

INTERNATIONAL IRRIGATION

INTERNATIONAL WATER & IRRIGATION REVIEW

Abstract

A sensor which continuously monitors leaf thickness in the field with an accuracy of ± 1 micron was developed and field tested over a period of six growing seasons. The suitability of three different electrical components were investigated as transducers of linear

trouble free with a functional life of at least four years. Notwithstanding the low output intensity of the device, a Campbell CR-10 datalogger was able to trigger and read with sufficient accuracy, signals transmitted through standard, unshielded cables from a distance of up to 200 meters. The datalogger was programmed to monitor and interpret the

AUTOMATED ORCHARD IRRIGATION BASED ON MONITORING TURGOR POTENTIAL WITH LEAF SENSOR

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changes in leaf thickness to a measureable electrical signal. A strain gauge based on a miniature printed circuit of a wheatstone bridge fastened integrally to the face of a spring steel blade was found to be sufficiently accurate, able to withstand all ambient weather phenomena and agrotechnical practices, without interfering with normal leaf function. The simplicity of this configuration makes it easy to install,

data received, and to open and close irrigation valves as a real-time response to leaf thickness variations. This created a high frequency, low volume irrigation regime which reacted to and reduced incipient stress with a resultant reduction of total water application of up to 30%. Concurrent research demonstrated that there is a linear and significant correlation between leaf thickness and leaf turgor potential ($R^2 > 0.9$), which in

turn has been shown to be an accurate and sensitive measure of plant water status as it affects plant metabolism. The system was tested in commercial plots (citrus: 6 years; avocado: 3 years; cotton: one season) and compared with several variations of standard irrigation regimes. Cropping weights and quality of the sensor triggered treatments were equal to or better than control treatments, but water use efficiency (WUE) was consistently and significantly higher in the sensor treatments.

Introduction

The goal of irrigation systems has always been to optimize water use so that crop value is maximized, while the costs of water delivery are reduced to a minimum. This remains the test of irrigation efficiency today. In the past, the solution to the water balance of a given soil, plant, atmosphere continuum was consistent with the state-of-art of extant irrigation technology. Irrigation schedules were calculated to periodically replenish accumulated soil water deficits. The frequency of water applications was a function of the water retention capacity of the volume of soil permeated by the root system. While it was understood that this entailed cyclic variations in soil water availability, it was claimed that this mimicked natural intermittent soil wetting, and that plants evolved in a way that ensured optimal functioning under such a regime. However, evolution develops optimal survival techniques, and not necessarily maximum profit. Biotechniques have improved on nature by developing more prurient varieties of almost all agricultural crops.

The quest for a solution to the plant water balance has seen the development of numerous mathematical models which integrate one or more soil, atmospheric or environmental variables. The weakness of these models lies in the fact that they include only variables external to the plant, while relating to the plant itself as if it was an inanimate hydraulic vessel. Plant factors are considered to be constant, as if living processes don't affect plant water status, but this hardly reflects the truth of the matter. Evolution has armed plants with sophisticated systems by which they are able to regulate their internal water status. The

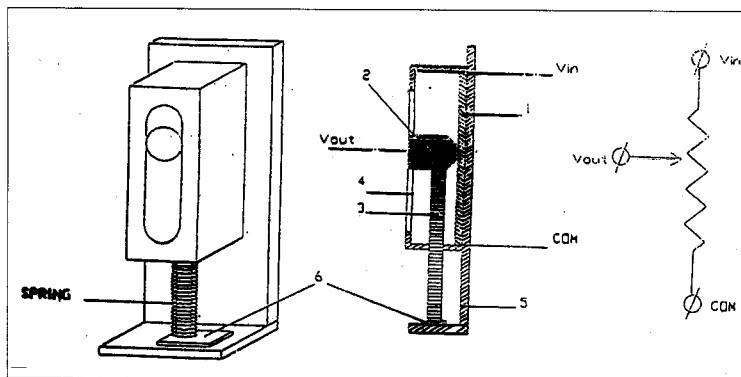


Fig. 1

tendency is conservative. That is, in the face of cyclic variations in their external environment, plant systems operate to maintain a steady state insofar as this is possible. However, endogenous regulatory systems don't always successfully deal with extreme conditions in the external environment. Temporary water stress is a frequent condition experienced by most crop plants, and these periods of stress can seriously affect key plant functions. Farmers instinctively understand this and attempt to regulate key growth processes by controlling water application. In arid zones where precipitation is scarce or completely absent during the growing season, irrigation is a powerful agrotechnique. The question is which of the numerous factors which affect plant water status should be monitored in order to assess the effects of the irrigation regime. In most instances only a small fraction of the many environmental factors are employed. Less frequently, attempts are made to integrate both meteorological and soil factors. In only rare instances are plant variables included in the equations describing the dynamic balance of plant water content. Models which utilize only part of the factors involved must assume that the variables not considered remain constant, which is obviously not the case. Consistent, reliable assessment of the soil-plant-atmosphere continuum has escaped even the most sophisticated models, while collection of input data to feed these models has become a complicated and expensive affair. One of the delightful features of plant life lies in the fact that plants themselves are continuously assessing their own water status, both elegantly and accurately. It, therefore, seems logical to bypass the futile efforts of science, and

go directly to the final integration as it is manifested in the plant itself. In short, by directly monitoring the plant, it is possible to obtain a continuous, current record of plant water status. In order to do this, it is necessary to understand how the plant senses its own water status. Those who investigated this question became convinced that the plant cell membrane is the tissue that senses and accumulates data on the level of cell water, and then triggers metabolic systems accordingly. The cell membrane is comprised of a lipid bi-layer and integral proteins which contain the protoplasm and itself fulfills vital metabolic functions. Critical in the functioning of the membrane is its spatial conformation which is controlled by its physical and chemical environment. Cell water content is a primary component of the membrane's physical environment. The cell sap presses the membrane against the rigid retaining cell walls. Consequently, the level of cell water will effect the pressure

which develops on the membrane and thus its three-dimensional conformation. This pressure is responsible for maintaining the turgidity of plant tissue. It is turgor pressure which allows gas exchange with the atmosphere by keeping stomatal pores open. In the absence of turgor, stomata will close, plants will wilt, and eventually die. In short, the level of turgidity integrates all the factors influencing plant water status. The cell membrane is delicately sensitive to the slightest change in turgor pressure, and regulates metabolism accordingly.

The expansion and contraction of plant organs in response to changes to tissue water status is a phenomenon that has been studied in the past. Tree trunks and the stems of vegetative plants shrink as they lose water. Twigs and fruits also experience volume variations in consequence of changes in water content. A number of investigators have demonstrated that leaf volume is well correlated with leaf turgor potential. The relationship is dependent on the degree

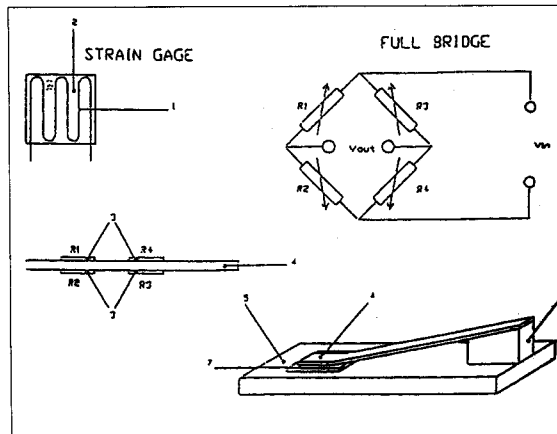


Fig. 3

of elasticity of cell walls and has been described for many species. Leaf volume is a function of leaf thickness and leaf area, but since volume changes are manifested almost exclusively by variations in leaf thickness, leaf turgor potential can also be calculated as a function of leaf thickness. Therefore, once this relationship has been determined, turgor potential which is the plant's own measure of its water

status can be assessed in vivo by monitoring leaf thickness.

Background Research

1) Variability in leaf thickness responses was studied among leaves in the same tree canopy, between leaves in other tree canopies under the same and under different irrigation regimes, during the course of an entire solar day, several times during the growing season. Results showed that:

- The leaf whose relative thickness most closely approximated the statistical average of all leaves measured simultaneously within the same canopy, was consistently located in the same position in the canopy.
- Variability between leaves located in the same relative positions in different trees under the same irrigation regime was negligible.
- Variability between leaves located in the same relative positions in trees under different irrigation regimes was significant and consistent.

It was concluded that a single leaf

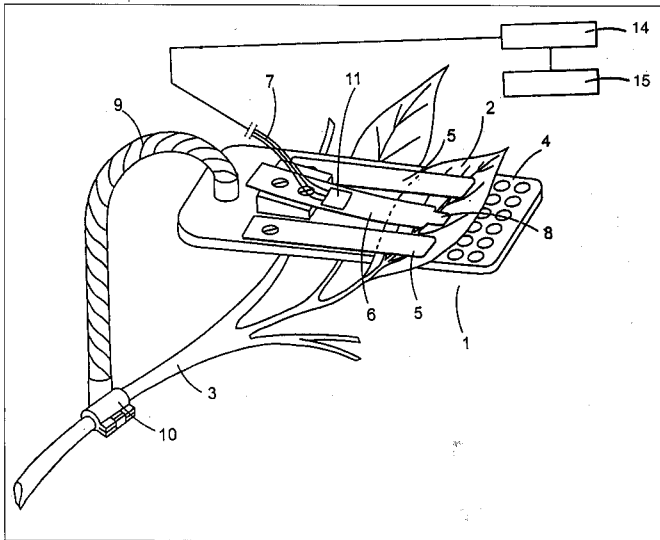


Fig. 4

sensor placed on a leaf located in the position representative of the statistical average could serve as an indicator of the water status of an entire orchard.

- 2) In a series of experiments employing several different approaches, the correlation between leaf thickness and turgor potential was investigated. It was found that although the relationship is a product of several variables over time, it is determinate and essentially linear.
- 3) Leaf thickness sensor readings were calibrated against a hand-held micrometer both in the laboratory and in the field, and compensated for temperature effects. Corrected sensor readings were accurate within 1 micron. Linear variation was less than 0.1%. Since the linear correlation coefficients of the relationships between turgor potential and leaf thickness on the one hand and leaf thickness and sensor readings on the other, were more than 95%, it was concluded that sensor readings could be utilized directly in irrigation controller algorithms without translation to either leaf thickness or turgor potential.

Summary of the Irrigation System.

The proposed system is composed of three integrated elements:

- 1) An instrument attached to a plant leaf capable of detecting variations in leaf thickness of 1 micron.
- 2) A controller programmed to activate

and read signals from the sensing device, interpret the data and activate an in-place irrigation system in accordance with the concept of "real time" water application in response to incipient plant water stress, as outlined above.

3) An automatic irrigation system based on mini or micro-emitters. The unique features of the system are the sensing device and the accompanying controller software. The system is compatible with

automated drip irrigation systems in general use in Israel and abroad.

The sensing device necessarily fulfills the following requirements:

- 1) Sensitivity of ± 1 micron and linearity of 0.1%
- 2) Immobility relative to the leaf to which it is attached.
- 3) Non-interference with the normal functioning of the leaf.
- 4) Dependability unaffected by all natural conditions and cultural practices.

The controller program has a capability for all functions that irrigation controllers currently on the market feature, such as automated fertigation and high and low flow cut-off. It will also include an optional standard irrigation program based on time or volume as is in general use. This optional program will also serve as an emergency program to be triggered in the event of malfunction of the main sensor based system.

Detailed Description of the Sensing Device

- 1) During the period from 1991 to the present date, a device incorporating a linear potentiometer transducer (Device "A", Fig. 1) was developed and successfully field tested. The potentiometer is a commercially available component. The linear movement of the pin protruding from the lower face of the potentiometer case is translated into a change in the relative resistances of the upper and lower parts of the potentiometer. To the potentiometer case is attached an

"L" shaped, transparent (so as not to interfere with light collection by the leaf) 4 mm. thick plastic holder. The horizontal face of the "L" shaped holder is covered with myriad 1 mm. holes which allow gas exchange between the leaf and the atmosphere. A trapezoidal plate of the same plastic material is attached to the threaded end of the pin protruding from the potentiometer case and is extended to the lower plate by the action of a stainless steel spring, developing a force no greater than 250 mg./mm². The leaf is inserted between the upper and lower plates. Since the lower plate is immobilized in relation to the potentiometer, a change in leaf thickness will result in the movement of the pin protruding from the potentiometer case and a consequent change in the relative resistances of the upper and lower parts of the potentiometer. This in turn will vary the voltages on a circuit which is initiated by and terminated in the controller.

The sensor holder is held in place by a flexible arm attached to the same twig upon which the sensor leaf grows. The flexible arm is positioned so that the holder will be in the exact spatial orientation as the leaf to which it is attached, thus preserving the natural orientation of the leaf.

- 2) In the period 1995-1996, an alternate sensing device based on the principle of a "strain gauge" has been tested (see Device B, Figures 3 & 4). The advantages of this device lie in greater sensitivity, simpler construction less given to failures, and cheaper production costs. It has the disadvantage that its output signal is in the order of several microvolts only, and thus more vulnerable to random interference. The sensing tongue is made of stainless spring steel (thickness, 0.3 mm.). On it is glued a miniature printed circuit of a Wheatstone bridge. Bending the tongue changes the relative resistances of the four bridge resistors and the voltages developed in the two alternate paths. This component was supplied by Vishay, Israel, Ltd. according to our specifications. The tongue is attached to the spacer on a clear plastic plate, in such a way that the 1 cm² tongue tip is contiguous to

Table 1. Irrigation treatments.

Treatment	Irrigation Frequency	Irrigation Quantity
D3	Every three days	24 ltr/day
D1	4 daily pulses	24 ltr/day
W1	4 daily pulses	32 ltr/day
W3	Every three days	32 ltr/day
S	daily pulses	according to sensor

the plate in the nil position. The plate is holed in the area upon which the leaf will lie, and constructed of the same material as described in 1). The entire unit is attached to a flexible arm and fixed as described above. When a leaf is placed between the tongue tip and the plate, variations in leaf thickness are translated into an analogue signal read by the controller.

Since the force holding the leaf in position is minimal, it became necessary to widen the entire plate assembly in order to add two additional spring steel tongues on either side of the sensor tongue. The additional tongues are made of stainless spring steel 0.5 mm. thick and therefore develop a greater force on the leaf. In this way the leaf is immobilized in relation to the plate and sensor tongue.

- 3) The flexible arm is a "Lockline" 40413 1/4" X 25 cm. standard arm. It is bolted to the sensing unit at one end and the device gripping the twig or stationary 4 mm. diameter peg at the other.
- 4) The gripping device, constructed of plastic, consists of two opposed halves, hinged together on one side (see Figure 5). The twig or peg is positioned in the cylindrical channel running the course of the opposed faces, and fixed in place by two bolts on the unhinged side of the two opposing halves.

Some Results from Associated Field Tests.

The data given are results obtained over five years from a commercial citrus orchard.

Table 2. Effect of irrigation treatment on yield and water use efficiency.

Treatment	1996 kg/tr	1992 kg/tr	'96-'92	WUE Kg/M ³
S	82.25 a	23.7 b	3.46 a	18.63 a
D1	65.02 b	27.9 ab	2.33 b	14.94 bc
D3	72.1 b	24.8 b	2.91 ab	16.38 b
W3	80.3 a	32.7 a	2.45 b	15.90 b
W1	71.4 b	29.7 ab	2.43 b	14.05 c

1. Duncan's Multiple Range Test, p=0.05

2. WUE=water use efficiency, kilogram yield divided by cubic meters water applied.

3. The orchard is planted with 833 trees/hectare. 82.25 kg/tree is the equivalent of 68.54 tons/hectare.

Table 3. Increase in Trunk Cross-sectional area and comparison with increase in yield.

Treatment	A-'92	A-'96	A-'96-A-'92	Y93:Y96-Y92	dY/DA
S	50.21	90.89	40.68	189.5	5.4
D3	51.45	86.59	35.14	181.1	6.2
D1	51.49	80.66	29.17	232.5	8.4
W1	55.05	82.77	27.82	235.6	8.7
W3	57.06	84.11	27.05	243.0	6.0

A= cross-sectional area(cm²); Y=yield(kg/tr); dY/dA=cumulative increase in yield divided by cumulative increase in trunk cross-sectional area (column 5 divided by column 4).

An 0.4 hectare plot of CV.Oroblanco on Troyer rootstock was divided into two blocks, each containing one randomly selected replicate of the 5 irrigation treatments. Each replicate is composed of 23 contiguous trees in a row. The plot was planted in 1988 with saplings nursery-infected with exocortis viroid; spacing: 6m X 2m.

The plot is irrigated by a single line of 4 l/hr pressure regulated "Netafim"



Fig. 5

drippers spaced one meter apart (2 drippers per tree). The drippers are positioned 50 cm. on either side of the trunk. Until the 1992 growing season, when the experimental system was installed, the orchard was irrigated as a unit twice a week according to recommended extension service practice based on Class "A" pan evaporation coefficients.

From Table 2 it can be seen that yield for the "sensor" treatment in the base year, 1992, was statistically less than control treatments, but by 1996, yield was significantly greater than yield of controls. Water use efficiency (WUE) was also statistically higher than im controls. Table 3 demonstrates that this impressive increase in cropping was achieved concurrently with a significantly greater increase in trunk cross-sectional area, which is a gauge of total tree growth.

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