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Review
STEM DIAMETER FLUCTUATIONS AS STRESS INDICATOR IN FRUIT TREES AND ITS USE IN IRRIGATION MANAGEMENT

Revisión bibliográfica
Fluctuaciones del diámetro del tronco como indicador de estrés en frutales y su uso en el manejo del riego

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ABSTRACT. Indexes derived from stem diameter fluctuations (SDF) and leave water potential have been used in irrigation programs for different cultures. Several studies have been conducted to address SDF indixes in irrigation water management. This work has as aims to emphasize main progresses using derived indexes and reference equations obtained from SDF indixes to do an accurate management of irrigation. Of these, maximum daily trunk shrinkage (MDT) and trunk growth rate (TGR) are the most used. Thus far recent studies have shown that certain factors may affect the outcomes of SDF indixes prior to obtaining base lines. These include crop load, tree age and size, and soil moisture at different depth regardless of the water deficit of the plant. In addition, SDF indixes are related to climate variables such as air temperature and vapor pressure deficit. In order to study these variables, a wide number of sensors are required for their measurement. This makes the methodology more complicated for irrigation management in commercial agriculture.

RESUMEN. El empleo de los índices derivados de las Fluctuaciones del Diámetro del Tronco (FDT) y potencial hídrico foliar han sido empleados en el manejo y programación del riego en varios cultivos. Numerosos han sido los trabajos realizados en función de abordar los índices derivados de las FDT para ser utilizados en la programación del riego. Este trabajo tuvo como objetivos señalar los principales avances en el empleo de los índices derivados de las FDT y las ecuaciones de referencias obtenidas a partir de dichos índices para realizar un manejo preciso del riego. Dentro de estos índices, la Máxima Contracción Diaria del Tronco (MCD) y la Tasa de Crecimiento del Tronco (TCT) son los más empleados. Por otra parte, se ha encontrado que varios son los factores capaces de afectar los valores obtenidos de dichos índices para obtener las líneas de base, como son la carga productiva, la edad y el tamaño del árbol, así como la humedad del suelo a diferentes profundidades, independientemente del grado de estrés hídrico en la planta. La temperatura media del aire, así como el déficit de presión de vapor son las variables climáticas relacionadas con los índices derivados de las FDT. Para realizar las determinaciones de esta variable, son necesarios un número elevado de sensores, lo que hace más complejo el empleo de esta metodología en parcelas comerciales.

Key words: tree, leave water potential, irrigation, environmental temperature

Palabras clave: árbol, potencial hídrico foliar, riego, temperatura ambiental

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INTRODUCTION

Water management is vitally important, since short and medium-term solutions are to be taken in it to ensure water resource protection and integrity (1). In this sense, making an optimal determination of plant water requirements through physical and biological criteria has gained great interest (2), which has generated innovative and precise irrigation management practices (1).

Trunk wood structure is made up of a porous, hygroscopic and heterogeneous material, with an anisotropic behavior; thus, its properties vary in magnitude (towards radial, tangential and axial direction), so its physical properties are also variable (3). In this sense, the trunk develops a contracting and expanding behavior along the day, which is called trunk diameter fluctuations (TDF).

Several authors have shown the possibility of improving an efficient water use through precise irrigation management based on physiological indicators, which report plant water status (4, 5).

Irrigation management by using climatic variables and plant water status allows a substantial water saving. However, there should be correlations of these determinations with plant water status through physiological processes, such as trunk water potential (Ψt) (6). The use of indices derived from TDF and stem water potential, as plant water stress indicators and their use in irrigation management and scheduling, has been previously described (4, 5). These authors have presented the main aspects of indicators above mentioned in irrigation programming. In this regard, research studies have been done with the objective to address those issues in detail that shed light on the possibilities of employing indexes derived from the TDF to schedule irrigation. Therefore, this paper aims to conduct a review on the main results obtained in this area.

GENERAL INFORMATION ON TRUNK DIAMETER FLUCTUATIONS

All plant stems and trunks have daily cycles of expansion and contraction, which is known as TDF (7). The continuous record of these trunk diameter variations have been proposed as a useful tool for irrigation management (8, 9).

In recent years, there has been renewed interest in using sensors to measure trunk diameter fluctuations, which in turn are indicators of plant water status, mainly because this technique could provide automated information on plant water status in real time (5).

It is stated that the use of this methodology involves fewer field trips and a significant workforce reduction, compared with measurements of other indicators of plant water status, as leaf water potential (Ψf).

Leaf water potential has been the most widely used parameter to assess plant water status[A] (10). However, it has been shown that stem water potential at noon (Ψtmd) is more suitable for irrigation scheduling in woody crops (11); also, it has proved to be a better indicator of plant water status than Ψf (12).

However, these indicators have some drawbacks that affect irrigation scheduling, such as: frequent field trips and a large number of necessary measurement practices (13).

Recent studies performed in lemon orchards suggest the use of water Ψf and stem (Ψt) potential as indicators of plant water status when there are not any possibilities of continuous records of other indicators (14).

Ψt, as mentioned above, has been widely used as a model indicator of water status of woody plants; therefore, much research has been directed to the search for plant indicators that allow automating irrigation by checking its veracity with that indicator. In this sense, gas exchange indicators have been evaluated as appropriate to indicate water deficit situation. Nevertheless, these assessments cannot be automated, so it is necessary to pay attention to those indicators that have the possibility to be automated, such as trunk diameter fluctuations (15).

One of the advantages of using parameters derived from TDF is the possibility to automate irrigation (5), as well as the quick and reliable response to water deficit (16). TDF measurements are generally taken with linear and variable displacement sensors (LVDT). Characteristics and general information on this type of sensors used for these evaluations have been described in detail (5).

[A] Lu, P. ''Mango water relations and irrigation scheduling'' [en línea]. En: *International Conference on Mango and Date Palm: Culture and Export.*, edit. University of Agriculture, Faisalabad, Pakistan, 2005, pp. 20–23, [Consultado: 29 de noviembre de 2015], Disponible en: <http://www.geocities.ws/mdce2005/MDCE2005/10-9_19.pdf>.

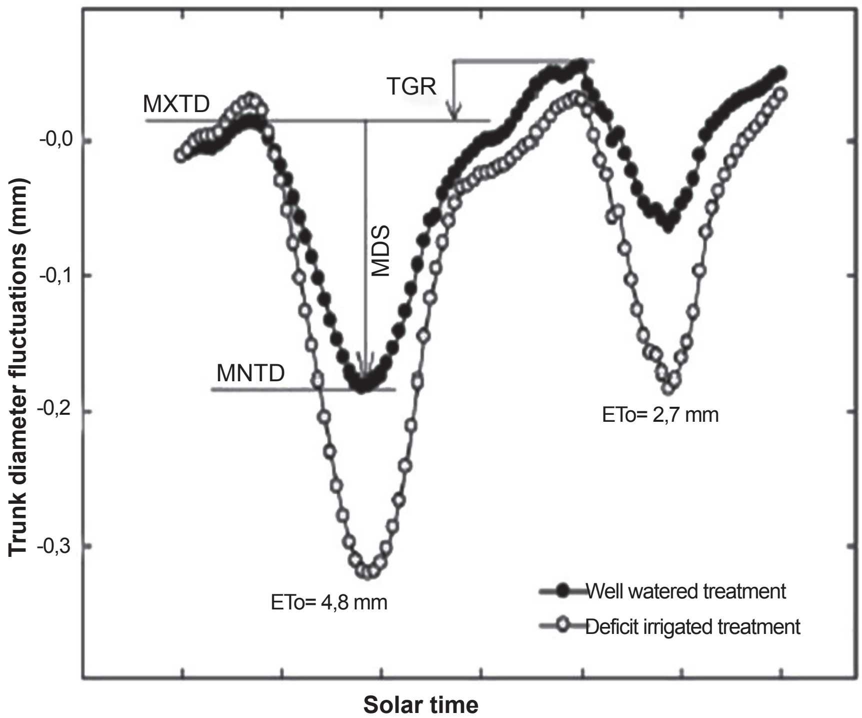
Several indices are obtained from the daily cycle of trunk growth (Figure). In this sense, the most common TDF indicator is the maximum daily trunk contraction (MDC), which presents very low levels and could not be used as water stress indicator under high trunk growth rate (9). On the other hand, a trunk growth decline in young trees is one of the first plant responses to water stress; thus, trunk growth rate (TGR) has been proposed as a more appropriate stress indicator (17, 18). Consequently, MDC and TGR are, in that order, the most widely used indices derived from trunk fluctuations for irrigation management (4).

The use of trunk diameter variations as stress indicators in olive trees decreases with tree age and productive load. However, when these indices are related to trunk growth, mainly TGR and the maximum trunk diameter (MXTD), they have a great potential as stress indicators (19).

Significant relationships between stem water potential and TGR (r^2= 0,60), as well as with daily fruit growth (r^2= 0,78) show the great connection between trunk and fruit variations caused by water stress in orange crop (20).

Data correspond to two days with different evaporative demand (ETo) on well-watered plum trees under water deficit conditions. Source: 5

Trunk diameter fluctuations are closely linked with water availability in the soil, so that a moisture content variation could affect MDC values. In early maturing fruit trees under water deficit conditions, increased MDC values has been associated with decreased trunk water potential at noon (5). In this regard, several studies have been conducted in different fruit species and such indicator values vary depending on the species in question. Thus, stem water potential values of about -1,5 MPa in olive (*Olea europaea* L.), -1,8 MPa in lemon (*Citrus limon* L.), -1,0 MPa in grape (*Vitis vinifera* L.) and -1,4 MPa in mandarin (*Citrus clementine* H.) have been recorded (5). Several factors have been identified as responsible for this behavior in MDC changes, which have been described in detail (5).



Indices derived from trunk diameter fluctuations (TDF), maximum (MXTD) and minimum (MNTD) daily trunk diameter, maximum daily contraction (MDC) and trunk growth rate (TGR)

Previous studies which refer to indicators derived from TDF (4, 5) agree that these variations not only depend on water stress, but also growth pattern in different periods, fruit fall, tree size and its age as well as other factors limit the use of parameters derived from TDF as water stress indicators. Several authors have shown how usefulness this parameter is as an indicator of plant transpiration intensity, as long as there is adequate soil moisture (21, 22), that is, trees irrigated at 100 % crop evapotranspiration.

MDC has been poorly correlated with soil moisture. In several fruit species, determination coefficients (r^2) of 0,35 at 0-120 cm deep (23) were obtained, indicating a negative correlation between MDC and soil moisture at the mentioned depth. This behavior has been observed in lemon trees at 0-20 cm deep (23), in peach (24) and apple trees (25) at 0-60 cm deep and in young cherry trees at 0-100 cm deep (26). Regression equations between MDC, weather variables and soil moisture content at a depth up to 120 cm have been used to estimate MDC in apple plots under non-limiting soil water conditions (25).

As a water stress indicator in pomegranate trees (*Punica granatum* L.), MDC was more appropriate than stem water potential and gas exchange parameters as stomatal conductance and photosynthesis for irrigation scheduling in this crop (15).

Recent research suggests that water stored inside tree trunk is controlled by canopy transpiration, so it can be inferred that trunk structural properties have great influence on plant water storage (27).

In fruit crops like apple, there has been a close relationship between maximum trunk contraction and climatic variables, as well as water relation indicators as stem water potential (25). In evergreen trees, such as mango, MDC has shown to have greater sensitivity in detecting stress conditions than sap flow, which has more possibility of using the parameter derived from trunk diameter fluctuations for irrigation scheduling (10).

The close relationship between MDC and soil water potential (r^2= 0,65) reflects its sensitivity by decreasing soil water content. In this sense, a trunk contraction value of 0.30 mm is obtained where MDC is stabilized, which has been proposed as a threshold value to be used in irrigation scheduling [A].

In young cherry trees, MDC is a good indicator for irrigation management, suggesting a threshold value of 0,30 mm. Moreover, joint measurements of other continuous variables, such as sap flow with indices derived from TDF, could provide more detailed information on the daily evolution of plant water status[A].

Several works have pointed out MDC variability between trees (11, 28). In this case, it would be better to select trees with similar characteristics in terms of stem diameter, and especially the height where LVDT devices are placed, which should not be too close to the soil to avoid contact with any animal. Some authors attribute this variation between trees to the great stem anatomical variability (15). Four trees, each treated as replicate, have been mentioned as sufficient to eliminate the variability that may occur in olive trees located at the same plot with similar soil moisture conditions (19). Data obtained from MDC in olive trees presented great variability, so that a large number of sensors (about 34) are necessary (12).

Despite the results of this area, many trees are needed for determinations; besides, occasional determinations are required on plant water status to complement MDC values (13).

Although indices derived from TDF have proved to be a useful tool for irrigation scheduling, mainly due to their direct relationship with indicators of plant water status, even for its practical applicability to commercial conditions they should be yet exploited for the sake of selecting those parameters derived from TDF more directly related with stress indicators in each species concerned. Moreover, the selection of a stress indicator must have the possibilities of being automated, which would make irrigation scheduling more efficient.

REFERENCE EQUATIONS

Reference values of an indicator of plant water status can be obtained in plants under non-limiting soil water conditions (29) or by reference equations relating the indicator values of plant water status with data from plants under non-limiting water conditions and atmospheric evaporative demand (11, 29).

Several investigations have been focused on finding climatic variables that better relate to MDC, in order to use these equations in irrigation scheduling (30). In this regard, previous studies suggest average daily temperature as the better related weather variable with MDC in citrus (31, 32) and olive crops (33). However, such variable has been mentioned as a non-accurate evaporative demand indicator (34), as the physiological response of each species is different depending on its environmental condition; despite this, some authors state it is easily measured (32) and automated, and in case there are not any modern measurement technologies, it could be done by conventional methods.

Moreover, vapor pressure deficit (VPD) has proved to be an appropriate climatic variable in crops such as almond (35), apple (25) and nectarine (36) (Table).

Despite previous results, several authors have pointed out a series of factors that may affect MDC values, regardless of environmental conditions, such as tree age (35, 37), tree size (38), phenological period (37), productive load (15, 39) and productive alternation (40).

However, it was noted that MDC was not significantly influenced by productivity and/or productive load in lemon trees (32). This behavior between bone fruit trees and citrus orchards could be attributed to the fact that citrus fruits are on the tree almost all the year[B].

Moreover, studies made on peach crop during post-harvest period indicate that MDC values were closely related to active root growth[B]. These recent results suggest that the use of reference equations for irrigation management is more complex than expected, which implies a reference equation obtained under certain conditions can not be used in subsequent years if tree characteristics are different (5).

Due to the series of factors that may affect the use of parameters derived from TDF, reference lines should be pre-calibrated before used in the plot (32).

In this regard, some authors have stated to link current MDC values of a given treatment with data obtained in well-watered trees of the same plot (29). Recent results have proved that base lines previously obtained in an olive cultivar can be employed to estimate base lines in different plots, even with similar conditions and different cultivars (41).

This methodology involves a greater process complexity, since there should be different irrigation programs inside the same plot, as well as increased investment costs; that is, a greater sensor number (5). Moreover, trees to be used as reference in the field should be well irrigated, either by increasing dripping number or its discharge rate; thereby, different irrigation plots are not needed (5).

One of the main aspects that must be taken into account for the use of reference equations on irrigation management is to be able to use them throughout crop cycle, as well as its accuracy in subsequent years. Studies performed in lemon crop show that MDC reference equations related with evaporative demand (mVPD and mT) have annual validity (32).

List of reference equations of the maximum daily trunk contraction (MDC) on selected climatic variables and water status variables of some fruit trees

Species	Age	Phenologic period	Reference equation	r^2	Source
Almond (*Prunus dulcis*) cv Marta	Young	Annual	MDS= 0,16 DPVmx	0,80	37
Lemon (*Citrus limon*) cv Fino	Adult	Annual	MDS=_0,04 + 0,01 Tm	0,77	34
Mandarin (*Citrus clementina* x *Citrus reticulata*) cv Fortuna	Adult	March-October	MDS=_0,17 + 0,27 DPVm	0,81	33
Olive (*Olea europaea*) cv Arbequina	Young	August-September	MDS=_0,18 +0,01 Tmd	0,80	39
Plum (*Prunus salicina*) cv Black Gold	Adult	Annual	MDS= 0,01 + 0,11 DPVm	0,65	40
Apple (*Malus communis*) cv Golden Delicious	Adult	April-September	MDS= -380,37Ψt -102,06	0,76	26
Olive (*Olea europaea* L.) cv Manzanillo	Adult	Annual	MDS= 0,23+0,14 DPVm	0,48	35
Olive (*Olea europaea* L.) cv Manzanillo	Adult	April-October	MDS = −667 + 34 Tmx	0,60	43
Nectarine (*Prunus persica* L.) cv. Flanoba	Adult	Annual	MDS = -16,0-333, 3 Ψt	0,63	38

mxVPD, maximum vapor pressure deficit mVPD, medium vapor pressure deficit mT, air temperature at noon
mxT, maximum air temperature Ψt, stem water potential

In nectarine crop, equations were stable for three years without any productive load effect. However, phenological period has a negative effect on fruit growth phase and post-harvest (36). Differences obtained in several plots with the use of reference equations may be associated to the reference cultivar, as well as the current environmental conditions (12).

In general, despite inquiries about the use of base lines for irrigation management, there is a great coincidence between authors to use them for this purpose. Significant r^2 obtained between MDC and climatic variables leads to perform a more precise irrigation programing and automate the process.

TDF USED IN DIFFERENT DEFICIT IRRIGATION STRATEGIES

Encouraging results have been obtained in orchards by using parameters derived from TDF in deficit irrigation strategies (31). In olive crop, recent studies indicate that MDC is not the most recommended indicator for an optimum irrigation monitoring; however, it is considered appropriate for deficit irrigation strategies (40). In this case, stress level is indicated by lower values than those obtained from reference equations (41). Studies in this species raise the validity of using parameters derived from TDF in different deficit irrigation strategies (19). In peach crop, determinations obtained from MDC have been proposed for deficit irrigation strategies (15).

Significant correlations between stem water potential and TDF and FDF (fruit diameter fluctuations, r^2= 0,60 and 0,78 respectively) show the strong connection between organs evaluated under stress conditions. Accordingly, deficit irrigation strategies can be applied by TDF, preventing a negative effect on fruit growth (20).

Previous studies indicate that indices derived from TDF promise to be an alternative in different deficit irrigation strategies. Recently, some authors indicated the main advances in these studies (5). However, it should be noted that the values mentioned in such tests should not be used as reference in other studies without prior calibration. In general, several authors agree that by using these indices, a considerable amount of water is saved without affecting productivity and fruit quality (13, 36). In this sense, between 30 and 54 % was saved in pomegranate and mandarin, respectively (15, 31).

CONCLUSIONS

- ♦ Maximum daily contraction is considered a reliable index of trunk diameter fluctuations for irrigation programming and automation; however, more information should be included about other parameters, such as sap flow, stem potential or physiological variables as stomatal conductance to make a decision in irrigation.
- ♦ A high sensor number to eliminate tree variability constitute a limitation to apply this methodology in the plot and even for producers, just when using variable and linear displacement sensors.
- ♦ Obtaining base lines or reference equations related to plant water status as well as climatic variables allow establishing irrigation strategies.
- ♦ Reference equations can be obtained in well-watered trees inside the same plot; however, due to many factors capable of affecting these equations, they must be calibrated prior to be used in irrigation management, which might complicate its use in commercial plots.
- ♦ Validity of indices derived from trunk diameter fluctuations for irrigation management indicates positive findings on the use of deficit irrigation strategies; however, more information should be taken into account about trunk diameter fluctuations for its automation.

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