Automatic Irrigation Based on Monitoring Plant Transpiration

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ABSTRACT

We describe a means to automate irrigation by using sap flow gauges and an automatic raingauge, both installed in the irrigated field. Signals from the gauges are continually interpreted and recorded to determine the crop transpiration over a pre-set irrigation interval. The summed amount, expressed as a depth of water, is the amount to be delivered after a correction for surface evaporation, water salinity, and non-uniform distribution. Water is delivered by the opening of a valve and/or starting a pump for the required amount of time. The entire operation is realized with a stand-alone digital measuring and control system, contained in a weatherproof enclosure. While fully independent and automatic, the system is at all times accessible for retrieving information or modifying the instructions and parameters by direct or remote means. The first production FLOW-4 system is currently being tested in the field.

Keywords. Automation, Digital control, Sap flow, Stem gauge

INTRODUCTION

Numerous methods exist or have been proposed for scheduling irrigation effectively. They can be grouped into four categories: (1) entirely empirical and without any kind of ongoing measurement, (2) based on monitoring soil moisture, (3) based on estimates of water use from weather data, and (4) based on tracking the condition of the crop, usually referred to as crop water stress. None directly reflect the fact that the water requirements of plants derive almost totally from the transpiration process and that the purpose of irrigation must be, in first analysis, to make up the transpiration losses without waste. The growing emphasis on precision and conservation in the delivery of water to the root system by various irrigation techniques has given rise to a large and specialized industry, but it has not resulted in the development of control systems that are physically sensitive to the rate and amount of transpiration.

In this report, we introduce a new category of irrigation control in which the scheduling of water delivery is based on the measurement of the actual water use of the plant, as contrasted to the water use of the cropped field, usually identified as ET, for evapotranspiration. It has been shown by numerous investigators that there is a close linear relation between the accumulated transpiration and the accumulated dry matter yield of economic plants or stands of plants. A recent summary of the subject was given by Kramer and Boyer (1995, Chapter 12). There, it is also pointed out that the proportionality between transpiration and dry matter accumulation differs between species, between climates and management systems, and possibly even between growth stages of a crop.
However, this complexity does not alter the principle that the transpiration of a well-watered plant or crop must be matched on an ongoing basis to insure its optimum production under the circumstances at hand.

The technical problem in transpiration-based irrigation control has been the lack of a suitable field method to monitor transpiration continuously. This need has been met in the past decade by the gradual development of stem and trunk flow gauges that are commercially available and that are suitable for a wide range of economic plants, including trees. The original concepts were proposed by Sakuratani (1981), Steinberg et al. (1990), Cermak et al. (1973), and Granier (1985). The former two designs are non-invasive and suited for use on herbaceous plants or small trees, whereas the latter two require probes to be inserted into the trunk of larger trees. All these devices are installed permanently on the stem, branch, or trunk and function by injecting a small amount of heat into the xylem tissue at a constant rate of between 0.01 - 5.0 W, depending primarily on the size of the stem or trunk. The operating principle is that of a heat balance and signals are being collected frequently and continually, from which the sap flow rate is calculated and recorded in units of mass per unit of time. In addition, the transpiration is accumulated and can be reported for every hour, day, or periods of several days.

The question is, first of all, whether these devices are practical and accurate. A number of tests on individual plants or small trees have been used to test sap flow gauges and shown them to be practical in use and, in most cases, accurate to within 5% on a daily basis (Dugas, 1990). The first convincing evidence that they are accurate in measuring the transpiration on a field scale was given by Ham et al. (1990) and by Lascano et al. (1996, this conference). In the first study, it was shown that the water use by a stand of cotton plants, as measured by sap flow gauges, was equal to that found as the difference between evapotranspiration and soil evaporation, both measured independently. The second study shows that the measured transpiration from drip-irrigated cotton was equal to that calculated from a Penman-Monteith model and from a mechanistic computer model (ENWATBAL, Evett and Lascano, 1993), both of which use weather data as inputs. As we will see further on, the latter model is a necessary element in the proposed system for scheduling irrigation based on measured crop transpiration. In fact, the method we will describe follows a drastic simplification of the diagram of Fig. 1 in the paper by Lascano et al. (1996), cited above.

**GENERAL METHOD**

Our objective was to design a stand-alone, fully automated system, based entirely on measurements made with a few sap flow gauges. Second, we concentrated on irrigation methods that apply water frequently and directly to or below the soil surface, so as to produce a high degree of uniformity in application and a minimum of surface evaporation, in short: microirrigation. This is not to say that the system would not work for other methods.

Third, we envisaged the system as one that replaces the water actually used as transpiration, plus a minor, but essential allowance for distribution inefficiency, salinity control, and surface evaporation. Fourth, the system would calculate the accumulated water losses over a period of one to several days, make the necessary adjustments as per the previous paragraph, and open the valve(s) and/or start a pump for the required amount of time to dispense the calculated amount of water. Thus the system would be fully automatic, but would also permit an operator to access and modify a small number of parameters in the software, such as the frequency of irrigation, the time of day for watering, and the correction factors identified above.
In addition to the control operation, the system would also produce a record of its actions and the numbers on which those actions were based. This would be, for example, a daily or hourly log of the transpiration rate of the crop and its accumulated amount, the time and amount of irrigation water applied, plus any weather data of interest. The record would be automatically retrievable at set times, or on command, to be transferred to a separate memory or to paper.

PHYSICAL DESCRIPTION OF THE SYSTEM

The first design, identified as Dynamax FLOW-4™, uses 4 sap flow gauges of the appropriate size. These are to be installed, in the field that is to be irrigated, on 4 plants selected to represent the average plant size. This selection is not permanent, as sap flow gauges can easily be detached and re-installed on another set of plants, whereafter operation can be resumed in one or two hours.

The 4 gauges are connected with weatherproof cables to a recorder-computer device, powered by a solar panel with battery back-up and mounted in a weatherproof enclosure. The device has three outputs: one to a PC for occasionally setting parameters, monitoring its functioning when needed, and for retrieving records. The second output leads to an irrigation pump and the line valve(s), with their sequencing logic when required. The third output is for a remote alarm that is activated by pre-programmed limits to the gauge signals and that would indicate a sensor malfunction.

The heart of the recorder-computer device is a dedicated microprocessor that contains a single A/D converter and a sequencer, plus the algorithms needed to compute the sap flow rate for each gauge every minute. The outputs from each gauge are verified and processed before being averaged and expressed as the rate of transpiration of the field in depth of water per unit of time, such as mm per hour or day. The accumulated total since the last irrigation is also reported as a depth of water, such as mm or in.

At a pre-selected interval, the accumulated amount is determined and converted to the amount of time required for the water delivery system to apply this amount of water, but corrected for the inefficiencies as explained above. Irrigation then takes place and the transpiration (sap flow) accumulators are reset to zero, so the process can repeat itself.

The memory (EEPROM) of the device contains the setup parameters for each gauge, the irrigation frequency and correction parameters, as well as the data and trends for an entire month. As explained above, this memory can be accessed anytime and the parameters can be adjusted as required, using a PC. The connection between the FLOW-4 and the PC can be by standard cable, by telephone cable, by cellular phone, or by a radio link. The FLOW-4 will be an easily portable unit in a weatherproof enclosure.

The general arrangement of the automated irrigation system is shown in Fig. 1, which is adapted from Van Bavel (1995), who described a proposed system based on the use of a FLOW-32™, a more complex and general-purpose sapflow measuring system. The system (Fig. 1), can be seen as a closed loop, in which information is flowing continually in either analog or digital form, and in which water is flowing continually from the soil through the plant into the atmosphere, but intermittently from the water supply to the plant roots. The system can also be seen as a feedback loop, in that a depletion of soil moisture can reduce transpiration and, hence, the dry matter accumulation rate. This situation is, in principle, to be avoided, which is the reason for frequent irrigation in a system that uses water efficiently.
In a number of recent studies (cf. Van Bavel, 1995) stem and trunk sap flow gauges have been shown to be practical and accurate. Nevertheless, there is no assurance that they will be useful as the basis of an automatic irrigation controller. Lascano et al. (1996) showed that a number of sap flow gauges, installed in a micro-irrigated cotton field, functioned over an entire season and gave a record of daily transpiration essentially identical to that obtained by other, independent means. However, the gauges were not used to control the irrigation regime. This will be the purpose of a similar experiment in 1996, using a first production model of the FLOW-4 system.

Clearly, several similar experiments will have to be carried out to answer questions about irrigation scheduling based on measured crop transpiration. One of these is how large an irrigated field can be adequately represented by 4 gauges on 4 plants or trees, as in an orchard or vineyard. Indications are that the transpiration from a 2 - 5 ha area can be measured with a 5 - 10% accuracy over a period from 1 to 5 days. Meeting this goal will require skill of an operator in selecting representative plants and a close watch of the ongoing performance of each gauge.

Another problem is to know how much to allow for surface evaporation. The ENWATBAL model can be used to estimate these losses accurately from weather data, as shown by Lascano et al. (1994), but the majority of irrigation managers are unlikely to be willing to use a complicated model and maintain the needed weather records. Farm management or plantation-type organizations might be interested. An alternative is to use a correlation between the needed corrective multiplier (> 1.0) and the leaf area index (LAI). Such a correlation can be obtained from ENWATBAL for a specific crop and used in the form of a simple table, from which the operator would update the parameter weekly or so, and after estimating the LAI.
The corrections for irrigation water salinity and for non-uniform distribution are well understood in irrigation engineering and can be entered in the FLOW-4 software, as appropriate. Less straightforward is the correction needed for rainfall. First, the raingauge that is part of the FLOW-4 system must be automatic and accurate. The amounts measured must be credited to the water balance of the crop, but cannot exceed a maximum amount that equals the storage capacity of the root zone. For the latter one could enter the maximum or potential evapotranspiration (ET) over the irrigation interval. If the recorded rainfall is less than the latter number, part of the precipitation could be retained by the crop canopy and evaporate at potential rates, while the sap flow would be reduced (an observation made on corn plants by J. Tolk in Amarillo, personal communication). At best, automation of irrigation may be less feasible in humid climates.

REFERENCES