

# Sap Flow Response of Potatoes under Varying Soil Moisture and Environmental Conditions

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## ABSTRACT

The sap flow response of potatoes (*Solanum tuberosum* L. cv. Russet Burbank) to varying environmental (temperature, relative humidity and net solar radiation) and soil moisture conditions was investigated in 2006 and 2007 using the constant heat balance method (HBM) to monitor sap flow. Hourly and daily stem sap flow values were recorded and evaluated. Reductions in both hourly stem sap flow (g/h) and daily stem sap flow (g/day) were observed as soil moisture deficits increased. Sap flow rates were directly related to temperature and incoming solar radiation under non-limiting soil moisture. Temperature and soil moisture thresholds were not observed during this study.

## INTRODUCTION

Irrigated agriculture faces the possibility that climate change and urban demand may limit fresh water supplies for irrigated crops in southern Alberta, including potatoes. However, potatoes have a fairly low tolerance to water stress, are shallow rooted and require approximately 500 mm of soil water annually to ensure a healthy plant and proper tuber development (Alberta Agriculture, 2004). The irrigation management recommendation for irrigated potato production is to maintain the available soil water (ASW) between 70 and 85% for the entire growing season (King and Stark, 2003). Dry soil conditions, below 65%, suppress potato stolonization, morphology, growth, development, and productivity. These effects vary in intensity depending on the physiological stage at which the plants are exposed to the stress (Harris, 1978).

Successful potato production is generally limited to environments with relatively cool temperatures and adequate available water. Work by Ewing (1981) suggests that successful tuber initiation and tuber bulking occur with ambient temperatures below 20°C and Khedher and Ewing (1985) indicated that at ambient air temperatures above 18 - 20°C, potatoes tend to suppress tuber initiation and partitioning of assimilates (tuber bulking). Higher temperatures also produce lower tuber yields, taller plants with smaller leaves, higher ratios of stem to leaf dry matter, and lower ratios of tuber to leaf and to stem dry matter. Most models that predict onset or severity of potato blight diseases, set the temperature threshold at 30°C; above which, the assumption is, potato plant growth has slowed or ceased (Gent and Schwartz, 2002).

Monitoring the transpiration response of a potato plant to soil water levels or environmental conditions may be an indicator of how and when the potato plant uses water, and identify opportunities for revised irrigation management or water savings.

A relatively new method of monitoring plant transpiration is the heat balance method of Sakuratani (1981) and the modification by Baker and Van Bavel (1987). They demonstrated that gravimetric measurements of transpiration are within 10% of sap flow measurements. Heilman and Ham (1990) also illustrated that measured sap flows in *Ligustrum japonicum* compared with gravimetric estimates of transpiration, were within 10% of transpiration.

Gordon et al. (1999) conducted one of the few potato studies using the heat balance method (HBM) to measure sap flow. They found, in the cultivars they assessed, that transpiration was maintained close to the potential transpiration until approximately 70% of the available water was depleted. Each cultivar was more or less sensitive to soil

moisture deficits once more than 70% of available soil moisture was depleted. The interpretation of these findings would mean that the potato plant does not indicate a stress response to lowering available soil moisture until only 30% ASW is left in the soil profile. However, the research did not identify the impact the lower soil moisture values had on tuber size and quality.

Recent work on monitoring sap flow in grapes, olives, apples and Asian pear trees for use in scheduling irrigations by Fernandez (2007) has provided interesting results for sap flow use in scheduling irrigations. Only one of three methods tested was useful for irrigation scheduling and only in olives and grapes. That method, the transpiration ratio, is the actual daily water use of a plant divided by the potential daily water use of similar-sized plants under non-limiting soil water conditions (well irrigated plants).

By monitoring potato stem sap flow velocities during times of induced environmental stress plant physiological responses can be mapped. These plant responses may provide producers with the early indicators of plant stress needed to help in making irrigation management decisions.

The objectives of this study are to investigate potato sap flow thresholds for temperature and soil moisture, to determine potato sap flow response to limited water and extreme temperatures, and if thresholds were not reached, to identify the early indicators of plant stress as expressed in sap flow velocities. An additional objective was to determine the efficacy of using sap flow sensors for in-field monitoring of plant transpiration.

## MATERIAL AND METHODS

### Model Theory

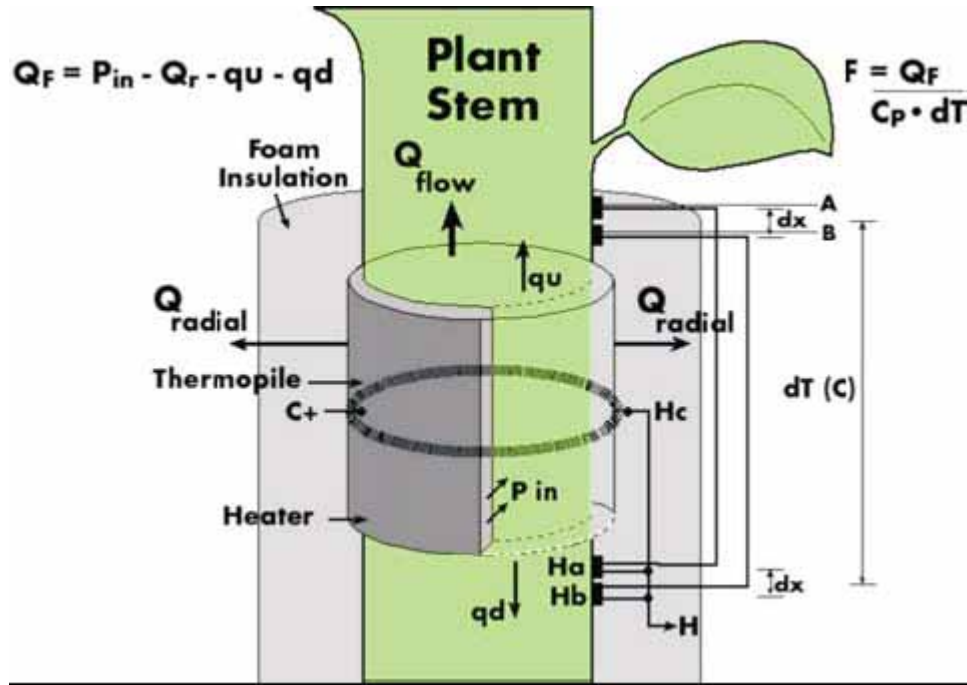
The heat balance method of Sakuratani (1981) and its modification by Baker and Van Bavel (1987), provide a non-invasive technique for measuring sap flow based on applying a constant heat source to the stem of a live plant. This constant heat source is equal to the power output to the stem by the heater. The power output equals the radial heat lost to the ambient (air outside stem gauge), axial heat lost up and down the plant stem, and convective heat lost to sap flow. Subtracting the radial heat and axial heat losses, a residual value for heat lost to sap flow. The actual flow rate can then be estimated by dividing the heat lost to the sap by the temperature difference as the sap enters and exits the heating element along with the heat capacity of the sap (specific heat of water 4.186 J/g°C)(Fig. 1).

The sap flow rate is determined using Equation 1:

$$F = \frac{P_m - q_a - q_r}{c_w \Delta T} = \frac{q_f}{c_w \Delta T} \quad (1)$$

Where  $P_{in}$  (power input) is the applied heat flux,  $q_v$  is the axial heat loss or the respective upward and downward stem heat flux,  $q_r$  is the radial heat loss,  $q_f$  is the convective heat

loss (heat lost to sap),  $\Delta T$  is the stem surface temperature difference between the upper and lower thermocouples, and  $c_w$  is the specific heat of water (4.186 J/g°C) (Gordon et al. 1997).



**Fig. 1.** Stem gage cross-section with heat loss components (Dynagage 2005).

A more detailed explanation of the heat balance method can be found in the Dynagage (2005) manual, Sakuratani (1981,1984), Baker and Van Bavel (1987), and Gordon et al. (1997).

## GREENHOUSE EXPERIMENT

A greenhouse trial measuring the sap flow response of *Solanum tuberosum* L., was conducted from August 16 to September 18, 2006, and from January 10 to April 6, 2007, in Brooks, Alberta. The selected cultivar was seeded into four plastic totes. Each tote measured 33.65 cm by 49.5 cm by 24 cm deep (interior tote measurements) and was lined with a 1.1 mm plastic bag with four small puncture holes to provide adequate soil drainage. The totes were then filled with a sandy loam textured soil with organic matter content of 2.5% and a pH (H<sub>2</sub>O) of 7.8.

During the first trial (2006), each plastic tote was seeded with Russet Norkotah at two seed pieces to a tote, planted 10 cm deep and 25 cm apart, and equidistant to each interior tote wall. During the second trial (2007) each tote was seeded with Russet Burbank at one treated potato seed piece, planted 10 cm deep and equidistant to each interior tote wall. For the first four weeks after planting, each tote was watered according to plant moisture requirements.

The totes for both trial dates were fitted with a granular matrix block (Watermark 200) soil tension probe manufactured by Irrrometer Company Inc., Riverside, California

(Appendix, Table 1), to aid in determining plant moisture demand. Manual watering commenced based on soil tension information and observational indicators of plant and soil moisture stress.

Prior to sap flow sensor installation, problematic plant stems were removed to facilitate proper sensor fit and left for two days to heal. After healing each stem was sprayed with a special canola release compound, which prevents sensor to stem adhesion. The stems were then wrapped in a thin layer of plastic food wrap to prevent the G4 silicone lubricant applied to the inner sensor wall from choking of the stem. The G4 lubricant provides three essential tasks, first it seals out moisture from penetrating the sensor, secondly it prevents thermocouple corrosion, and thirdly it aids in expansion and contraction of the heating element and gauge. The sensors were then wrapped with a reflective insulating bubble wrap to prevent water penetration and radiation flux. After installation of the sap flow sensors, each plant was bagged with a sealed plastic bag to provide accurate KSH values or a zero value for sap flow. After overnight readings, the bags were removed and the KSH values recorded. The new KSH values are then entered into the program to provide a more accurate picture of plant sap flow response.

Sap flow monitoring began on September 7, 2006, for the first experiment and on February 12, 2007, for the second experiment. The four potato plants included in each experiment were fitted with appropriately sized Dynagage sap flow sensors. Cumulative (g/day) and hourly (g/h) sap flows were recorded along with hourly temperatures ( $^{\circ}\text{C}$ ) in 2006. Additional parameters of net radiation, soil temperature and ambient RH were added for the second experiment in 2007.

On February 22, 2007, during the second experiment, the environmental controls on the greenhouse were adjusted to perform as follows:

- 1:00 am – 6:00 am –  $18^{\circ}\text{C}$
- 7:00 am – 11:00 am -  $25^{\circ}\text{C}$
- 12:00 pm – 1:00 pm -  $36^{\circ}\text{C}$
- 2:00 pm – 7:00 pm -  $26^{\circ}\text{C}$
- 8:00 pm – 12:00 am -  $18^{\circ}\text{C}$

This adjustment allowed for an extreme midday temperature to test for high temperature thresholds.

Ambient air temperatures were collected using a Campbell Scientific Model 107 temperature probe coupled with a Campbell Scientific 41303-5A radiation shield (Table 1 in Appendix). Installed within each of the four totes was an Omega type K (chromel-alumel) thermocouple for soil temperature collection and a Campbell Scientific – HTF3 Soil Heat flux plate. And lastly, a Kipp and Zonen NRLITE net radiometer was installed 20 cm above plant 2 and 3, to measure the energy balance between incoming short wave and long-wave IR radiation relative to reflected short-wave and outgoing long-wave IR radiation. All sensor data were collected using a Campbell Scientific AM16/32 multiplexer and a Campbell Scientific CR10X data logger recording at 15 min intervals and averaged hourly.

## RESULTS AND DISCUSSION

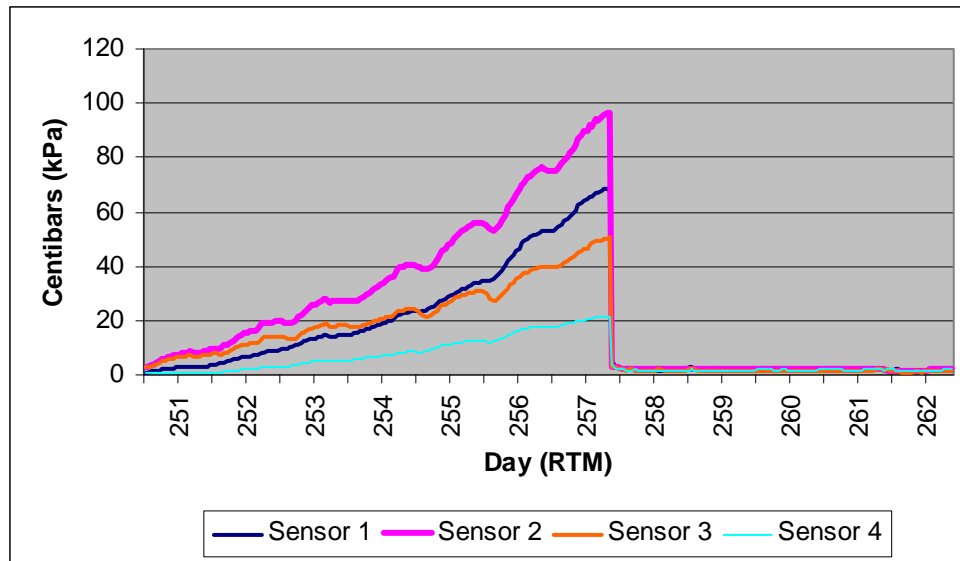
### 2006

The response to soil drying is shown in Table 1. Drying began on day 250 and resulted in 73 - 93% cumulative sap flow decreases during the 7-day drying period. The highest cumulative sap flow values were observed early in the drying event. The exception was sensor 4, whose highest sap flow values were seen on day 254, four days after commencement of the drying cycle (Table 1).

**Table 1.** Four sensor sap flow array cumulative daily values (g/day).

Day (RTM)	Sensor 1 (g/day)	Sensor 2 (g/day)	Sensor 3 (g/day)	Sensor 4 (g/day)
251	490.965	41.161	69.819	15.352
252	243.14	46.948	89.486	18.971
253	188.364	31.11	54.994	13.525
254	207.12	25.319	49.462	23.676
255	162.635	14.402	32.552	22.864
256	101.523	3.912	5.989	12.419
257	79.364	11.367	10.044	7.674
258	93.585	21.779	11.818	6.357
259	187.491	48.626	58.079	15.93
260	188.985	50.745	56.59	13.605
261	226.573	50.463	122.761	26.47

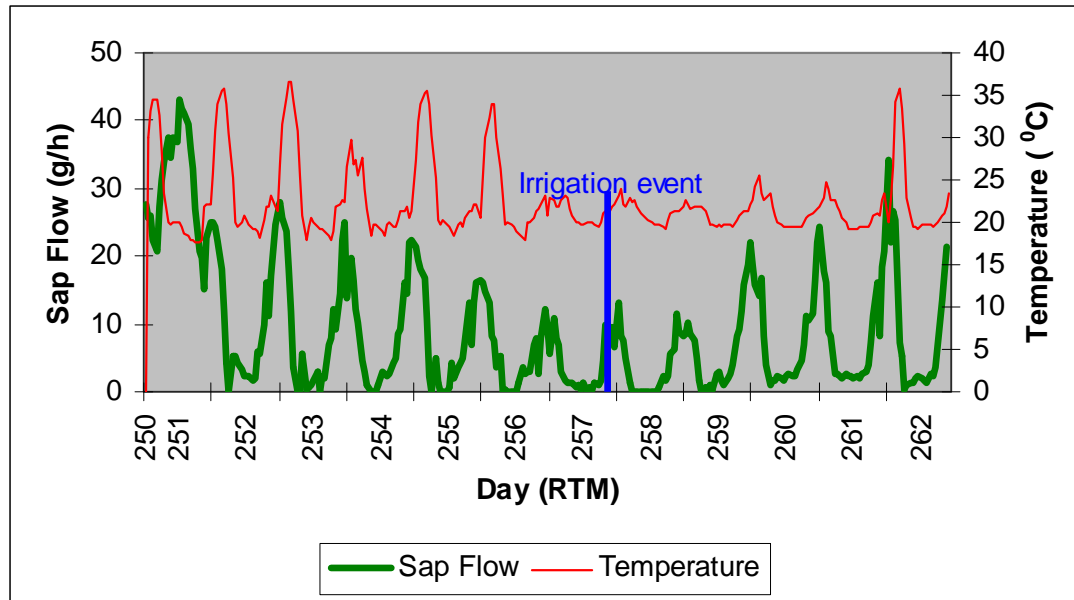
Despite considerable soil moisture losses in sensors 2 and 3 during the first four days (Fig. 2), sensors 1 and 4 read in the range of adequately wet to field capacity (0 to 25 centibars).



**Fig. 2.** Hourly soil moisture measurements in centibars (kPa) of soil water suction for four sensors.

Upon commencing soil wetting on day 257, after the drying cycle, cumulative sap flow increased to pre drying cycle values (Table 1). Hourly peak sap flows did not coincide with daily maximum ambient temperatures. Maximum sap flow generally occurred at midday and maximum temperatures were occurred 2 to 4 h later (Fig. 3).

On day 257, an irrigation event was introduced at 0930 h (Fig. 3). Cumulative flows responded by showing increases compared to previous days totals, in sensors 2 and 3 and decreases in sensors 1 and 4. Sensor 1 showed a cumulative sap flow increase one day after irrigation and sensor 4 two days after the first irrigation.



**Fig. 3.** Hourly sap flow response (g/h) with associated hourly temperature averages ( $^{\circ}\text{C}$ ).

Temperatures at or above  $30^{\circ}\text{C}$  gave no indication that sap flow responses had reached a threshold. This is contrary to the work of Burton (1972) who proposed, as air temperatures increase above  $30^{\circ}\text{C}$ , the net assimilation rate (NAR = measures the accumulation of plant dry weight per unit leaf area per unit time) in whole potato plants drops to zero.

The expected high temperature depression in sap flow may have been masked by normal daily sap flow responses, where midday temperature highs correspond to sap flow decline even when temperatures did not approach  $30^{\circ}\text{C}$ .

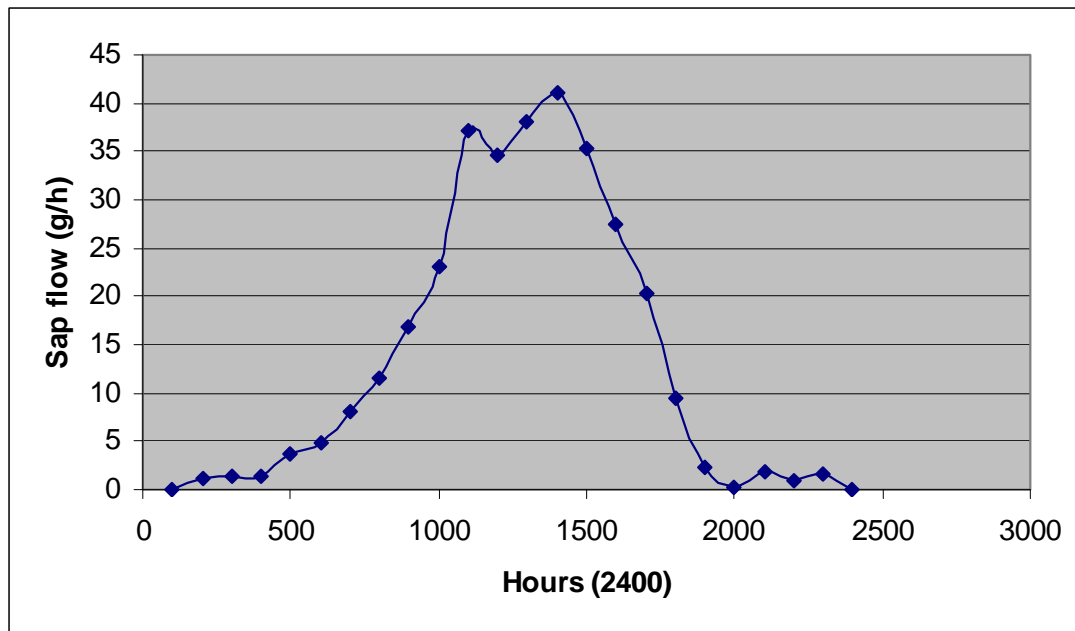
The problem in determining ambient temperature and soil moisture thresholds may be compounded by the work of Khedher and Ewing (1985), who suggest that above ground vegetative potato growth is increased under higher ambient temperatures. If the assertions are correct, increases in sap flow may only be a strong indicator of plant transpiration and have limited use as a tool for monitoring plant health.

## 2007

The monitoring of sap flow for all plants began on February 15, 2007 (day 46), and ended on April 6, 2007 (day 96). Cumulative (g/day) and hourly (g/h) sap flows were recorded along with hourly air and soil temperatures ( $^{\circ}\text{C}$ ) and soil tension values (centibars) for each sap flow sensor. Net radiation ( $\text{Wm}^{-2}$ ) was collected and averaged hourly along with hourly averages of soil heat flux for totes 2 and 3.

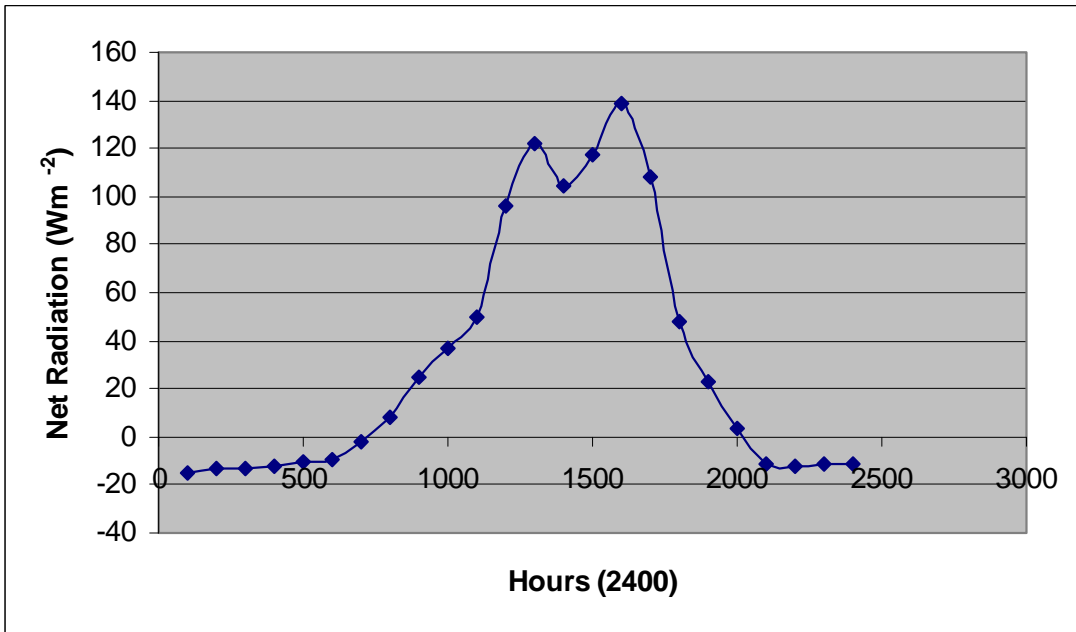
During midday, when peak flows were at their highest levels, a dip occurred in sap flow velocities between the hours of 1200 – 1500 h (Fig. 4). Gordon et al. (1999) discussed similar findings in his research and found a midday decline in net radiation was coincident with a reduction in sap flow and that peak flow rates were closely linked with the time of maximum temperature and vapour pressure deficit, but lagged behind maximum values of net radiation.

During this research, Gordon's conclusions were not realized. Drops in both net radiation (Fig. 5) and sap flows were identified during mid-afternoon, but rarely coincided as sap flow values dipped one to two hours before midday declines in net radiation. The midday sap flow decline was more coincident with peak temperatures (Fig. 6), but this trend was not always consistent. Overall, both temperature and net radiation are closely related to sap flow response with  $r^2 =$  values of 0.72 and 0.66, respectively (Fig. 7 and 8).

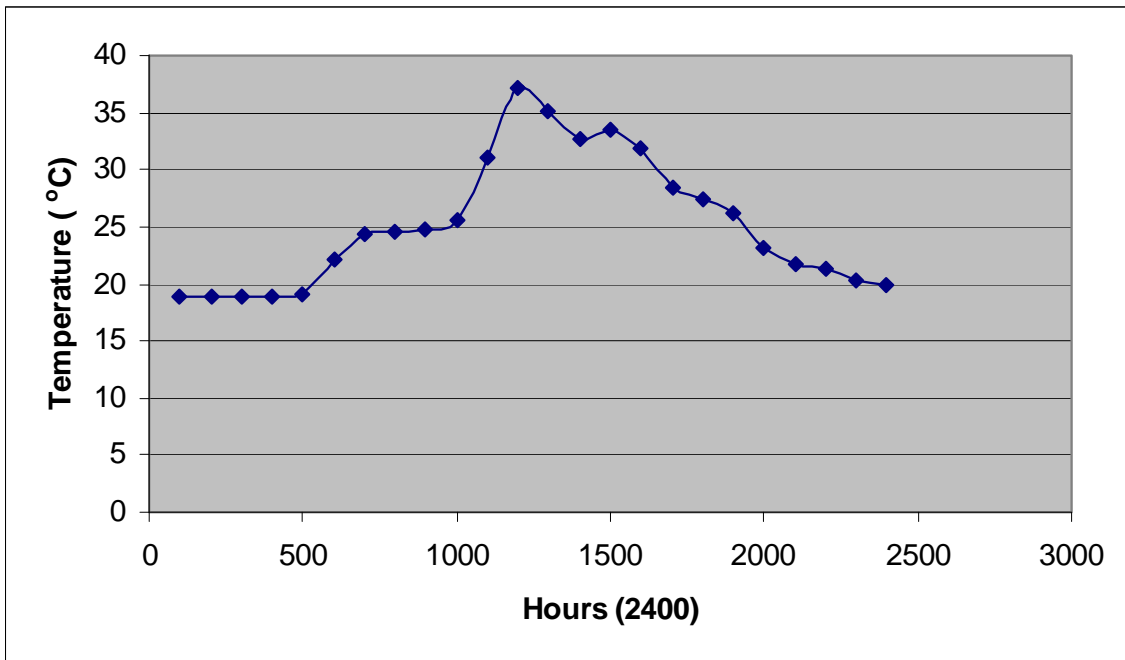


**Fig. 4.** Hourly sap flow measurements (g/h) sensor 2 for day 70.

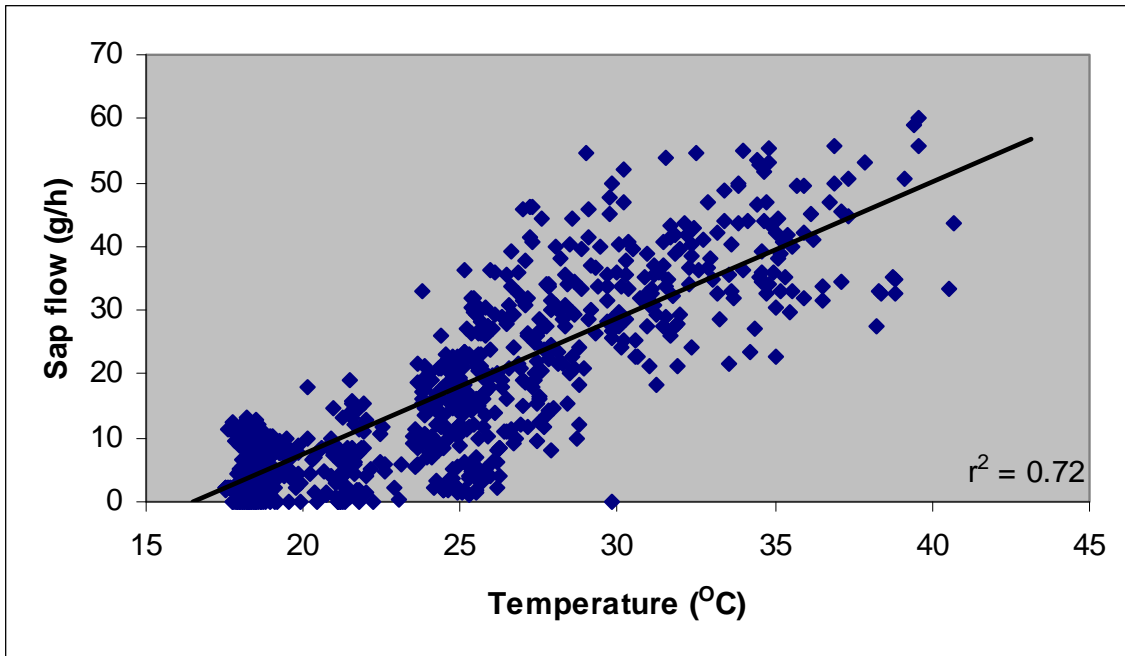




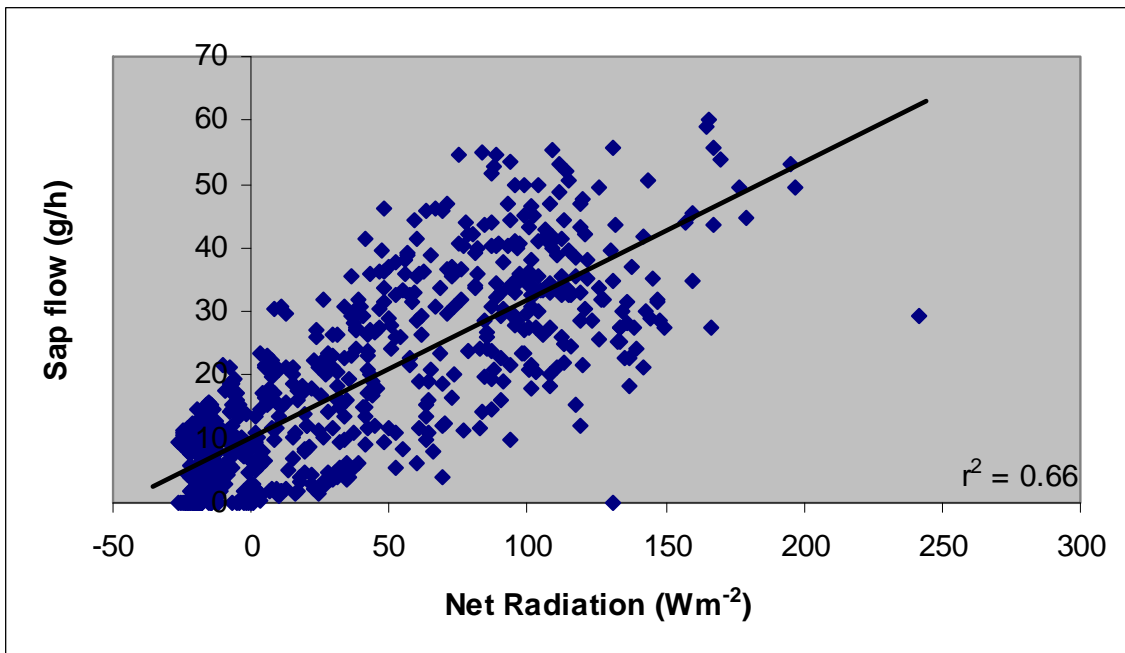
**Fig. 5.** Hourly net radiation values ( $\text{Wm}^{-2}$ ) sensor 2 for day 70.



**Fig. 6.** Hourly temperature values ( $^{\circ}\text{C}$ ) sensor 2 for day 70.



**Fig. 7.** Hourly sap flow measurements (g/h) vs. temperature (°C) sensor 2 (day 61-96).



**Fig. 8.** Hourly sap flow measurements (g/h) vs. net radiation (Wm<sup>-2</sup>) sensor 2 (day 61-96).

Through the use of the greenhouse internal environmental control system, daily temperatures were adjusted to represent temperatures identified by Burton (1972) as extreme (30°C). Fig. 4 shows the hourly sap flow response to temperature during a 24 h period. A dip occurred at midday and in this case corresponded to a peak temperature of 37°C, but the following hour the average temperature was 35°C and sap flow values increased. Temperature seemed to be an important factor in sap flow velocities, but there is something outside the scope of this research contributing to midday drops in sap flow.

Reductions observed in daily sap flow (g/h) between days 69 and 74 varied from a sap flow reduction of 5 % in one sensed plant to complete sap flow shut down in another. The complete sap flow shut down proved to be a one time response to soil moistures above .4 bars. Future drying events that pushed soil moistures above .4 bars didn't reach sap flow thresholds.

The sap flow response curves (Fig. 4) are representative of an average daily response of sap flow with time. These response curves are support the findings of Eguchi (2000). He used an on-line laser micrometer to measure diurnal changes in potato tuber growth under controlled environments. During his growth experiment, he found that the greatest tuber expansion generally occurred during the early night or beginning of the dark phase, and transient contraction of the tuber occurred at the beginning of the light phase. In our study, the lowest sap flow levels were seen during the beginning of the dark phase and prior to the beginning of the light phase before sap flow values started to increase. The results indicate sap flow movement from tuber bulking during the dark phase to plant transpiration and photosynthesis during the light phase.

## CONCLUSIONS

Cumulative sap flow decreases of 73 - 93% were observed in the 2006 study during a 7-day drying period. In the 2007 study, cumulative sap flow decreases were observed during a 5-day drying period, between days 69 and 74. Observed sap flow responses varied from 5 % (g/day) decreases to complete sap flow shut down. It must be mentioned that sap flow shut down occurred in just one sensed plant and in only one drying phase, another drying phase that reached similar lows in soil suction did not result in sap flow shut down for the same plant. This result however may provide the basis for determining thresholds for soil moisture in the future.

Strong relationships were observed between temperature ( $r^2 = 0.71$ ) and net incoming radiation ( $r^2 = 0.66$ ) and sap flow response.

Temperature and incoming net radiation closely mirror sap flow rates under non-limiting soil moisture. Temperature thresholds were not observed at ambient air temperatures up to 36 °C.

## **FUTURE WORK**

In-field monitoring of sap flow velocities using non-evasive sap flow monitors may prove difficult outside a research-based environment. The sap flow sensors require constant attention and significant technical expertise and training. The cost of purchasing sap flow sensors, data loggers and computers may also prove prohibitive for some producers.

Possible future research may include fine-tuning irrigation scheduling by looking at tuber bulking and transpiration and determining where improvements can be made in our recommendations. If the beginning of the dark phase is the biggest factor in tuber growth, perhaps light irrigations and fertigations can be scheduled just prior to the dark phase.

Another possibility for future work is an investigation into the cause of mid-afternoon dips in sap flow velocities.



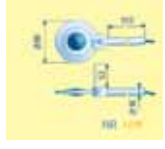
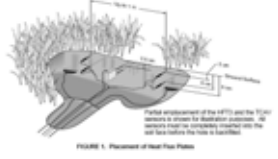


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## APPENDIX

<b>Sensor</b>	<b>Description</b>	<b>Sensor Photo</b>
Watermark 200 - granular matrix block soil tension probe manufactured by Irrometer Company Inc., Riverside, California.	The Watermark sensor is an indirect, calibrated method of measuring soil tension. It converts an electrical resistance reading to a calibrated reading of centibars (kPa) of soil tension.	
An Omega type K (chromel-alumel) thermocouple	Uses a thermocouple to measure soil temperature. Heavy-duty transition joint probe, type K, 304 SS sheath, 3/16 inch Dia., exposed junction, 6-inch length	
Kipp and Zonen NRLITE net radiometer	Measures the energy balance between incoming short-wave and long-wave IR radiation relative to reflected short-wave and outgoing long-wave IR radiation	
Campbell Scientific – HFT3 Soil Heat flux plate	The HFT3 Soil Heat Flux plate uses a thermopile to measure temperature gradients across the plate. Each plate is individually calibrated to output flux.	
DYNAMAX – Dynagage sap flow sensor	Sensitive sensors for use in measuring sap-flow in herbaceous plants and trees – the sensors sense milli-watt power transfers from a heater strip to the ambient, to the stem, and into the sap flow. Sap cools off the heater in varying amounts corresponding to the flow rate.	
Campbell Scientific Model 107 temperature probe & Campbell Scientific 41303-5A radiation shield	Temperature probe and radiation shield to prevent temperature flux	

**Table. 1.** Photos and descriptions of all sensors used in the 2007 research trial.