecting treatment differences. First, the irrigation frequency is fixed, according to the water needs of a strip of plants near the sprinkler line. Water application rate or soil moisture treatment effects are then confounded with effects of irrigation frequency. Without some way to manage frequency, such as replicated line-sources, no concomitant observation of frequency and moisture effects can be made. Second, soil water potential levels cannot be randomly assigned, so a probability value cannot be calculated for any treatment effect. That deficiency can be partially offset by the use of regression analysis.

The sprinkler heads we used enabled us to apply water rapidly so that several irrigation sets could be conducted in one day. Sprinkler heads that have adequate uniformity and an application rate similar to conventional agricultural sprinkler heads would also be highly desirable. Plot sprinklers would ideally be plumbed into each plot and electrically controlled to automate irrigation treatments. Such a system would allow researchers to spend less time managing the system and more time measuring crop response to the environmental variable being imposed.

Granular matrix sensor (GMS) technology is in a stage of rapid development. Treatment levels were well defined by GMS, as evidenced by the means separations between treatments for tuber quality variables. The treatments imposed were more pronounced than other plant stress factors in the field, although treatments were only transient 19 kPa increments of soil water potential, representing very small differences in the very wet end of the soil moisture range. These results dramatically emphasize potato sensitivity to soil water deficit. That sensitivity, and the silt loam soil, permitted the research to be conducted successfully as designed. Researchers using GMS to schedule irrigations with plot sprinklers on less responsive crops on sandy soil may experience profound difficulty managing experiments.

The research reported here used GMS to measure soil water potential on the drying side of the hysteresis loop. We did not characterize the hysteresis loop of GMS in our silt loam and do not know if one exists. Pertinent research is currently underway at the Malheur Experiment Station using tensiometers as the reference instruments. Hysteresis loops for gypsum blocks, which operate over a larger range of drier soil water potential, are ordinarily measured with pressure plate readings as the reference. GMS operate in a narrow range on the wet end of the soil water release curve where tensiometer readings may demonstrate hysteresis of GMS in the range of soil water potential useful for potato irrigation scheduling.

The hydraulic leaf press appears to be a valuable tool for evaluating crop response to water stress. The exponential calibration curve comparing leaf press estimates of potato leaf water potential to pressure chamber estimates is useful for plant stress measurements in the range where irrigation decisions would be made. The relationship between leaf turgor, leaf regrowth after a water stress, and leaf water status readings with the pressure chamber and leaf press should be more fully explored. Leaves that have experienced moisture stress are typically thicker, and respond differently to subsequent stresses than unstressed leaves. The leaf press could be an ideal tool for exploring crop response to water deficits. While pressure chamber readings on fully recovered leaves may not show differences after regrowth, the leaf press squeezes the cells and could create a different response measurement. Leaf press estimates of plant water status compare well to measurements of soil water status, but further research is needed to learn how to use the leaf press for irrigation scheduling.

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