Plant water stress derived indexes from water potential and diameter fluctuations measurements

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2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor) | 979-8-3503-1272-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/MetroAgriFor58484.2023.10424320

***Abstract*—This work addresses the comparison between plant water status indicators from trunk diameter fluctuations measured with LVDT sensors and novel trunk microtensiometers (MTs). During the postharvest of 2022 (Day of the year, DOY, 160-350), nectarine trees were subjected to different irrigation protocols based on soil maximum allowed depletion (MAD), automatically managed by real-time soil water content values measured by capacitance probes. Three percentages of depletion of available soil water (α) were imposed: (i) α=10% (well-irrigated); (ii) α=50% (moderate deficit) and (iii) α=100%, irrigation withheld until stem water potential (Ψ_{stem}) reached -2.0 MPa. Thereafter, irrigation was recovered to full crop water requirements. From both LVDT and MTs, real-time data, the following trunk indexes were calculated: MDS (maximum daily shrinkage, i.e. difference between the daily maximum and minimum trunk diameter), EDS (early morning daily shrinkage, from 09:00 h to midday) and LDS (late daily shrinkage, from midday to 16:00 h). The results showed that EDS was more sensitive to water deficits than MDS, and higher with MTs than LVDT. Our findings suggested the potential use of trunk microtensiometer as a valuable biosensor for monitoring the water status of nectarine trees, being the highest sensitivity in the range when EDS was calculated.**

Keywords— early-morning trunk shrinkage (EDS), LVDT sensor, microtensiometers (MTs), nectarine trees, plant water status indicators, sensitivity.

I. INTRODUCCION

Using plant measurements for irrigation scheduling is a promising tool for increasing water use efficiency since plant measurements include climate and soil water status factors [1] Stem water potential at midday (Ψ_{stem}) has been widely used as an indicator of plant water stress in many species [2] including peach [3] and nectarine trees [4] However, its measurement is tedious and requires using a pressure chamber, that cannot be automated.

Advances in IoT in agriculture have made it possible to continuously record the plant water potential. In this sense, novel sensors identified as trunk microtensiometers (MTs) are capable of continuously monitoring trunk water potential (Ψ_{trunk}) using a microelectromechanical pressure sensor [5]. As the sensor is embedded into woody tissue of the tree, the readings are accurate and stable. They have the advantage of providing real-time data in easy-to-interpret pressure units, similar to that of the pressure chamber technique [6,7] On the other hand, from the knowledge that plant growth is an excellent indicator of water stress, continuously trunk diameter fluctuations (TDF) [8] provided by the LVDT sensors have been widely used with irrigation purposes in the last decade [9,10]. Among the TDF-derived indexes characterizing plant water status, the maximum daily trunk shrinkage (MDS) measurements have demonstrated their sensitiveness to water deficit in a widely number of fruit tree species [11]. De la Rosa et al. [12] proposed two additionally TDF-derived indexes: early daily trunk shrinkage (EDS) which took place between 09:00 h solar time and midday solar time, and late daily trunk shrinkage (LDS), which occurred between midday and the moment that the minimum trunk diameter was reached (around 16:00 h solar time). These authors demonstrated that EDS was more sensitive than MDS to reveal nectarine water stress.

Plant water status indicators are not only affected by the soil water content, but they also depend on other variables such as atmospheric demand or phenological crop stage [1,4]. For this reason, it is better to use the concept of signal intensity (SI) for irrigation scheduling, normalizing indicator's absolute values with respect to values in non-limiting soil water conditions [11]. The SI of the plant water stress indicator is a dimensionless variable, in which values above unity indicate water deficit situation, and values equal to unity indicate the lack of water stress. The main property that an indicator should have is 'sensitivity' to water stress. Goldhamer and Fereres [11] defined this term as the ratio between SI and the "noise" (coefficient of variation, CV) of each indicator. Other desirable properties include the ability for automation, the rapid response to water stress, and the proportionality of the measures in relation to the level of the water deficit applied [4]

Automated irrigation based on Management Allowed Depletion (MAD) threshold values, and monitored by computed real-time volumetric soil water content (Θ_v) sensors has been proved as a valid strategy for precise irrigation scheduling in nectarine trees [13]. Furthermore, in a companion paper [7] Ψ_{trunk} measurements mirrored the established MAD-based irrigation protocols in the same nectarine tree orchard.

In this study, we test the sensitivity to water stress of trunk water status indicators obtained with TDF-derived indexes

(MDS, EDS and LDS), and those obtained with trunk microtensiometers at the same time of measurements than MDS, EDS and LDS in nectarine trees. Irrigation was automatically managed by real-time Θ_v values at different levels of MAD yielding water deficits and recovery processes. Our hypothesis is that MTs, which are related to trunk water potential, are more influenced by water stress and better reveal the MAD-based irrigation protocol than TDF-derived indexes.

II. MATERIAL AND METHODS

A. Experimental conditions

This experiment was conducted on the postharvest of 2022 (day of the year, DOY 160- 350) in a 0.5 ha orchard of twelve-year-old early-maturing (harvest in May) nectarine trees (*Prunus persica* (L.) Batsch, cv. Flariba, on GxN-15 rootstock), located at the CEBAS-CSIC experimental station (SE, Spain) (Illustration 1).

Illustration 1. Plot location of the nectarine trees orchard: (38° 06 'N, 1° 02' W) (source: www.maps.google.com).

Nectarine trees were spaced 6.5 m x 3.5 m and trained to an open-center canopy. The soil in the 0-0.5 m layer was stony with a clay-loam texture and low (1.3%) organic matter content. Volumetric soil water content (Θ_v) at field capacity (FC) and at permanent wilting point (WP) was 0.29 m^3 m^{-3} and 0.14 m^3 m^{-3}, respectively. The drip-irrigation system consisted of one drip line per row of trees, with 4 emitters (4 L h^{-1}) per tree located 0.5 and 1.3 m from the tree trunk. Usual cultural practices (e.g. weed control, pruning and fruit thinning among other) were carried out by the technical personal of the CEBAS-CSIC experimental station following the local fruit practices. Environmental data, including reference evapotranspiration (ET_0, [15]), air temperature (T_{air}) and relative humidity (RH) were recorded by an automated station located 0.25 km from the orchard, which read values every 5 min and recorded the averages every 15 min, allowing to calculate vapor pressure deficit (VPD).

The experiment consisted of an automated soil-based irrigation treatment, managed according to different irrigation criteria (see subsection B), which were randomly distributed in four replicates, each consisting of six nectarine trees (n= 24).

B. Automated soil-based irrigation protocol

The irrigation protocol was automated, based on real-time Θ_v threshold values that acted on solenoid valves by means of a telemetry system. Θ_v was monitored by multidepth EnviroScan® capacitance probes (Sentek Sensor technologies, Sidney, Australia). PVC access tubes were installed 10 cm from the emitter located close (0.5 m) to the tree trunk in one tree per replicate (n=4). Each capacitance probe had sensors at 0.1, 0.3, 0.5, and 0.7 m depth, and was connected to a radio transmission unit. The values were read every 5 min and the averages were recorded every 15 min. Radio-transmission units sent data to a gateway connected to an addVANTAGE cloud-based web server platform (ADCON Telemetry, Klosterneuburg, Austria) for data processing and visualization.

Threshold Θ_v values were based on the management allowed depletion (MAD) concept [14,15] as a percentage (α) of the total available soil water content (TAW) that can be depleted ($MAD = 100 \times FC - \alpha \times TAW$), where $TAW = FC - WP$. Irrigation was automatically activated when mean Θ_v values in the 0–0.5 m soil profile (active root zone, [16]) reached the MAD threshold value and stopped at FC. The following irrigation criteria were applied:

- α = 10 %: well-irrigated, from 15 to 29 June 2022 (DOY 160-180).
- α = 50 %: moderate soil water deficit, from 30 June to 29 July 2022 (DOY 181-210).
- α = 100 %: severe soil water deficit. Irrigation was withheld from 30 July to 1 September 2022 (DOY 211-245).
- Recovery: Irrigation recovered at full crop water requirements when Ψ_{stem} reached -2.0 MPa, from 2 September to the end of the experiment (DOY 246-350).

C. Plant-based water status indicators.

Both discrete and continuously plant-based water status indicators were measured as follows:

- <u>Discrete</u>

Stem water potential (Ψ_{stem}, MPa) using a pressure chamber (Soil Moisture Equip Corp. Model 3000, 153 Santa Barbara, CA, USA) at 12:00 h solar time. Mature leaves (n=4) located on the north face of the tree and near the trunk were covered with aluminum foil bags for at least 2 h prior to the measurements, following the recommendations of [17].

- <u>Continuous</u>

Trunk diameter fluctuations (TDF, µm) were monitored in one tree trunk per replicate (n=4), coincided with those monitored with capacitance probes, using a set of linear variable displacement transducers (LVDT, Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, precision ± 10 µm) installed on the southern side of trunks, 30 cm above the ground and mounted on holders built of aluminum and invar 64 % Fe and 35 % Ni that has minimal thermal expansion). The following TDF-derived indexes were calculated [11,12]:

1) Maximum (MXTD) and minimum (MNTD) daily trunk diameter.

2) Maximum daily trunk shrinkage (MDS = MXDT-MNTD).

3) Early daily trunk shrinkage (EDS = TD difference between 09:00h and midday solar time).

4) Late daily trunk shrinkage (LDS = TD difference between midday and the moment when minimum daily trunk diameter was reached, which occurred around 16:00h solar time).

Trunk water potential (Ψ_{trunk}, MPa) was monitored using microtensiometers (MTs; FloraPulse, Davis, CA, USA) embedded directly into the trunk on the shaded side of two nectarine trees (one per replicate in two replications of the same trees as for TDF), and located at 0.4 m from soil surface. Installation of the MTs was carried out according to the recommendations of the manufacturer [5,18]. The trunk water potential-derived indexes of MDS, EDS and LDS were calculated using the same hours and periods than with trunk diameter fluctuations.

Both trunk diameter fluctuations (from LVDT sensors) and trunk water potentials (from MTs) data were obtained every 15 min, and transmitted using the same telemetry network as for Θ_v (ADCON Telemetry, Vienna, Austria).

D. Sensitivity analysis

For the plant-based status indicators, the signal intensity (SI) was calculated as the ratio between all data registered at severe deficit and well-irrigation periods. To determine noise, the coefficient of variation (CV) of the measurements was calculated for each indicator. Continuous measurements were compared at the time when Ψ_{stem} was taken. In this sense, variables concerning the sampling day and type and size of the sample did not interfere in the analysis.

E. Statistical analysis

Data were depicted using the SigmaPlot v. 14.5 software (Inpixon, PA, USA). Statistical comparisons were considered significant at $p<0.05$, using Pearson's correlation coefficient. Relationships between plant-based water status indicators were explored by linear regression analyses. The coefficient of determination (R^2) and mean squared error (MSE) were used to assess the goodness of fit. All analyses were performed with SPSS v. 9.1 (IBM, Armonk, NY, USA).

III. RESULT AND DISCUSSION

A. Environmental and plant-soil data

During the postharvest (DOY 160-350), the weather was typically Mediterranean, with hot, dry summer and mild-wet autumn. Annual evapotranspiration and rainfall (concentrated during the recovery period) amounted 1082 and 109 mm, respectively (data not shown). Maximum T_{air} and VPD were observed in August coincided with the severe deficit irrigation condition ($\alpha = 100$ %), whereas daily ET_0 values decreased during the recovery period (Table I). More information about the environmental conditions can be found in Conesa et al. [7].

During the experimental period, the total irrigation applied in the automated soil-based irrigation treatment was 228 mm. Θ_v trend was clearly influenced by the imposed irrigation conditions and also by the climatic demand (Table I). At α= 10 %, Θ_v reached values close to field capacity, along with Ψ_{stem} values characteristic of well-irrigated nectarine trees [4, 12,13, 19]. The moderate water deficit imposed at $\alpha = 50$ % promoted an irrigation frequency of 2 or 3 days and a Ψ_{stem} of around -1.7 MPa (Table I). As expected, when irrigation was withheld ($\alpha = 100$ %), Θ_v exhibited a huge drop, with a minimum value of 17.13 % and Ψ_{stem} value of -2.03 MPa, a threshold that marked the initiation of the irrigation recovery.

At recovery to well-irrigation conditions (from DOY 245 onwards), despite of the Θ_v values get field capacity, Ψ_{stem} values were slightly lower than those obtained at $\alpha = 10$ % (Table I). This fact was likely due to the beginning of leaf senescence [20,21]. Lower Ψ_{stem} values accelerated leaf senescence [22] which is a mechanism for saving water to assure survival for maintaining production, but penalizing photosynthesis surface [21]. Moreover, Conejero et al. [23] explained the incomplete recovery after water stress in peach trees due to the high susceptibility of the crop to xylem cavitation, which caused a drastic reduction in hydraulic conductivity during the postharvest. This fact may have prevented the complete recovery of TD-based measurements when full irrigation was restored (Fig. 1A and 2).

TABLE I: MEAN VALUES OF VOLUMETRIC SOIL WATER CONTENT (Θ_V), STEM WATER POTENTIAL AT MIDDAY (Ψ_{STEM}), MAXIMUM AIR TEMPERATURE (T_{AIR}), VAPOR PRESSURE DEFICIT (VPD), AND REFERENCE CROP EVAPOTRANSPIRATION (ET_0).

DOY	Irrigation criteria	Θ_v (%)	Ψ_{stem} (MPa)	T_{air} (ºC)	VPD (kPa)	ET_0 (mm)
160-180	α= 10%	31.39	-0.78	32.81	3.07	4.58
181-210	α=50%	25.72	-1.68	33.73	3.17	4.32
211-245	α= 100%	17.13	-2.03	34.07	3.27	3.87
246-350	Recovery	31.04	-0.92	25.65	1.62	1.72

B. Continuous plant-based water status indicators

Trunk-derived indexes from LVDT sensors and MTS were apparently highly dependent of automated soil-based irrigation protocol and meteorological conditions (T_{air} and VPD) (Table I and Fig. 1). De la Rosa et al. [24] showed that MDS was strongly correlated with maximum VPD and T_{air} in well-irrigated nectarine trees. Generally, MDS and EDS, from both sensors, followed similar trends, while LDS exhibited a very different behavior. At $\alpha = 10$ %, MDS and EDS from LVDT averaged 291 and 195 µm and -0.46 and -0.35 MPa from MTs, respectively. The MAD based-irrigation protocol promoted a significant difference between MDS and EDS with the two kind of sensors. This behavior was even more pronounced at $\alpha = 100$ %. As such, MDS was higher than EDS, up to 35 and 25% in LVDT and MTs, respectively. The severe deficit imposed decreased Ψ_{stem} and induced the greatest daily trunk shrinkage values, since increasing amount of stem water reserves would have been recruited to sustain leaf transpiration as water stress progressed [25]. Moreover, the differences between both trunk water status indicators were minimized during the recovery period. In any case, LDS was the least sensitive trunk index to climatic demand and the imposed water deficit. De la Rosa et al. [12] also found that LDS was less dependent to deficit irrigation in nectarine trees.

Curvilinear relationship between Ψ_{stem} and trunk indexes were found (Table II). Interestingly, Ψ_{stem} was better correlated with EDS_{MTs} followed by MDS_{MTs}, whereas the worst adjustment was observed between Ψ_{stem} vs. LDS_{MTs}. It is important to highlight that Ψ_{trunk} measurements involves the complete water pathway from the roots, which absorb the water available in the soil, to the stem whereby water is transported through the xylem, to fruit and leaves where it evaporates into the air (transpiration via stomata). MTs are able to directly monitored the xylem water potential, determining the driving force for water transport between the bark and the xylem vessels [26]. That may explain the fact that they were more precise in detecting water stress situations than LVDT sensors. Conejero et al. [23] observed that MDS is a more suitable indicator than sap flow for irrigation scheduling in early-maturing peach trees. Similarly, Remorini and Massari [25] reported that trunk diameter fluctuations in peach trees were the first physiological indicator of variations in peach tree water functioning. With LVDT sensors, De la Rosa et al. [12] also obtained the best correlation between Ψ_{stem} *vs*. EDS. The authors explained this because before midday, the trunk diameter fluctuation increased proportionally with water stress when early stomatal closure is observed due to synergistic effects of diurnal increased in VPD and limited soil availability. That coincided with the period where EDS is calculated.

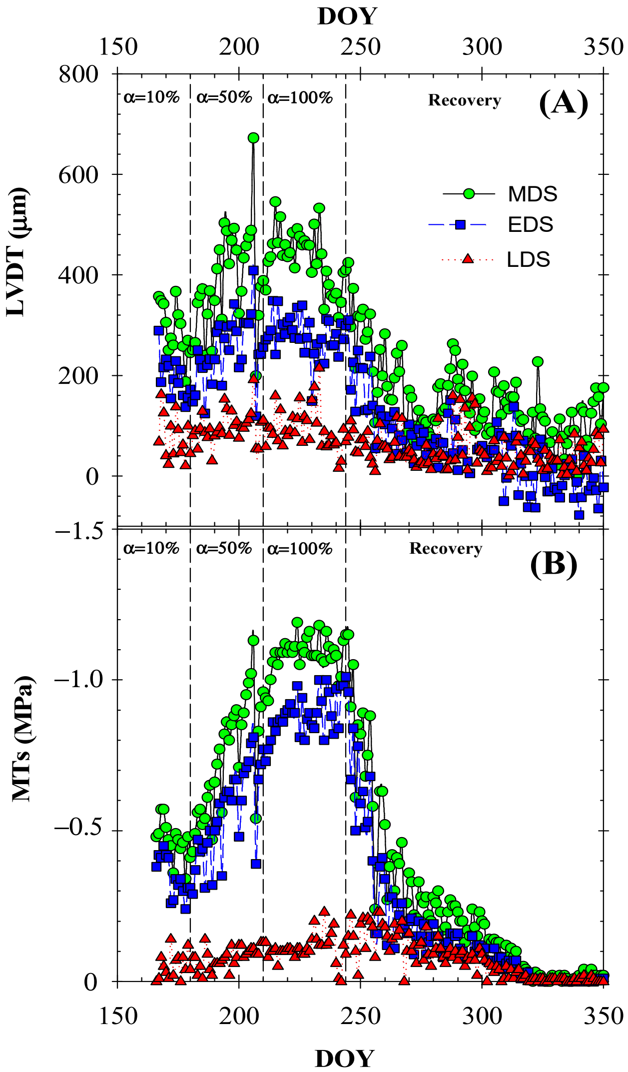

Fig. 1. Seasonal pattern of MDS (green points), EDS (blue squares) and LDS (red triangles) from (A) LVDT and (B) microtensiometer (MTs) sensors. Data are mean ± SE of 4 LVDT and 2 MTs. Vertical lines delimit the irrigation periods.

In the light with these results, the Fig. 2 shows the correlation between MDS, EDS and LDS obtained with the two studied sensors. For MDS and EDS, continuously trunk water potential measurements were able to explain 84% of the changes in trunk diameter. Indeed, the relationships obtained had similar slopes and were highly significant (p<0.001). A poor correlation was found between LDS from MTs and LVDT, reflecting a lower sensitivity to water stress of this indicator.

TABLE II: RELATIONSHIPS BETWEEN Ψ_{STEM} AND DIFFERENT TRUNK DERIVED INDEXES OBTAINED WITH LVDT AND MTS SENSORS.

Ψ_{stem} vs.	R^2	Significance
MDS_{LVDT}	0.60	**
EDS_{LVDT}	0.90	***
LDS_{LVDT}	0.40	*
MDS_{MTs}	0.93	***
EDS_{MTs}	0.97	***
LDS_{MTs}	0.10	*

*p:<0.05; **: p<0.01; ***: p<0.001

In the light with these results, the Fig. 2 shows the correlation between MDS, EDS and LDS obtained with the two studied sensors. For MDS and EDS, continuously trunk water potential measurements were able to explain 84% of the changes in trunk diameter. Indeed, the relationships obtained had similar slopes and were highly significant (p<0.001). A poor correlation was found between LDS from MTs and LVDT, reflecting a lower sensitivity to water stress of this indicator.

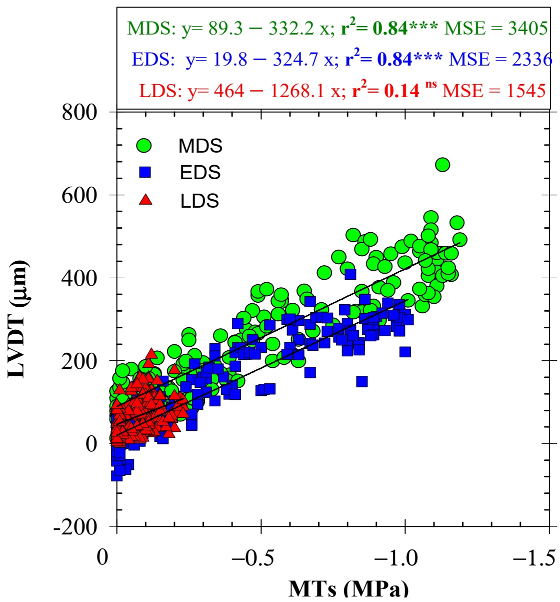

Fig 2. Relationship between the MDS (green points), EDS (blue squares) and LDS (red triangles) obtained with MTs and. LVDT sensors. Each point corresponds to daily average of 4 LVDT and 2 MTs. ***: p<0.001; ns: not significant.

C. Sensitivity of plant water status indicators

Signal intensity (SI, ratio of the severe deficit and control treatment value) of the trunk derived indexes with LVDT and MTs sensors was higher in EDS_{MTs} (2.07) followed by MDS_{MTs} (1.79) (Table III). Just considering LVDT sensor, EDS_{LVDT} (1.39) had higher SI than MDS_{LVDT} (1.27) but lower than Ψ_{stem} (1.54).

The CV was slightly lower in EDS than MDS in both studied sensors. Measurements of Ψ_{stem} were less variable than MDS_{LVDT}. Intrigliolo et al. [27] attributed the high variability in MDS to trunk irregularities and the variable resistance to water flow (between the bark and the trunk xylem) in pomegranate trees. Our results showed less variability in MDS_{MTS} than MDS_{LVDT}, suggesting higher accuracy in the Ψ_{trunk} measurements than trunk diameter variations.

Among the trunk derived indexes, the highest sensitivity (SI CV^{-1}) was found for EDS_{MTs} followed by MDS_{MTS}. De la Rosa et al. [12] indicated that EDS, of LVDT sensors, was more sensitive than MDS, which has practical advantages related to ease calculation (requiring data acquisition at known times each day). Furthermore, we have observed higher accuracy of MTs compared with LVDT, highlighting the feasibility of continuously Ψ_{trunk} measurements in the range of EDS to properly assess deficit irrigation in nectarine trees.

TABLE III: SENSITIVITY ANALYSIS (SI: SIGNAL INTENSITY; CV: COEFFICIENT OF VARIATION).

Plant indicator	***SI***	***CV***	***SI CV⁻¹***
Ψ_{stem}	1.54	0.08	19.25
MDS_{LVDT}	1.27	0.12	10.58
EDS_{LVDT}	1.39	0.05	27.80
LDS_{LVDT}	0.68	0.34	2.03
MDS_{MTS}	1.79	0.05	35.80
EDS_{MTS}	2.07	0.04	51.75
LDS_{MTS}	0.88	0.19	4.63

IV. CONCLUSIONS

Our findings coincided with the study of De la Rosa et al. [12] that proposed the new index EDS (TD difference from 09:00 h to midday) derived from LVDT sensor as better plant water status indicator than the standard MDS to assess plant water stress in nectarine trees. In this study, we have demonstrated the greater feasibility of the new emerged MTs compared with LVDT sensors to assess deficit irrigation in a continuous manner. EDS measured with MTs might facilitate the continuous and necessary knowledge of the plant water status. Given the automation with real-time Ψ_{trunk} is possible, further research is needed to determine threshold Ψ_{trunk} values for successful precise irrigation. Furthermore, the stability and the long-term performance of trunk MTs need to be checked.

ACKNOWLEDGMENT

This research was funded by the Spanish State Research Agency project (PID2019-106226RB21/AEI/10.13039/501100011033), and AGROALNEXT program supported by MCI-NextGenerationEU (PRTR-17.I1) and Fundación Séneca-Región de Murcia. M.R. Conesa thanks to the Spanish JdlC program (IJC2020-045450-I) funded by MCIN/AEI/10.13039/501100011033 and European Union NextGenerationEU/PRTR.

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