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Specific micromorphometric reactions of fruit trees to water stress and irrigation scheduling automation

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SUMMARY

Continuous recordings of diameter variations using LVDT gauges were made on potted or field grown apple and peach-trees to seek a reliable indicator of water stress. The first and general indication of water stress was the decrease and stoppage of daily growth in stem diameter. When water was sufficiently available in the soil, maximum daily shrinkage was a versatile indicator of transpiration stream intensity. When water availability in the soil strongly decreased two kinds of specific daily shrinkage patterns appeared: a) 'peach-tree' pattern, whose maximum daily shrinkage markedly increased as water stress became more severe, and b) 'apple-tree' pattern, where maximum daily shrinkage under severe water stress was smaller than its well watered value. Parameters for irrigation automation designs are proposed by processing both daily growth data and daily shrinkage data.

ACCURATE measurement and continuous recording of the diameter of stems or fruits, i.e. the micromorphometric method, is reputed to assess the water status of fruit trees (Kozlowski, 1968; Lassoie, 1973; Huguet, 1985; Garnier, 1986). A device which uses this relationship to control irrigation was patented by INRA (Institut National de la Recherche Agronomique) in 1984.

Two measurements describe the diameter changes observed on a living stem over a 24 h period: a) Maximum daily shrinkage (MDS) which is the difference between the maximum diameter usually observed in early morning and the minimum diameter, generally reached in mid-afternoon, and b) Daily evolution (DE) which is taken as the overall change in diameter over time in 24 h units, since dawn.

The maximum daily shrinkage of plant tissues appears to be linked to environmental factors affecting plant transpiration, e.g. water availability in the soil and potential evapotranspiration. Most plant tissues act as water reservoirs and their shrinkage reflects the redistribution of water modified by both water potential gradients and the various resistances to water transport within the plant (Molz and Klepper, 1972).

Daily evolution is a general indicator of plant behaviour linked to various disturbances or stress affecting its physiology: solar radiation, temperature, leaf efficiency, damage by pests, water stress, etc.

In this study we attempted to understand the micromorphometric reactions of peach and apple trees to water stress. Our aim was to test whether maximum daily shrinkage and daily evolution were good indicators of plant water stress and, in addition, to propose general rules for data interpretation to help make irrigation decisions automatic.

MATERIALS AND METHODS

The study was conducted in our greenhouse and experimental orchards in the southern Rhône Valley of France where the Mediterranean climate makes the moisture deficit in the soil severe during the main growing season.

Stem diameter changes

Stem diameter changes (final accuracy ±0.01 mm) were measured with linear variable

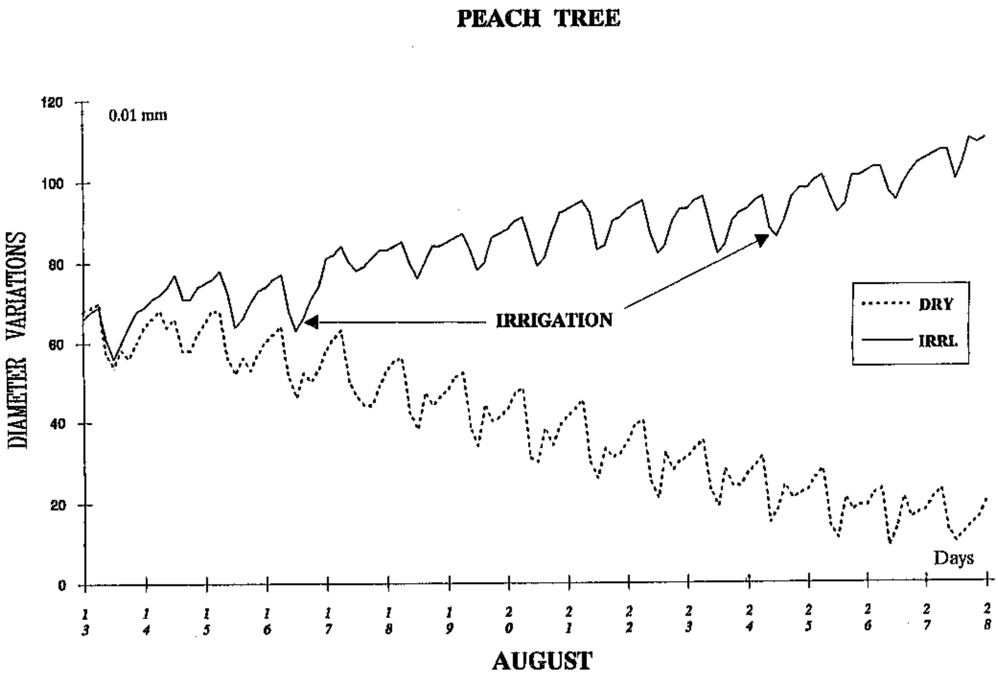

FIG. 1
Stem variations of diameter, water stressed peach-tree (DRY), watered peach-tree (IRRI).

differential transformers (LVDTs) mounted on an INVAR frame (Li and Huguet, 1989a). The same frame can be adapted to both fruits and stems. All sensors are connected to a specific 'Pepista' microcomputer (Pelloux, 1990) which records data every 30 min, can control irrigation and makes it possible to transfer data to a computer.

Leaf water potential

Pre-dawn leaf water potential was measured using a pressure chamber (Scholander *et al.*, 1965). One sunlit mature leaf was tested on each tree, and five replications (trees) were performed for each treatment.

Stomatal resistance

Stomatal resistance was measured with a diffusion porometer (Delta-T Device, MK-2 Model) on the lower side of two given leaves per tree. Measurements were made between noon and 1300 hours, when leaves were quite sunlit.

Meterological data

Short wave radiation and wind speed were provided by our meteorological station, close to the experiments.

Experimental sites and plant materials

The stony alluvial soil of the mature peach tree orchard was had a mechanical composition of 15% clay, 30% silt and 54% sand after removal of stones. The apple tree orchard had a loamy soil (39% clay, 52% silt, 9% sand).

Young peach trees (cv. Alexandra /GF305) were cultivated in a greenhouse in 60 litre pots filled with a vermiculite substrate, which has a high capacity for water retention (50% in volume). Two treatments were applied: wet treatment and dry treatment.

Wet treatment: trees were watered every morning until the full water capacity was replenished by weighing (Li and Huguet, 1990).

Dry treatment: trees were watered only when the relative moisture of the substrate became too low (<40%).

RESULTS

Micrometric changes in peach-trees

Reactions of field grown trees: Figure 1 makes

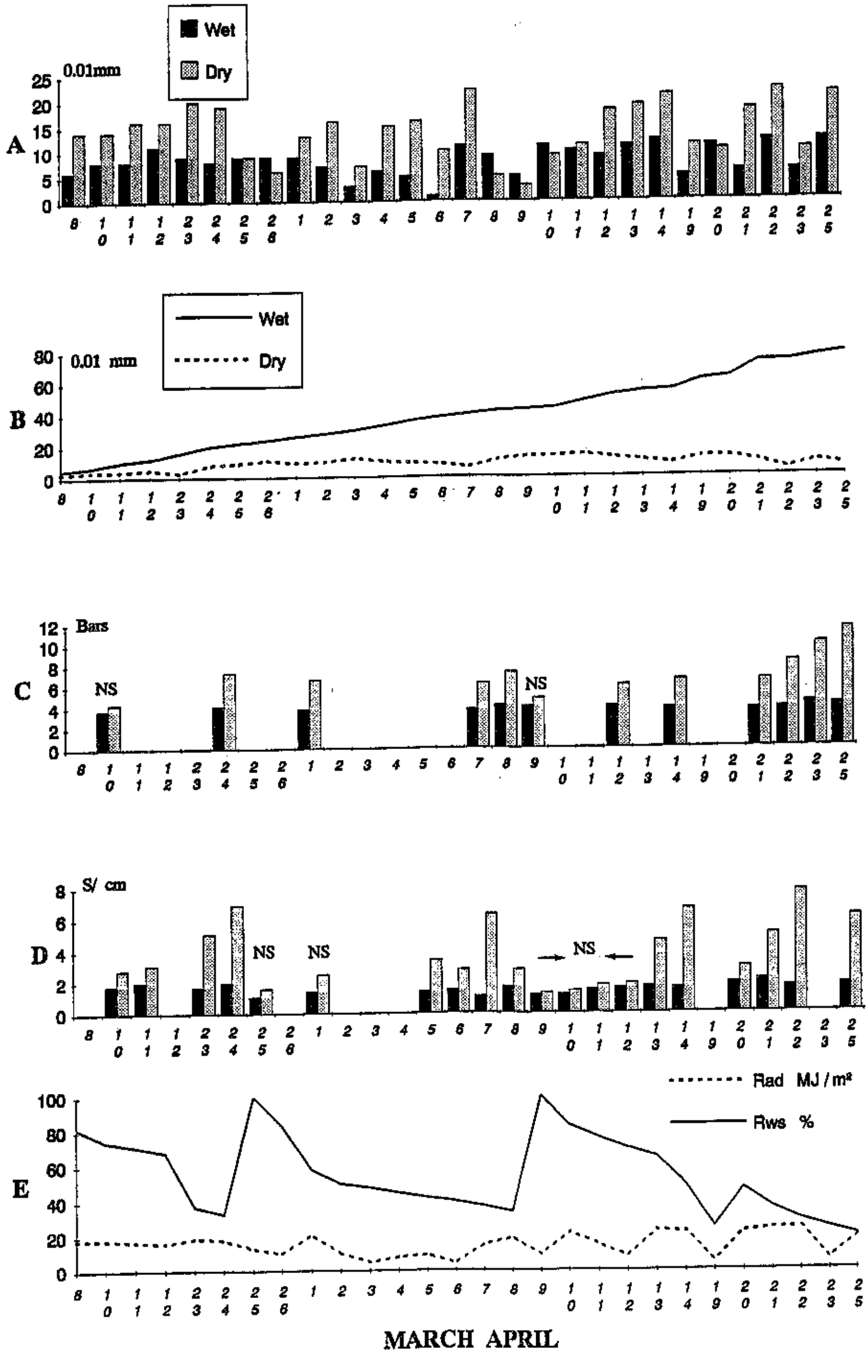

FIG. 2
Behaviour of potted peach-trees.
A: Maximum daily shrinkage of stems. B: Daily evolution of stem growth. C: Leaf pre-dawn hydric potential. D: Leaf stomatal resistance. E: Solar radiation per day (Rad) and relative water content (Rws) of dry treatment substratum.
NS: Differences not significant at $P = 0.05$.

it possible to compare variations in stem diameter (diameter approx. 40 mm) for two different field-grown peach trees (cv. Merrill Sundance/Rubira). The control tree was irrigated by micro-sprinkler whenever the mean of the soil water potential (3 tensiometers at 0.5 m depth and 0.5 m from the emitters) reached approx. −60 kPa. The soil water potential usually rose to about −10 kPa after irrigation. Stressed trees were not irrigated after mid-July.

During this 15 day period the control tree was irrigated twice and showed a 0.43 mm increase in diameter, the diurnal increase stopped the day before irrigation and became high the night after irrigation. DE (daily evolution) after irrigation remained positive and MDS (maximum daily shrinkage) increased as the availability of water in soil decreased.

During the same period the stressed tree was not irrigated and showed a 0.47 mm decrease. The DE was negative or occasionally equal to zero. The MDS remained high and was always higher than that of the control.

Reactions of potted trees: The E part of Figure 2 gives the value of solar radiation (outside the greenhouse) and the changes in substrate relative moisture for the Dry Treatment. Obviously, the Wet Treatment relative moisture was always ca. 100%. Dry Treatment was irrigated three times (24 March; 8, 19 April) during the experiment, but the third irrigation did not replenish to full field capacity.

Part A makes it possible to compare the respective progression of MDS in the two treatments. Wet MDS did not rise above 0.12 mm, and the maximum value was reached only on days with high solar radiation. Dry MDS were equal to, or smaller than, Wet MDS only for days after irrigation when relative moisture was close to 100%. Dry MDS increased following irrigation as the relative moisture of the substratum decreased.

Cumulative daily evolutions presented in part B are in marked contrast. The growth rate in the Wet Treatment was very regular and with an 0.82 mm total increase during the period. However the stem diameters of plants in the Dry Treatment were the same at the end of the period as at the beginning. This zero growth in the Dry Treatment was the result of water stress.

On Dry Treatment leaves, pre-dawn hydric potentials (Figure 2 part C) and stomatal resistances (Part D) were higher with lower substatum water availability. In the Wet Treatment, hydric potentials remained very regular (ca. 4 bar), and stomatal resistances never exceeded 2 $s\,cm^{-1}$. However in the Dry Treatment, when relative water content of the substrate was very low, these variables reached three times the mean values of the Wet Treatment.

Stress was severe when the roots from a young peach tree cultivated in nutrient solution emerged from solution (Figure 3). Here MDS was higher the day after root removal and then decreased day by day as the tissue reserves became more and more empty and were not replenished. The first day MDS was about three times the mean MDS observed on previous days when roots were in nutrient solution.

Micrometric changes in apple-trees

Reactions of field grown trees: Figure 4 makes it possible to compare variations in stem (diameter approx. 45 mm) and fruit (diameter approx. 56 mm) diameter for two different apple-trees (cv. Golden Delicious) when drip irrigation was stopped or when a regular daily amount of water (3 mm) was supplied. During this period in July the soil water reserves have already been used up and potential evapotranspiration remains high (Penman PET = >7 mm). Under these conditions, daily irrigation is vital and its stoppage immediately leads to a very low fruit growth rate and to a negative daily stem development. However, as opposed to peach-trees, the MDS for stressed days were smaller on apple-tree stems than their values on watered days.

When drip irrigation is regular and daily, the growth rate of apples immediately returns to normal values for this season. The growth of stems also increases, but its normal rate remains much lower than that of the fruit.

Figure 4 also shows the lack of diurnal shrinkage on apples: during this period thermic expansion of fruit masks the diameter change caused by water departure from the fruit which acts as a reservoir (ca. 1 $cm^3\,day^{-1}$).

The seasonal observation of stem MDS and DE from May to July makes it possible to link their variations with water availability in the soil and with some climatic factors.

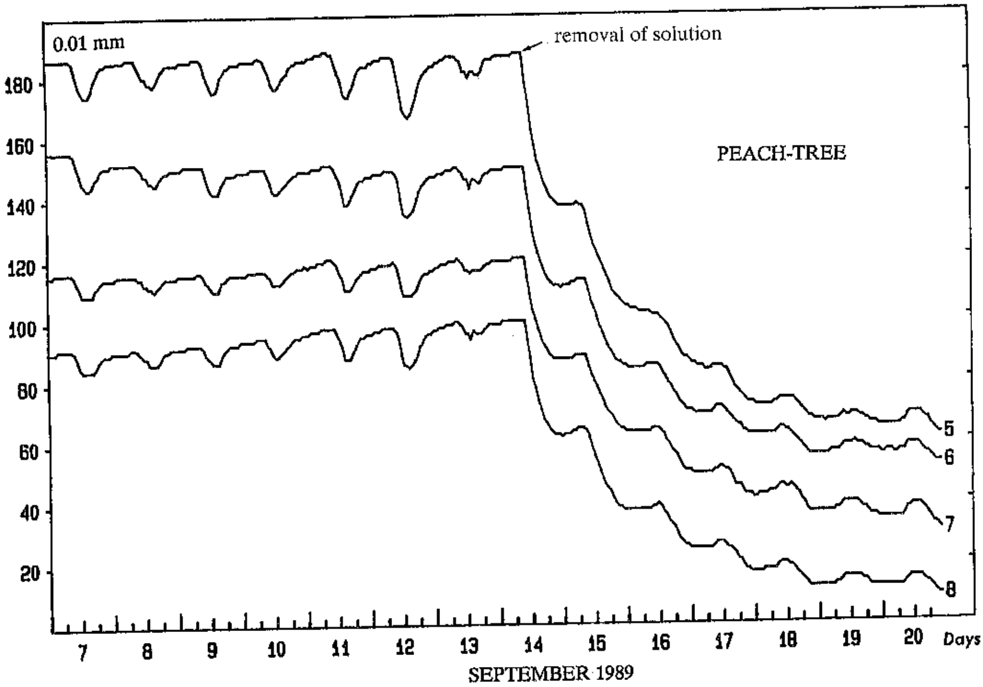

FIG. 3
Diameter variations on stem and shoots of a peach tree cultivated in nutrient solution, before and after removing the solution (14 September). (5): stem, diameter 45 mm. (6), (7), (8): shoots, diameters 14, 14, 13 mm.

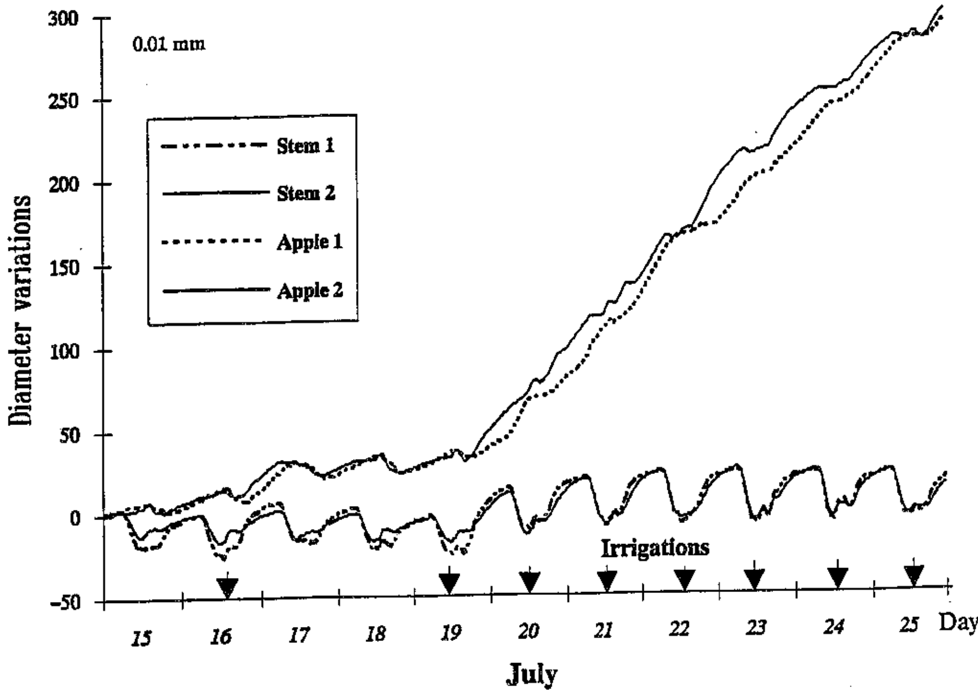

FIG. 4
Irrigation effects on stem and fruit diameters of apple.

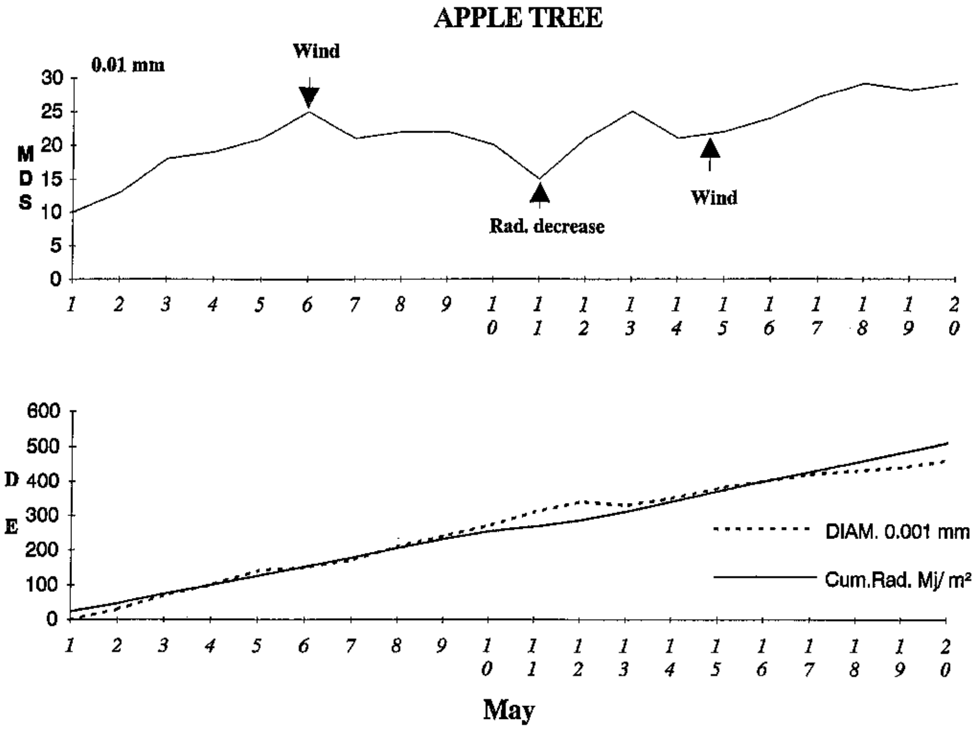

FIG. 5
Spring apple tree behaviour. Maximum Daily Shrinkage, MDS. Cumulative Daily Evolution, DIAM. Cumulative solar radiation, Cum.Rad.

Spring behaviour

Figure 5 shows an increasing trend for MDS which can be related to increasing leaf area index and increasing potential evapotranspiration, along with decreasing water availability in soil. During this period strong winds increased MDS, on the first day and decreased it on the next day. DE is very regular during the two first weeks and related to cumulative solar radiation but a cloudy day (11 May) seemed to produce first an increase in DE, followed by a slight decrease two days later.

At the end of this period, after 17 May, MDS was high with a decrease in DE and the rate of diameter growth fell below the value of the previous weeks. This could indicate the beginning of water depletion in soil.

Late spring behaviour

Figure 6 shows mainly the effects of a very large unplanned amount of water (160 mm, 23 May) which markedly increased DE. This could indicate incipient water stress. MDS was immediately lowered by irrigation and remained roughly stable afterwards.

Summer behaviour

Figure 7 shows what occurs when irrigation is really necessary to maintain trees at normal activity (see Figure 4 comments). Roughly, MDS for this period are high and DE are positive when drip irrigation is working. However MDS are low and DE are negative when irrigation is stopped. Strong winds which began to increase MDS during the May period seem to immediately decrease MDS in July.

DISCUSSION

According to previous results (Huguet, 1985; Li, 1989b; Schoch, 1989; Katergi, 1990) the first indication of water stress for many plants is the decrease and stoppage of stem diameter increase (Daily Evolution). Even if cell walls can show temporarily repressed growth without water input to the cell, it is obviously necessary for water to enter cells to express the expansive growth (Cosgrove, 1987).

But water stress is not the only factor capable of decreasing plant growth. Occurrences such as cold periods with low solar radiation or leaf

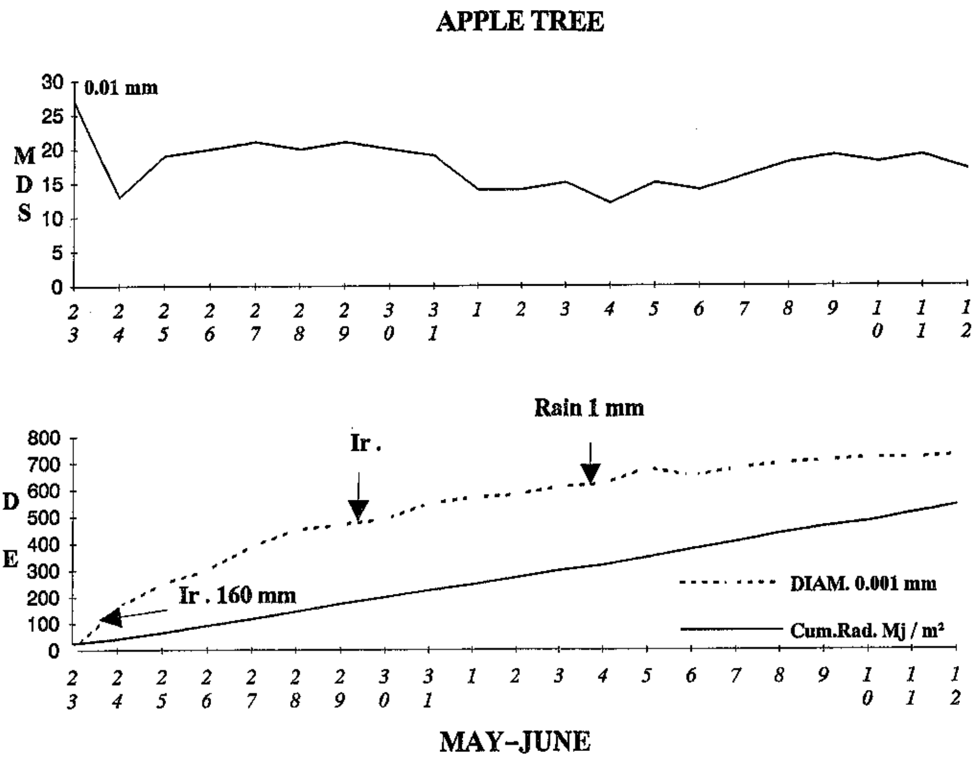

FIG. 6
Late spring apple tree behaviour. Maximum Daily Shrinkage, MDS. Cumulative Daily Evolution, DIAM. Cumulative solar radiation, Cum.Rad.

destruction by pests can also reduce and stop growth. In these last two cases the low transpiration rate makes the Maximum Daily Shrinkage very small.

MDS evolution seems to increase gradually as the water stress becomes more severe with the peach tree, but is more complicated with the apple tree.

In woody plant stems, extensive tissues are located in a cortical ring outside the dead xylem vessels and the thickness of cortical tissue, compared with total stem diameter, seems to be nearly the same in both trees. But, under similar climatic conditions and water availability in soil, apple-tree stem MDS are markedly higher (two or three times more) than MDS of peach trees.

It has been noted with peach trees, that water stress MDS can be three or more times the mean value observed when water availability in soil is at its maximum. However under severe water stress apple-tree, MDS is smaller than the well-watered value.

Thus, two kinds of specific reactions to water stress can be found in fruit trees:

'*Peach-tree' pattern*: water stored in reservoir tissues seems to be well-protected against release into the transpiration stream, therefore it can be released gradually as water stress becomes more severe.

Other woody species reacting like the peach include plum, cherry, apricot, citrus and kiwifruit (Garnier, 1986; Huguet, 1985; Li, 1989a; Vannière, 1991). Many herbaceous plants also seem to follow the same pattern, including tomato, egg-plant, corn (Schoch, 1989; Schoch, 1990).

'*Apple-tree' pattern*: availability of water stored is high, so tissue reservoirs empty quickly. We have results showing a similar behaviour on vine.

Understanding of these physiological patterns might show the different ways plants avoid water shortages. As this was not the aim of this work, only some suggestions (related or not) can be made: root absorbtion efficiency

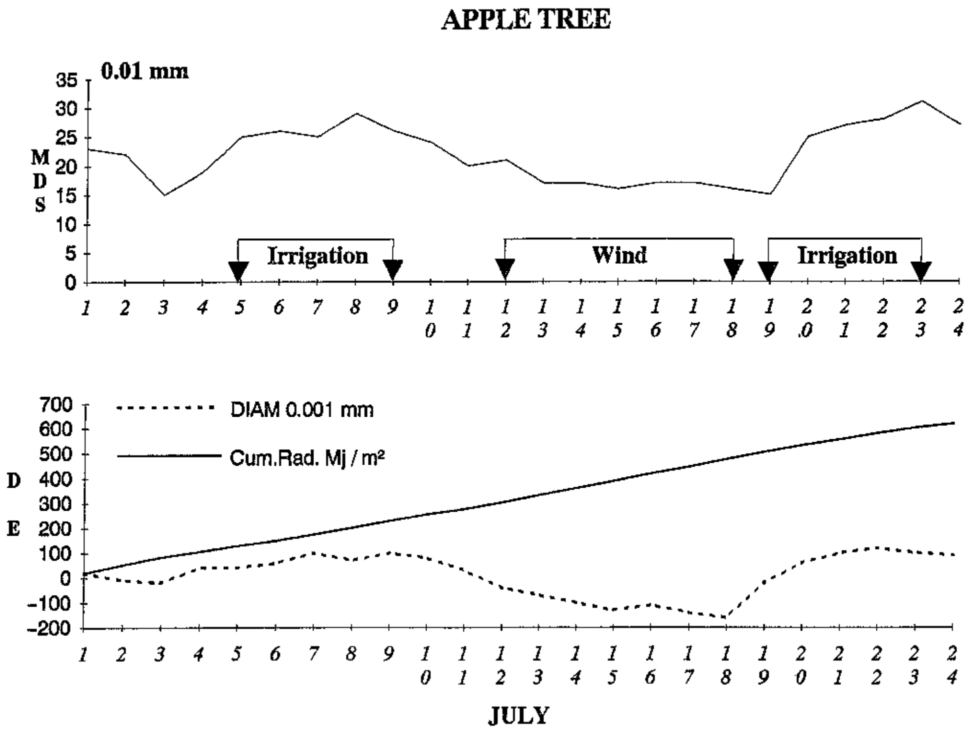

FIG. 7
Summer apple tree behaviour. Maximum Daily Shrinkage, MDS. Cumulative Daily Evolution, DIAM. Cumulative solar radiation, Cum.Rad.

would be better in peach-tree and the availability of stored water in extensible tissues would be more restricted by osmotic regulation. In addition the critical level of leaf water potential which acts on stomatal regulation would be more negative on peach than on apple.

The main purpose of continuous recording of diameter variations was its suitability for practical use and it has been utilized to identify the moment when the physiology of the plant becomes disturbed by water stress. Using this method it is possible to see when a supply of water is needed to avoid detrimental effects on crop yield or quality. This method does not, however, give any direct information on how much water has to be supplied to the orchard.

The knowledge of the right amount of water has to be approached experimentally: the management of irrigation has to begin by supplying a small, estimated amount which will be progressively increased as far as the water stress will be found to occur too quickly. In Figure 4 the daily evolution of apple-tree stems remained positive from 20 to 23 July but this DE became negative on 24 July showing that the daily amount of drip irrigation was not sufficient enough to meet the plant's water demand.

It has been established that DE always stops at first and then becomes negative when water stress occurs. To avoid confusion with other stresses (i.e. reduced photosynthesis or low temperature) it is necessary to test MDS by checking if its value is high enough (>MDS

TABLE I
Maximum daily shrinkage, practical values

Species	Stem diameter mm	Healthy MDS 0.01 mm	Stress MDS 0.01 mm	Limit Values MDS 0.01 mm
Apple	30–50	0–50	<50	20–25
Peach	30–40	0–15	20–40	5–8
Plum	30–80	0–20	25–40	5–10
Kiwifruit	30–50	0–25	30–55	7–13
Citrus	30–50	0–20	25–60	5–10
Maize	25–35	0–8	10–22	3–4
Tomato	8–15	0–15	20–50	5–8
Egg plant	8–15	0–15	20–80	5–8

limit value, Table I) i.e. the transpiration rate is sufficient.

DECISION RULES FOR IRRIGATION AUTOMATION

Sprinkler irrigation management

We believe that irrigation decision can be made by software processing both DE and MDS data. In practice, homologous parts must be chosen on different representative trees: for instance, four stems with the same diameter on four trees within an orchard. Then two decision parameters have to be input into the memory of the processing unit: a) The limit value for Daily Evolution, and b) The limit value for Maximum Daily Shrinkage.

In addition, the number of channels on which these limits have to be reached or exceeded to activate irrigation must be selected by the operator. In the previous case this number may be chosen between 1 and 4. Usually with four monitoring channels, two or three would yield satisfactory results.

If three is chosen, then three channels must be equal to or greater than the MDS limit (50% average MDS on sunny days without any pests or too low temperatures, Table I) *and* three channels (the same or different) must be equal to, or lower than, the DE limit before automatic switch-on of irrigation. Generally the DE limit would be equal to zero, but it can be positive in spring and negative in late summer to match as closely as possible the water supply with the actual growth rate of the tree.

Drip irrigation and soil-less culture

Here, decision-making software only processes MDS data. It has been shown that diurnal shrinkage is a common factor in plant growth, even if water availability in soil is at the optimum. MDS is thus closely linked to climatic water demand and, in most temperate climates, the higher it is, the more efficiently the plant functions. Thus, it is first necessary to measure the maximum MDS reached when soil hydric potential is at its optimum.

If half of this value is used as the MDS limit, irrigation will occur once only, approximately half-way through each sufficiently sunny day, and the software prevents more than one irrigation per day. When using this system, the irrigation amount must be adjusted to the maximum daily water demand of the plant.

To match irrigation to actual climatic conditions, it is necessary to choose a smaller proportion of the maximum MDS as the MDS limit, which triggers an amount of irrigation which is in the same proportion as the estimated daily water requirement. Watering will be required several times on very sunny days and more infrequently when weather is less favourable.

CONCLUSION

Micromorphometry seems to be a reliable method of logging changes in plant water status as reflected both in stem shrinkage and in fruit and stem net growth which are obvious indexes of plant health. Microcomputer technology has been used to develop and manufacture hardware and software capable of automatically adjusting to meet the actual requirements of plants, as closely as possible. Under field conditions this methodology can be used as a flexible tool and is equally applicable to studies of general plant behaviour.

Further extensive investigations are, however, necessary to understand how best to utilize the variables to obtain an objective irrigation scheduling which will lead to water conservation and an improvement in yield quality.

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