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INFRARED THERMOGRAPHY AS A PREDICTION TOOL FOR THE IRRIGATION REQUIREMENT IN AGRICULTURE

Summary

This paper deals with the possibility of using infrared thermography to determine the irrigation requirement for a given field depending on the water stress level of the plants. The experiments were performed on vines at the site in the village of Jadrtovac near Šibenik, Croatia. The water stress level of plants was determined through leaf temperature measurements and measurements of leaf water potential (LWP). Leaf temperature measurements were performed using infrared thermography. Based on these measurements the relationship between the LWP and a derived factor, Crop Water Stress Index (CWSI) was investigated.

The results obtained show that infrared thermography could be successfully used to measure the leaf temperature, which is the input parameter for calculating the CWSI.

Key words: *irrigation, crop water stress index, leaf water potential, infrared thermography*

1. Introduction

During the last decades, irrigation management has increasingly become the subject of interest because of climate-change-induced water shortages and price. At the same time, more precise irrigation results in a better harvest. Today, we have different systems that provide information about the irrigation requirements of a field. These systems are aimed at special types of plants or crops (cotton, vines, strawberries, asparagus, etc.). A unifying feature of all these systems is that they all rely on sampling of specific locations within a larger field, which means their effectiveness depends on the experience of the installer in selecting proper sampling locations. An improvement of this system would be monitoring the entire (surface of the) field, which could be achieved by using infrared thermography.

Climate change, increasing population and industrial-scale crop irrigation are causing and will continue to cause water shortages in many areas of the world. This presents an economic, social, ecological and technological challenge that needs to be resolved in the near future. There are generally two ways of solving water shortages. Either the supply of water needs to be increased, which is often either unfeasible technologically or economically, or the demand for water needs to be reduced. In this paper a method for achieving the latter is discussed.

Irrigation of crops demands significant quantities of water. This is partly unavoidable, as crops need to be irrigated to achieve sufficient yields needed to meet the demand for food, but it is also partly avoidable as there is considerable room for optimisation of the process to reduce water wastage. This would also provide economic benefits, as water is a costly resource. One of the main areas where improvement is possible is in irrigation management. Various crops have differing irrigation requirements, and by modifying the irrigation process to deliver exact quantities of water to specific crops, or even specific plants, the wastage of water can be curbed significantly. Furthermore, higher quality of crop can be achieved by carefully regulating irrigation, notably so for grapevines. A lack of available water during some parts of grapevine's life cycle causes a state known as water stress that can lead to better grape quality [1]. However, failing to properly and accurately regulate such a decrease will cause damage to the grapevine, as noted by Pool et al. [2] This then presents a challenge, as irrigation needs to be tailored to a specific crop's needs or even individual plant's need – which in turn vary with climate zones, soil types, local weather and even individual sections of the same field.

Currently, the most commonly used irrigation system for such cases is a “drip” irrigation system, which offers a high degree of control and minimises water wastage, provided it is regulated based on the best available data on the actual irrigation requirements of individual plants [3]. This requirement is usually determined on a field-wide basis, where samples need to be taken from individual plants that are assumed to be representative of the field as a whole, which disregards localized variations in the field and depends on the experience of the person choosing the sample group of plants. Such process is also not readily able to be automated, and is labour intensive. It can therefore be concluded that a new approach and new technologies are needed to solve this problem and improve the management system for irrigation.

A possible solution that has been presented for this problem is the application of infrared thermography as a tool for determining the irrigation requirement. The basis for this suggestion is the fact that since local water scarcity reduces evapotranspiration, its cooling effects will be diminished or absent, and a higher temperature of the plant's canopy will be observed. The feasibility of this approach depends on the existence of a stable relationship between this temperature change and the water stress level of a plant, which has been subject to research in the last decade. Strong correlations between the two values were found.

Cohen et al. [4] were among the first to consider this issue and found a linear relationship between Leaf Water Potential (LWP), which is a measure of water stress, and the Crop Water Stress Index (CWSI), which is a dimensionless number determined by characteristic temperatures of the canopy of a cotton plant. While the model could not predict the LWP of the plants with high accuracy year-round, it did show promising results. In [5] further research was conducted to determine the optimal process of using infrared thermography to observe a grapevine's reaction to water stress, with the conclusion that using average values over a number of leaves provides superior reliability in comparison to using single leaves.

[6] evaluated different approaches for estimation and mapping of CWSI in cotton using infrared thermography, concluding that the obtained LWP map corresponded well to the situation in the field and that the technology was promising. At the same time [7] shows that an artificial reference surface may be used in this process, and even discusses the potential for use of this technology with drones. In [8] a stable relationship between LWP and CWSI is found.

Grant et al. use infrared thermography in conjunction with measurements of carbon isotope analysis in [9] to analyse plant water stress, obtaining a statistically significant correlation for the relationship between water stress and CWSI in strawberries. It should be noted that in all these examples the relationships obtained for one sort of crops were not applicable to another – not even for the same crops in different climate zones. This indicates that the relationship between those values needs to be determined experimentally for a wide variety of crops and climate zones, but due to the advantages of the technology that effort would likely be justified.

In a later paper Cohen et al. [10] publish a more comprehensive model for the LWP and CWSI relationship based on a multi-year model, again obtaining statistically significant correlations. Spatial and temporal variation in the water status of grapevine is considered in [11], with a number of statistically significant correlations being found. It should be noted that [11] did not consider LWP, but rather stem water potential, which is a similar but distinct quality of the plant. Furthermore, not all directions of imaging showed equal results, with some being more favourable than others.

Based on all of this it can be concluded that infrared thermography seems to be a promising technology for determining the irrigation requirement of crops, but more research is needed before it can become a standard method. This paper therefore continues this research by exploring the relationship between LWP and CWSI obtained via infrared thermography in the specific climate zone of costal Croatia.

2. Location and research period

The measurements were conducted on 27th July 2017 between 9:30am to 1:30pm in a vineyard located in Donje Polje near Jadrtovac, a village near the City of Šibenik. The elevation above sea level of the location is between 30 m and 150 m.

The soil on which the vineyard was planted is a cultivated karst soil [12].

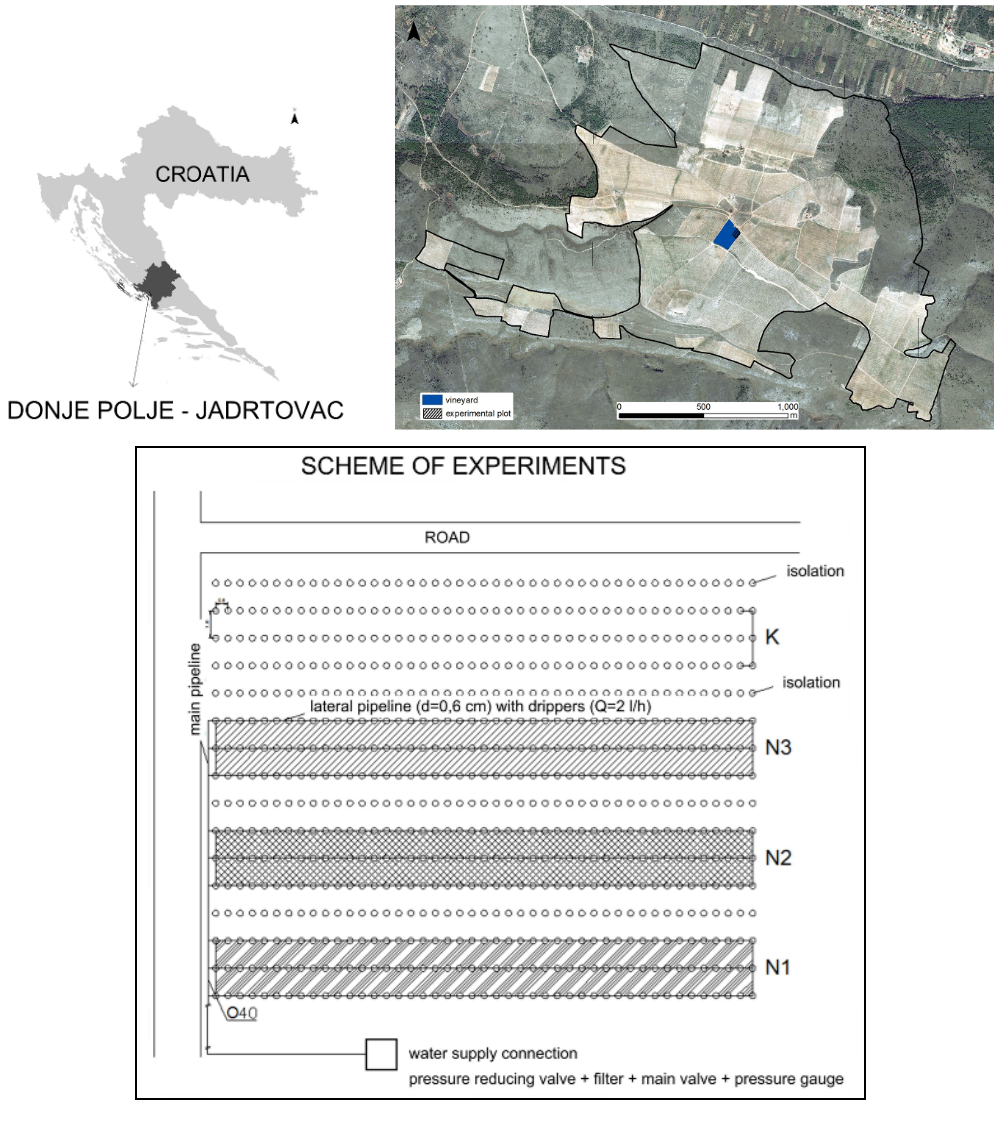

Fig. 1 Aerial photograph of the study area and the maps of the vineyard plot with respective treatments (Zovko et al., 2017)

The measurements were carried out on experimental terrain, a grapevine crop that is divided into four experimental zones, each of them consisting of three rows of grapevine of the sort Babić. The experimental zones were separated with one row of grapevine that is referred to as an insulation row.

Four different modes were applied in measurement process:

1. Irrigation that satisfies 100 % of calculated grapevine water requirement (up to 100 % evapotranspiration);
2. Irrigation that satisfies 75 % of calculated grapevine water requirement (up to 75 % evapotranspiration);
3. Irrigation that satisfies 50 % of calculated grapevine water requirement (up to 50 % evapotranspiration);
4. Without irrigation (used as a reference).

Each mode was represented with three rows of grapevines.

Fig. 2 Vineyard on location Jadrtovac

3. Measurement and results

An estimate of plant water stress can be obtained by measuring the plant water potential using a pressure chamber. There are three types of measurement: measurement of leaf water potential (LWP), measurement of stem water potential (SWP) or measurement of predawn water potential (PDLWP). Within the framework of this research, measurement of leaf water potential (LWP) is used. The reliability of the applied method in the case of grapevine or cotton crops is shown by Williams and Araujo [4].

Since the measuring equipment is mobile, the measurements were done *in situ*. The measurement of leaf water potential is done using a mobile pressure chamber (Plant Water Status Console, Soilmoisture Equipment Corporation, USA). Using this device, the measurements could be carried out in real time and thus it's possible to obtain information on the spot. This device measures the value of pressure that is needed for liquid water extraction from the cut petiole. The measured value of pressure corresponds to leaf water potential, i.e. the stress that needs to be exceeded to release liquid water from leaf structure. Thus, higher value of pressure is related to higher plant water stress. The leaf water potential is expressed as the negative value of measured pressure, usually expressed in bars or MPa.

The measurements on-site in Jadrtovac were carried out by cutting off a carefully selected fully formed leaf (without any surface defects) from the vine with a sharp knife. The cut leaf was then placed in the pressure chamber which was filled with pressurized nitrogen until the first droplet of water is noticed on the petiole, and the pressure recorded at that time corresponds to the leaf water potential.

The measurement setup is shown in figure 3.

Fig. 3 Leaf water potential measurements

Recently, in a lot of research the estimates of leaf water stress included measurement of leaf temperature using infrared thermography.

For thermographic imaging, an infrared camera with the following characteristics was used:

- thermography camera FLUKE Ti25 (Fluke, USA);
- Detector type 160 x 120 focal plane array, uncooled microbolometer
- temperature measurement range from - 20 °C to + 350 °C;
- temperature measurement accuracy ± 2 °C or 2 %;
- field of view 23 ° x 17 °;
- thermal sensitivity (NETD) $\leq$ 0,2 °C at 30 °C (200 mK);
- infrared spectral band 7.5 μm to 14 μm;
- visual camera resolution 640 x 480.

The measurements at each irrigation mode were performed so that for each mode thermographic imaging was conducted for three selected vines in each row. This means that for each measurement mode, nine images of selected vines were done, supplemented with nine additional images of accompanied leaves used afterwards for determination of leaf water potential. Hence, 18 thermographic images were created for each measurement mode.

The thermograms were processed using computational software SmartView 4.3. Furthermore, the analysis of the thermograms was carried out with the following parameters:

- the emissivity factor for leaves was 0.96 [13] (average value applied for thermograms);
- reflected apparent temperature 25 °C (measured value for analyzed thermograms).

Some universal features were noted by reviewing the recorded thermograms, which need to be taken into account while analyzing the thermogram. On the thermograms it can be seen that the temperature decreases towards the center of the leaf, while the edge of the leaf has lower temperatures. Furthermore, the effect of the reflectance of Sun's radiation can be noticed on the leaves as well. Even though the assumed emissivity can be relatively high (0.96 in this paper), the fact that emissivity changes with the angle – and with it, the measured temperature – needs to be taken into account (see figures 4 and 5).

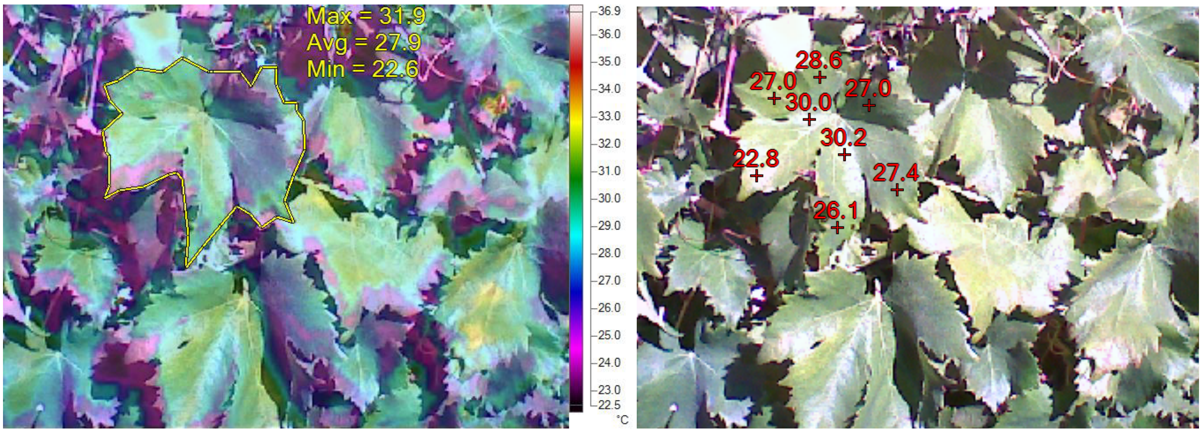

Fig. 4 Thermogram (number 650) of grapevine leaf, irrigation regime of 100% of vine water demand

Figure 4 depicts thermogram number 650 (100 % evapotranspiration). The temperature of the leaf ranges from 22.6 °C to 31.9 °C, with an average of 27.9 °C.

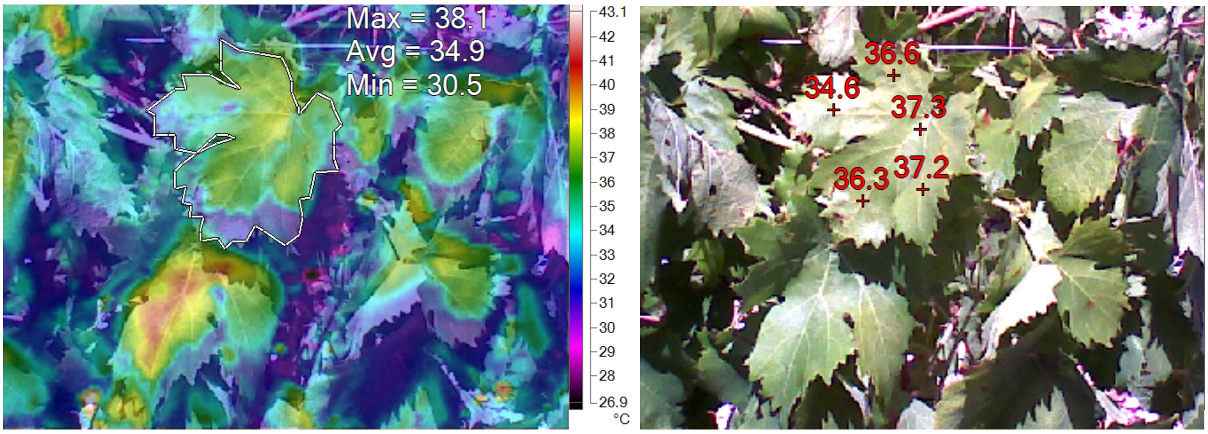

Fig. 5 Thermogram (number 716) of grapevine leaf, without irrigation

Figure 5 shows thermogram number 716 (without irrigation). The temperature of the leaf ranges from 30.5 °C to 38.1 °C. The range of the temperature is smaller, but the overall temperature of the leaf is much higher than the figure 4 example. The average temperature is 34.9 °C.

If the histograms (representations of the distribution of numerical data) are analyzed (left - thermogram 650 and right - thermogram 716) the same trend of temperature increase for all the leaves on the thermogram is noticed.

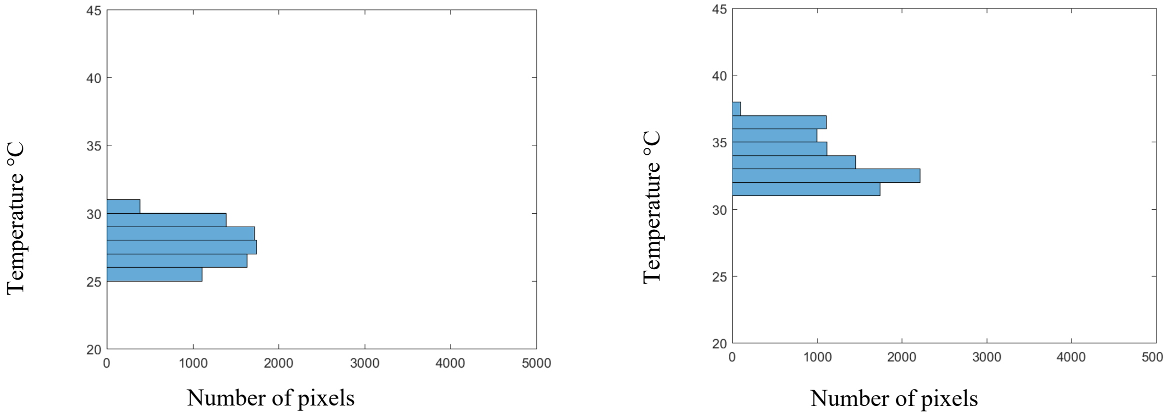

Fig. 6 Histograms of the thermograms 650 and 716

The following are the thermograms and histograms for all of the observed irrigation levels.

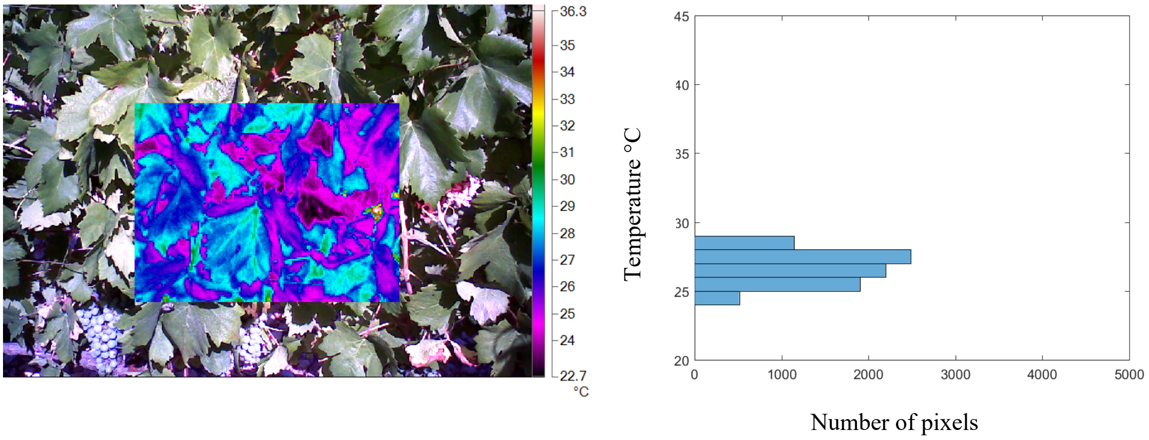

Fig. 7 Photo and thermogram (652) of grape vines, irrigation regime of 100% of vine water demand

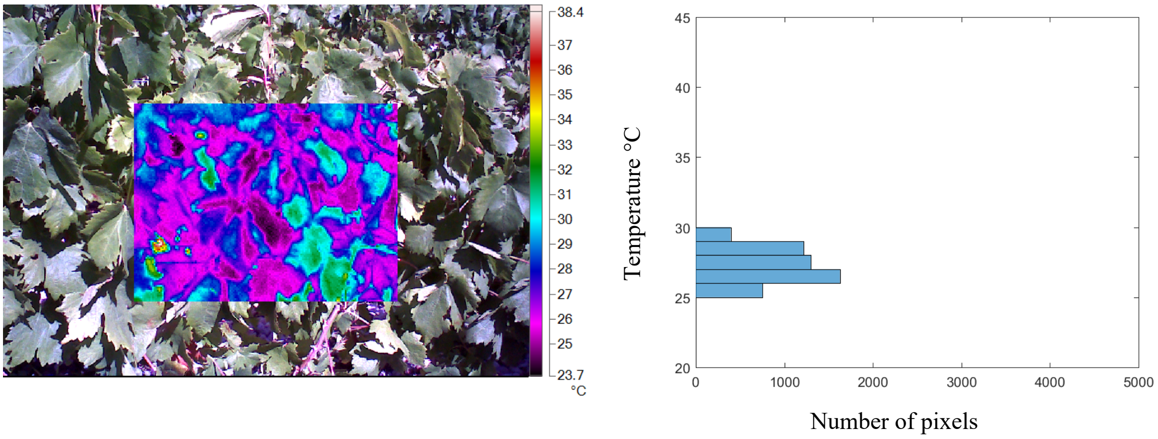

Fig. 8 Photo and thermogram (678) of grape vines, irrigation regime of 75% of vine water demand

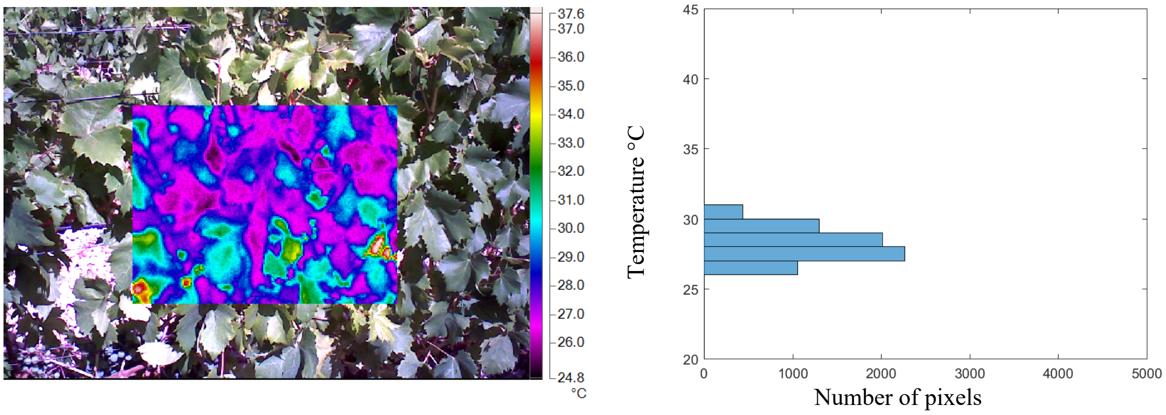

Fig. 9 Photo and thermogram (682) of grape vines, irrigation regime of 50% of vine water demand

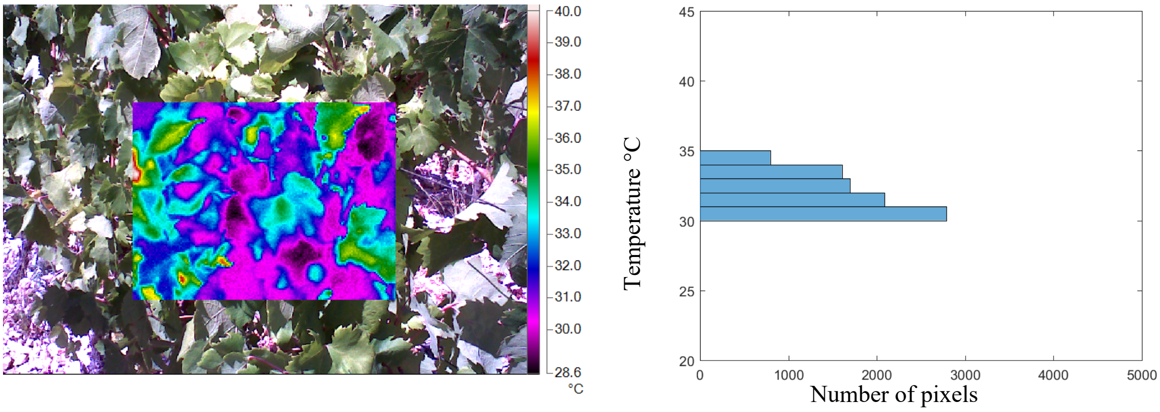

Fig. 10 Photo and thermogram (702) of grape vines, non-irrigated regime

As the measurement data obtained by meteorology station Jadrtovac was available for this research, this data was used as relevant data on air temperature and relative humidity within the period of these measurements. The meteorological data was available for every 10 minutes and is given in the table below.

Table 1 Meteorological data example for some representative thermograms

Time	Mode	Row	ϑ_{air}	RH%
09:30	3	1	28.1	34.1
09:40	3	2	28.4	32.9
09:50	3	3	28.5	32.2
10:00	2	1	28.5	32.6
10:10	2	2	28.7	32.5
10:20	2	3	28.8	32.3
10:30	1	1	29.2	31.9
10:40	1	2	29.6	31.1
10:50	1	3	29.6	31.0
11:00	0	1	29.8	30.6
11:10	0	2	29.9	31.5
11:20	0	3	29.5	30.6

4. Result analysis

Figure 11 shows the processing method applied for all thermal images (for every mode and row). First, on the visual images of the grapevine, the area which was covered by the thermal image was identified (upper left). Then a color selection algorithm was applied to this section to identify pixels containing leaves of the plant. This algorithm was easily applicable here due to the fact that the soil is covered with gravel and therefore substantially different in color than the leaves. This also excluded heavily shaded areas of leaves and the trellis. The obtained filter is shown in the upper right. Finally, this filter was applied to the thermal image (lower left) and the temperatures recorded exclusively on the pixels leaves in the canopy were taken into further account. To account for shaded areas and high reflection areas, the top and bottom 10th percentile values were removed. This provided a filtered temperature dataset for the canopy, which could then be used in following steps in data processing. An example histogram of temperature values obtained in this process is shown in bottom right.

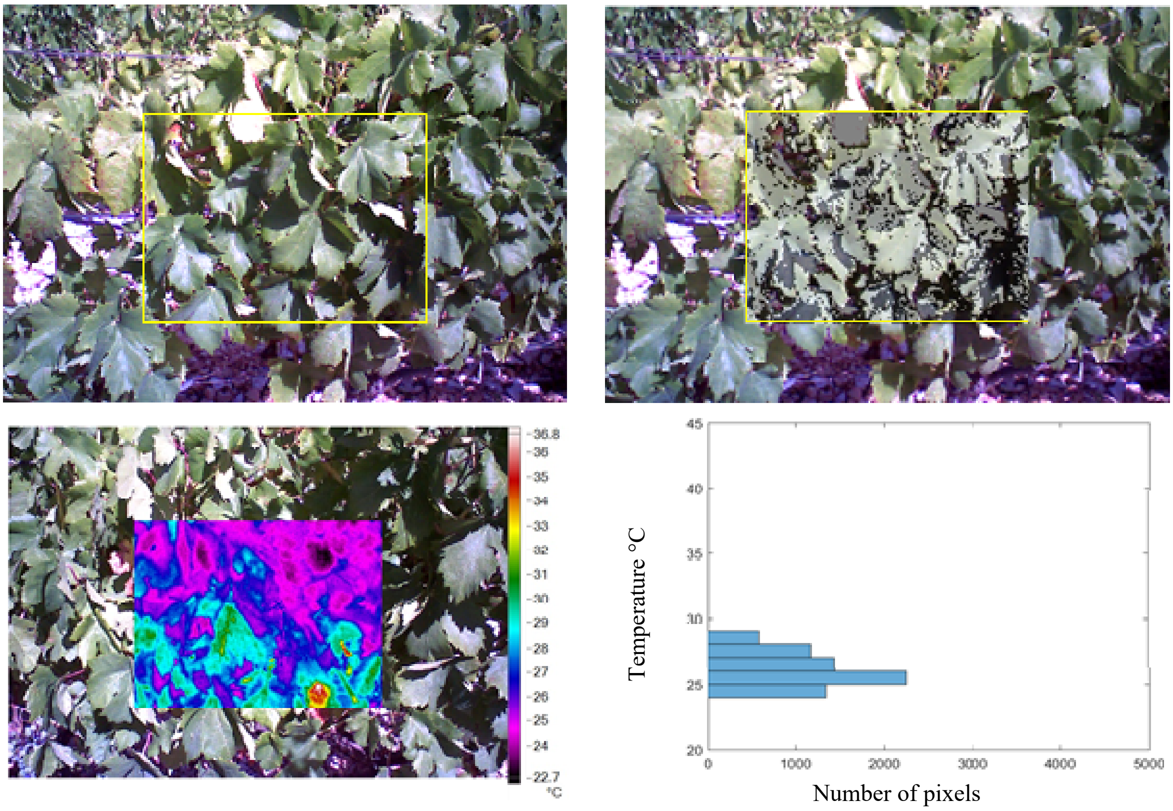

Fig. 11 Photo and thermogram of selected grapevines

Result analysis was performed by processing all thermal images for specific irrigation regimes, and the obtained canopy temperatures were used to calculate the CWSI, defined by the following equation according to Jackson [14]:

$$CWSI = \frac{\vartheta_i - \vartheta_{wet}}{\vartheta_{dry} - \vartheta_{wet}} \tag{1}$$

Where:

- ϑ_i is the canopy temperature;
- ϑ_{wet} is the wet reference temperature, i.e. the temperature of a leaf, which is well supplied with water and has all of its stomas fully opened. In this paper it is taken to be equal to the wet bulb temperature as it is a theoretical minimum for the wet reference temperature;
- ϑ_{dry} is the dry reference temperature, i.e. the temperature of a leaf which has all of its stomas fully closed. In this paper it is calculated as: $\vartheta_{dry} = \vartheta_{air} + 5$ °C [13].

The canopy temperature was calculated by first determining specific pixels in the thermal image that correspond to leaves, and then determining the average temperature recorded in that dataset (ϑ_{avg}). Using this value, the CWSI for every thermal image was calculated. Additionally, during the processing, the top and bottom 10-percentile values for temperature were discarded.

The wet bulb temperature was calculated (for every analyzed thermogram) from relative humidity, air pressure and air temperature using the equation provided by Roland Stull [15].

By performing nine measurements of the LWP for each irrigation regime, the average values of LWP were calculated and are shown in Table 2.

Table 2 Changes in LWP according to irrigation regimes

LWP (MPa)	Irrigation regimes			
	0 %	50 %	75 %	100 %
Average	-1.7	-1.3	-1.1	-1.0
Standard deviation	0.14	0.13	0.16	0.07
Expected value [16]	< - 1.4	- 1.3 to – 1.4	- 1.1 to – 1.3	> - 0.9

Analysis was limited by the number of available LWP measurements, as each LWP measurement required significantly more time than thermal imaging and therefore couldn't be repeated as many times while still obtaining results relevant for situation captured in the thermal images. Due to this LWP dataset has fewer datapoints than there are thermal images. This means that only a smaller number of thermal images could be used in the final analysis. This could be improved in future research by having more LWP measurements.

In order to determine all influences on this methodology, the same experiment would need to be repeated at various times of the day and year, as well as with plants in different stages of development. The method has so far been used only for plants with fully formed canopies during the summer months.

Figure 12 shows the relationship between calculated CWSI and the measured values of LWP.

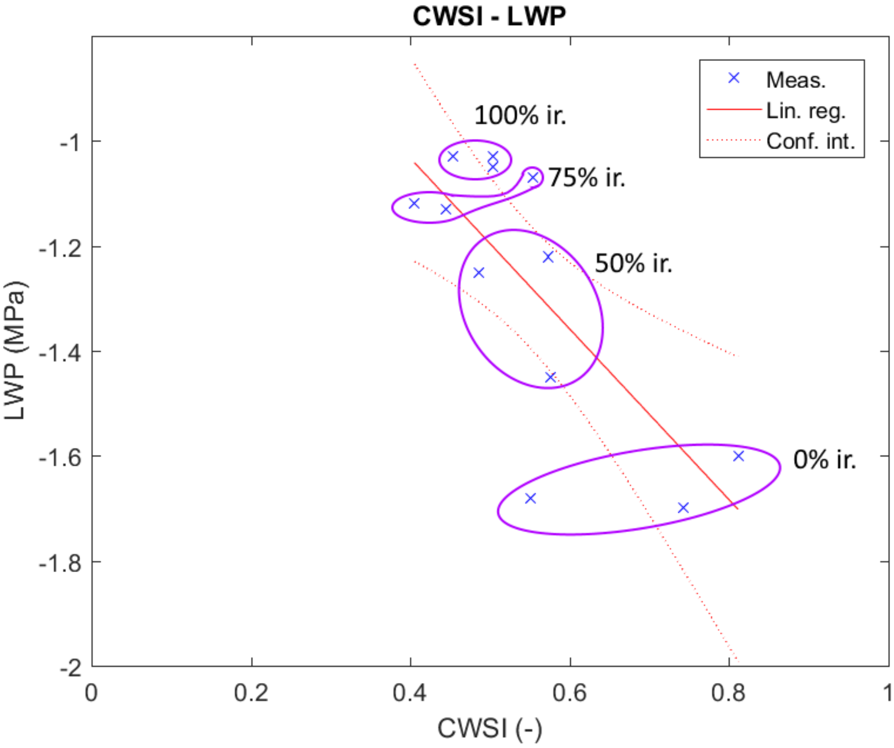

Fig. 12 Results of CWSI-LWP analysis obtained for vineyard

The relationship between CWSI obtained based on temperatures from thermal images and the measured LWP was obtained by using a linear regression model. On the plot above the four modes of irrigation are clearly marked. The correlation obtain is given by the following equation:

$$LWP = -0.38184 - 1.6275 * CWSI \tag{2}$$

This relationship has an R^2 value of 0.558, while its *p*-value is 0.00522.

While the correlation found is not perfect, there is a clear trend visible in figure 12 and further research with a larger number of LWP datapoints is needed before a final expression linking CWSI and LWP can be obtained.

5. Conclusion

Thermography provides a practical method for measuring the temperature distribution on the canopy of the whole plant rather than just on single leaves from the canopy. This enables the mapping of the plant water status distribution in the field. By calculating the CWSI from the thermographic measurements and by concurrently measuring the LWP, the relation between them is found for different types of plants.

The results obtained show that thermography could be successfully applied for measuring canopy temperatures, the input parameter for calculation the CWSI.

Given that the LWP measurement is time consuming procedure and that in order to obtain reliable results samples must be taken from various points in the field, it is not very practical. Because of this, only a few leaves in a representative area are sampled. This data is then used as a basis for the calculation of another parameter, a temperature-based water stress index.

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