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INFRARED THERMOGRAPHY IN THE DETECTION OF WATER STRESS IN PLANTS

INFRARDEČA TERMOGRAFIJA PRI ODKRIVANJU VODNEGA STRESA V RASTLINAH

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Keywords: thermography, water stress, plant, UHI, electrical energy

Abstract

Plants and green islands in urban areas are one way to mitigate climate change and reduce the energy demand for air conditioning. Like humans, plants are also exposed to the urban heat island effect, which manifests itself in the fact that air temperatures in urban areas are on average 2-5°C higher than in rural areas. In addition, plants are exposed to water stress, which occurs when the amount of available water exceeds or falls short of the plants' water requirements. The paper presents an increase in electricity demand, with a special focus on Croatia, Slovenia and countries with similar electricity consumption. The effects of the urban heat island are illustrated using a graphical comparison from the recent literature. Infrared thermography, as one of the methods for detecting water stress, is explained with the physical background of long-wave radiation detection, and compared with near infrared digital photography. All possible aspects are presented of radiation detection that occur during thermographic analysis. A specific overview of water stress is given, and its effects are illustrated using examples of plant height and flower size. The application of infrared thermography in the detection of water stress is illustrated using thermograms of wheat in a dry field and after irrigation. On the basis of the presented information, a conclusion was drawn about the possibility of using infrared thermography in the detection of water stress.

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Povzetek

Rastline in zeleni otoki v urbanih območjih so eden od načinov za ublažitev podnebnih sprememb in zmanjšanje povpraševanja po energiji za klimatske naprave. Tako kot ljudje so tudi rastline izpostavljene učinku mestnega toplotnega otoka, ki se kaže v tem, da so temperature zraka v urbanih območjih v povprečju za 2–5 °C višje kot na podeželju. Poleg tega so rastline izpostavljene vodnemu stresu, ki nastane, ko količina razpoložljive vode presega ali pade pod potrebe rastlin po vodi. Prispevek prikazuje porast povpraševanja po električni energiji s posebnim poudarkom na Hrvaški, Sloveniji in državah s podobno porabo električne energije. Učinki mestnega toplotnega otoka so prikazani z grafično primerjavo iz novejše literature. Infrardeča termografija kot ena od metod za zaznavanje vodnega stresa je pojasnjena s fizikalnim ozadjem zaznavanja dolgovalovnega sevanja in primerjana z digitalno fotografijo blizu infrardečega sevanja. Predstavljeni so vsi možni vidiki detekcije sevanja, ki nastanejo pri termografski analizi. Podan je poseben pregled pomanjkanja vode, njegovi učinki pa so prikazani na primerih višine rastline in velikosti cvetov. Uporaba infrardeče termografije pri zaznavanju pomanjkanja vode je prikazana s termogrami pšenice na suhem polju in po namakanju. Na podlagi predstavljenega so sklepali o možnostih uporabe infrardeče termografije pri detekciji vodnega stresa.

1 INTRODUCTION

Since the 1990s climate change has had a negative impact, which is particularly evident in agriculture and the electricity supply. The need for space cooling is increasing. For example, from July 1, 2023, certain types of air conditioning systems in South Australia may only be installed or connected to the electricity distribution network if they meet demand-side management requirements [1]. The International Energy Agency (IEA) stipulates that air conditioning systems installed after July 1, 2053 must be equipped with a demand response system, i.e., they must be controlled via the electricity distribution grid, [2]. All this points to the important role that the availability of split air conditioning systems plays for the electricity system. The development of electricity consumption is best illustrated in Figure 1, data source the International Energy Agency (IEA) [3]

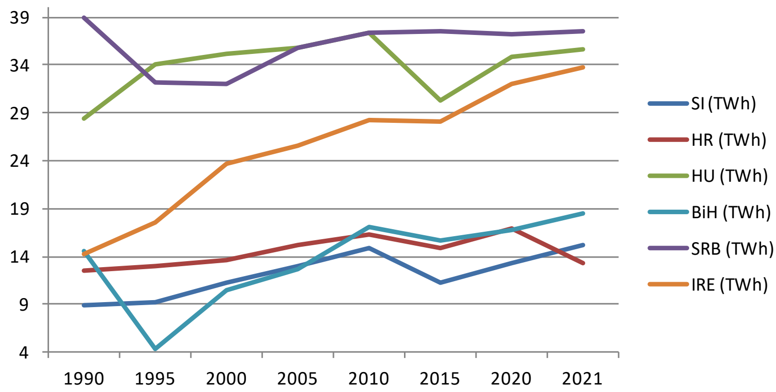

Figure 1: *Electricity consumption in Croatia and Slovenia in TWh compared to arbitrarily selected countries*

Urban centres exposed to solar radiation are built from construction materials with high specific heat capacity, and roads are dark in colour, which makes it easy to absorb and store heat energy. Irradiated energy is released in the form of long-wave radiation, and, since the energy radiating into neighbouring buildings is absorbed and re-emitted into the local environment, it results in warming known as an Urban Heat Island (UHI), [4] The UHI effect manifests itself in the way that air temperatures in urban areas are, on average, 2-5°C higher (in some cases even more than 12°C) compared to rural areas. The spatial trends of the temperature differences can be seen in Figure 2. Each dot represents the temperature difference in a specific city. The mean temperature differences for each country are indicated by the stacked bars.

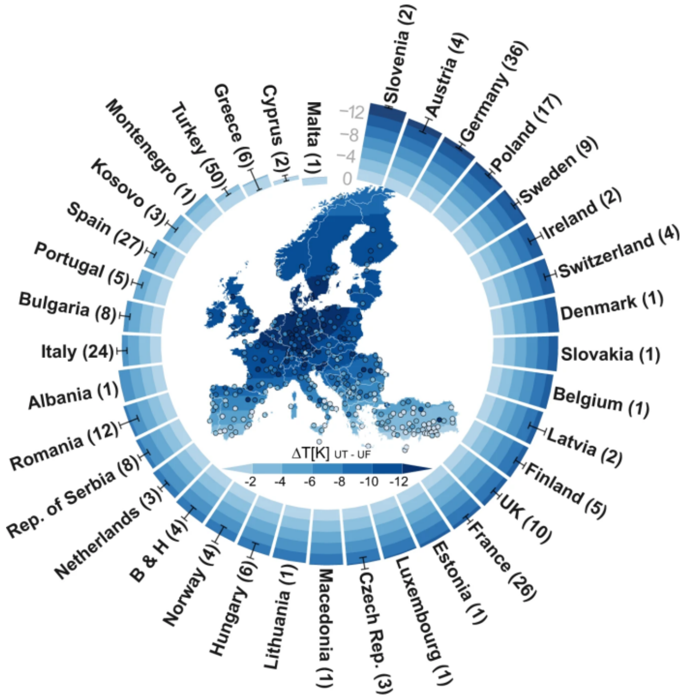

Figure 2: *Spatial trends of the temperature differences during hot extremes between areas covered by trees and urban areas, source [6]*

The rise in temperature in urban areas leads to considerable ecological and social consequences [5]. A study by the Joint Research Center from May 2023 predicts that more vegetation in certain urban areas can mitigate the extreme heat [7]. More and more attention is being paid to vegetation in the reconstruction of urban areas. The last reconstruction of the Tvrđa Fortress in Osijek [8] resulted in the formation of green islands on the main square, as can be seen in Figure 3. The thermogram shows that the temperature of the trees is 33.8°C and that of the ground is 34.7°C, much lower than the surrounding area at 53.2°C. The lower temperatures are the result of water evaporation. The secondary contribution of the trees is that the area under the canopy reduces the energy radiated by the sun onto the paved area, and the energy is accumulated in materials with a high heat capacity.

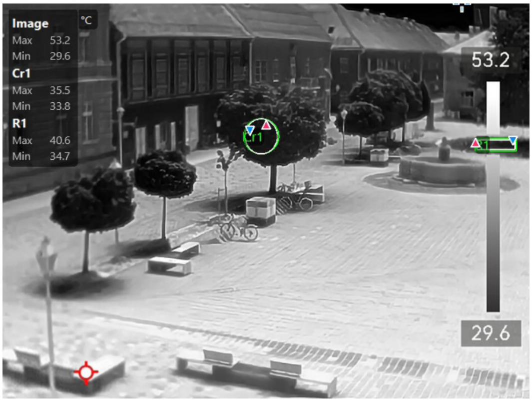

Figure 3: *Thermogram of the newly formed green islands of Osjecka Tvrdja*

2 INFRARED THERMOGRAPHY AS A METHOD DETECTION OF THERMAL RADIATION

Infrared thermography is a method for detecting thermal radiation (usually in the long-wave range), which is converted into a visible image. Based on a calibration and precisely selected physical parameters that affect the radiation, the corresponding temperature value is related to the amount of radiation. In terms of resolution, which reaches 2560 x 2048, infrared thermography is at the same stage of development as digital photography was more than twenty years ago. This is important to know, because, 10 years ago, there was a major shift in the spread of thermal imaging cameras to the wider market with the emergence of small manufacturers. The similarity ends there, because, unlike photography, which detects light and requires light for excitation, thermography detects radiation, which is a consequence of the internal energy of the observed object, Figure 4.

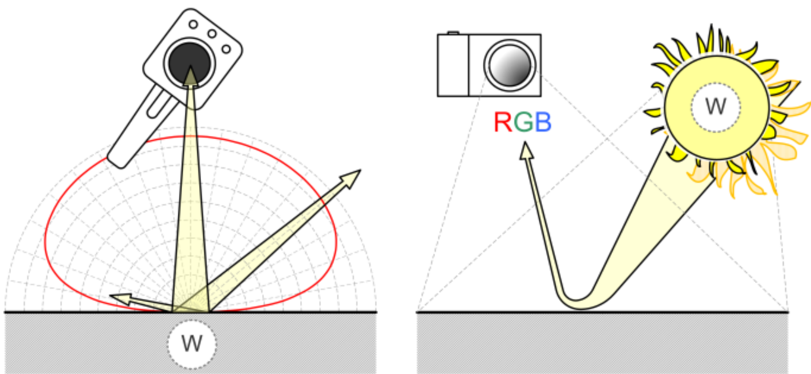

Figure 4: *The basic difference between photography and thermography, source [9]*

Urban centres exposed to solar radiation are built from construction materials with high specific heat capacity, and roads are dark in colour, which makes it easy to absorb and store heat energy. Irradiated energy is released in the form of long-wave radiation, and, since the energy radiating into neighbouring buildings is absorbed and re-emitted into the local environment, it results in warming known as a Urban Heat Island (UHI), [4] The UHI effect manifests itself in the way that air temperatures in urban areas are, on average, 2-5°C higher (in some cases even more than 12°C) compared to rural areas. The spatial trends of the temperature differences can be seen in figure 2. Each dot represents the temperature difference in a specific city. The mean temperature differences for each country are indicated by the stacked bars.

Figure 5: *Photo of the trees through a 720 nm filter*

The reason why the leaves are white at 720 nm lies in the fact that the absorption (a) of the leaves is high in the visible, or photosynthetically active (=PAR) wavelength range between 400 and 700 nm, while the reflectance (r) and transmittance (t) are higher in the near infrared, Figure 6.

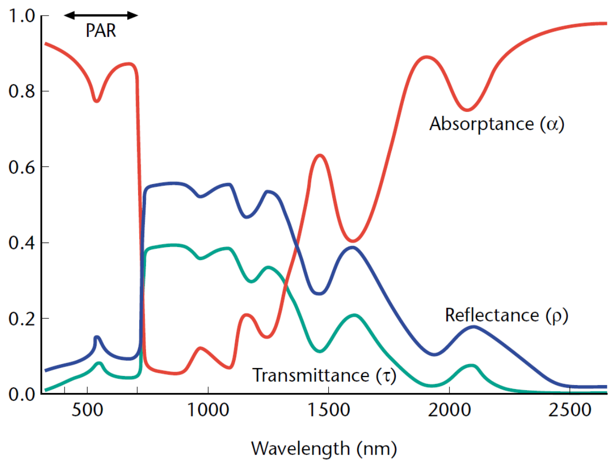

Figure 6: *Absorption, transmission and reflection spectra for ‘typical’ leaves, source [10]*

The region of spectrum detected by most modern infrared thermal cameras is located from 7 µm to 14 µm, as can be seen in figure 7.

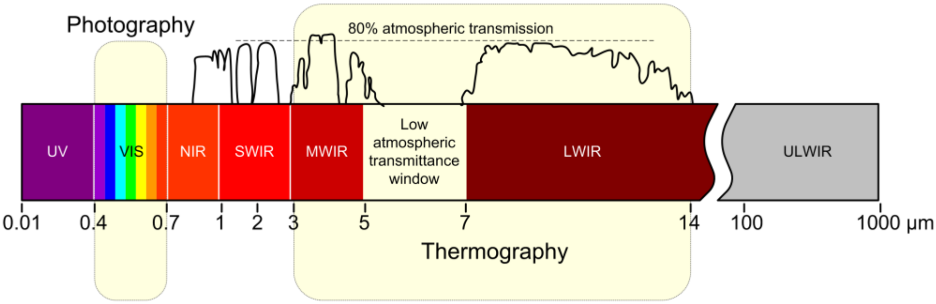

Figure 7: *Classification of thermography in the field of Electromagnetic Radiation.*

The reason why the detectors were developed in the mentioned area is the need to detect the maximum radiation of most objects on earth. In Figure 8. can be see the maximum radiation of the sun, for which our eyes were developed, and the maximum radiation of the earth at approximately 300 °K.

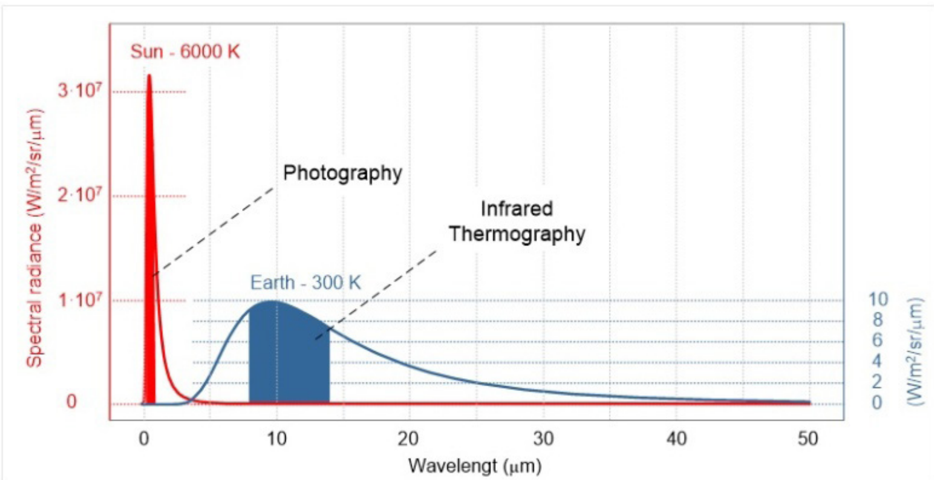

Figure 8: *Comparison of radiation in the visible part of the spectrum and long-wave infrared.*

The summary of everything presented is that, contrary to the general opinion, although it shows the temperature, the infrared thermal camera does not measure the temperature, but the radiation in the infrared part of the spectrum, as can be seen in Figure 9.

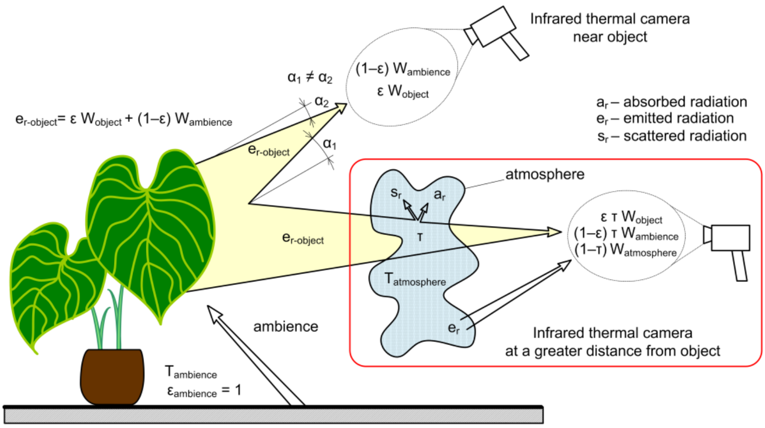

Figure 9: *Plant radiation that can be detected by the IR camera*

3 WATER STRESS

Water stress in crop growing occurs when the amount of available plant water exceeds or is less than the plant water requirements, i.e., evapotranspiration. Nowadays, in crop production, water stress represents an increasing challenge, because agricultural producers have to compensate for the lack of water in a timely manner through irrigation, or remove excess water from the production area. The problem is increasingly pronounced during the intensification of the negative consequences of climate change, which are manifested in the complex phenomena of periods of intense drought accompanied by extremely high air temperatures and the occurrence of large amounts of precipitation in a very short time, resulting in water scarcity and water-related hazards. As an example, we can highlight the year 2010, when a natural disaster due to flooding and excessive rainfall was declared, resulting in 6.7 million euros of estimated damage. Then two extremely dry years followed, when the 2011 and 2012 drought and heat stresses caused more than 64 and 105 million euros, respectively, in direct losses to agriculture (Marković et al., 2015) [11]. Increasing variations in weather conditions are shown on the example of growing period rainfall and air temperatures deviations from the long-term average (LTA, 1961-1990, Figure 10).

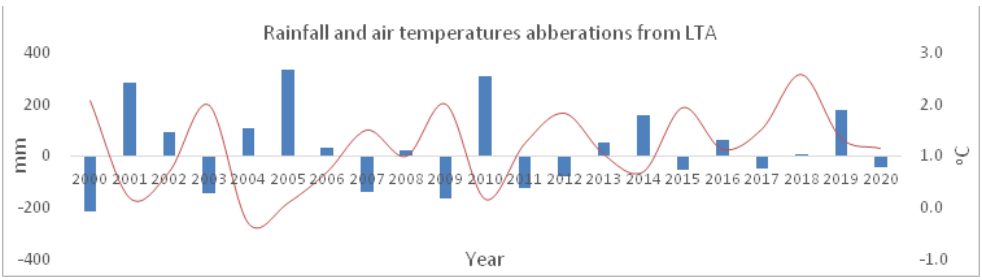

Figure 10: *Growing season (April-September) rainfall and air temperatures deviations during 2000-2020 period from long-term average (1961-1990)*

From the presented Figure, the aforementioned variations in air temperatures and the irregular rainfall pattern are clearly visible, indicating an increasing need to find solutions to alleviate and to detect water stress in plants. The complex plant growing processes, from germination to the mature stage are affected directly or indirectly by an adequate water supply, whereby different plant species have a certain degree of tolerance to water stress caused by drought or flood (waterlogging) conditions. While the stress caused by drought occurs due to the lack of water easily accessible to the plant and high air temperatures, the stress caused by waterlogging occurs due to intense rainfall, poor drainage systems, soil type and compaction or over-irrigation.

In general, plants respond to water stress with changes to different physiological, morphological and biochemical traits, and it can be studied at a whole plant level as an integrated tissue system, or at the cellular level. Previous study results have shown that drought stress inhibited plant growth significantly, and that the negative physiological response is more pronounced with increasing intensity and duration (Sun et al., 2020, Wu et al., 2022) [12], [13]. As for morphological traits, plants react to drought stress at different growth stages with changes in plant height, fresh weight, dry weight, total biomass as well as yield and yield components. In addition, as a result of the drought, there is a change in the composition of the fruit of the cultivated crop, the content of protein, oil, starch and nutritional elements. The mentioned negative consequences of water stress are important for plant production, growing food and fodder. Furthermore, the negative consequences of water stress are also significant in the cultivation of ornamental plants, where changes in the morphology of flowers, colour and size of flowers and the appearance of the first buds are clearly visible Figure 11, Figure 12.

Figure 11: *Plant height and flower size of Tagetes patula L. in different drought treatments*

Figure 12: *The first bud and flower appearance of a Petunia grown in different drought treatments*

As for water stress caused by flooding, due to the lack of oxygen, there is reduced root growth or complete death, while poor water and nutrient absorption result in lower yield and quality, that is low field production efficiency. As with drought, stress caused by drought results in numerous negative changes in the morphological, biochemical and physiological sense.

Water stress in plant production can be detected and monitored in different ways, i.e., by measuring the water content in the soil with different soil moisture sensors, by estimating stomatal conductivity, leaf turgor, thickness, water content and temperature, cell pressure, etc. Each of the mentioned methods has its advantages and disadvantages. However, the most important thing to point out is that it is important to detect water stress as early as possible, which is a key element of modern plant production, i.e., precision agriculture. In that sense, plant phenotyping, applied to precision agriculture, is a valuable tool for the diagnosis and detection of plant stress, even in the absence of symptoms (Pineda et al., 2021), [14].

4 APPLICATION OF IR THERMOGRAPHY IN THE DETECTION OF WATER STRESS

The accessibility of infrared cameras has led thermography to be a method that can be applied in everyday water stress analysis. The thermal images shown in Figure 13. and Figure 14. were taken on the same date under dryland and irrigated conditions, and represent research from 2015.

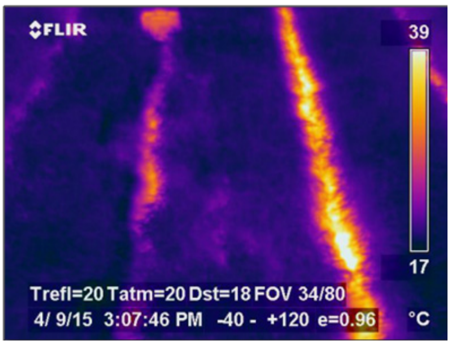

Figure 13: *Wheat at dryland, source [15]*

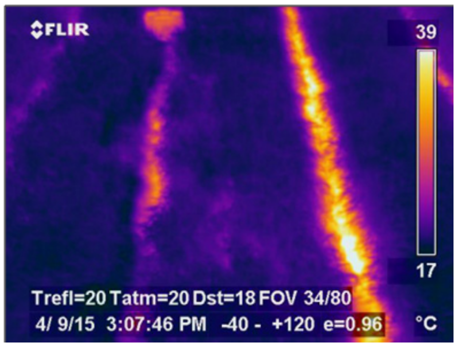

Figure 14: *Wheat after irrigation, source [15]*

The difference on the thermograms is manifested in the reduction of the temperature of the plants and the soil due to the evaporation of water and the hydration of the plants. Crops which are under water stress tend to have higher temperatures compared to well-hydrated crops, due to transpiration, the process by which plants lose water through their leaves, being reduced under water stress, leading to higher leaf temperatures. Since the time of use of stationary cameras until the realisation of the review presented in the paper, significant changes in interpretation have occurred thanks to the adoption of drones and specialised software support. One of the pioneers in the field of the thermovision detection of water stress is the company Workswell. The WIRIS thermal camera, supported by the DJI S1000 UAV platform and specialised software, can generate temperature maps or thermal indices [16]. These maps can help identify areas of the crop that are experiencing higher temperatures, indicating potential water stress. 5

5 CONCLUSION

The effects of climate change are not only reflected in living conditions, but also in energy requirements, especially in urban areas. The rise in temperature leads to considerable ecological and social consequences. The growing demand for electricity to power air conditioning systems can, and must, be reduced wherever possible. According to the International Energy Agency, air conditioning systems installed after July 1, 2053 must be equipped with a demand response system to manage consumption. South Australia has had such a requirement since 2023. The formation of green islands and the planting of trees and other vegetation have a positive effect on the microclimate and reduce the effects of the urban heat island. Like humans, plants are also sensitive, especially to water stress, which occurs when the amount of available water exceeds or falls short of the plants' water requirements. Infrared thermography is a method of detecting radiation in the long-wave region of the electromagnetic spectrum and is an ideal method for monitoring water stress. Over the last ten years, the prices of the devices have fallen, so that thermography is now used widely, as are thermographic monitoring systems based on drones with special software. The physical background of the detection is based on temperature changes due to water evaporation. Plants under water stress tend to have higher temperatures than well-humidified plants, because transpiration, the process by which plants lose water through their leaves, is reduced under water stress, resulting in higher leaf temperatures. The paper aims to give an overview of the field presented without going into the complexity of control methods to reduce water stress through drainage and irrigation.

References

[1] **Government of South Australia:** *Department for Energy and Mining, 'Demand response capability requirements for installation of all air conditioning types',* Technical Regulator Guideline, Energy and Technical Regulation, 2023

[2] **C. Camarasa**, Public webinar - IEA's Energy Efficiency 2023 Report: Key findings and a chance to discuss with Lead Authors, Odyssee-Mure, 7 December 2023

[3] **International Energy Agency – IEA**, Available: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=CROATIA&fuel=Energy consumption&indicator=TotElecCons (April 30, 2023)

[4] **V. Monteiro, M. & H., Phillip & Morison, J. & D., Kieron,** *The role of urban trees and greenspaces in reducing urban air temperatures*, 2019

[5] **S. Önder, A. Akay**, *The Roles of Plants on Mitigating the Urban Heat Islands' Negative Effects*, International Journal of Agriculture and Economic Development, ISSN : 2331-0200

[6] **J. Schwaab, R. Meier, G. Mussetti, et al.** *The role of urban trees in reducing land surface temperatures in European cities*. Nat Commun 12, 6763 https://doi.org/10.1038/s41467-021-26768-w, 2021

[7] **E. Massaro, R. Schifanella, M. Piccardo, et al.** *Spatially-optimized urban greening for reduction of population exposure to land surface temperature extremes,* Nat Commun 14, 2903, https://doi.org/10.1038/s41467-023-38596-1, 2023

[8] **H. Glavaš, M. Hadzima-Nyarko, I. Haničar Buljan, T. Barić**, *Locating Hidden Elements in Walls of Cultural Heritage Buildings by Using Infrared Thermography*. Buildings 2019, 9, 32. https://doi.org/10.3390/buildings9020032

[9] **Č. Livada, H. Glavaš, A. Baumgartner, D. Jukić**, *The Dangers of Analyzing Thermographic Radiometric Data as Images*, Journal of Imaging 9, no. 7: 143. https://doi.org/10.3390/jimaging9070143 2023

[10] **H. G. Jones, Hamlyn, E. Rotenberg**, *Energy, Radiation and Temperature Regulation in Plants,* In eLS, John Wiley & Sons, Ltd (Ed.). https://doi.org/10.1038/npg.els.0003199, 2001

[11] **M. Marković, M. Josipović, V. Tadić, V. Zebec, M. Josipović, V. Filipović,** *Efficiency of maize irrigation scheduling in climate variability and extreme weather events in eastern Croatia*. Journal of water and climate change, 6(3): 586-595, 2015

[12] **Y. Sun, C. Wang, H.Y.H. Chen, R. Honghua**, *Response of Plants to Water Stress: A Meta-Analysis*. Front. Plant Sci., 11: 978, 2020

[13] **J. Wu, j. Wang, W. Hui, F. Zhao, P. Wang, C. Su, W. Gong,** *Physiology of Plant Responses to Water Stress and Related Genes*: A Review. Forests, 13, 324, 2022

[14] **M. Pineda, M. Barón, M.-L. Pérez-Bueno,** *Thermal Imaging for Plant Stress Detection and Phenotyping*. Remote Sens., 13, 68, 2021

[15] **M. Bhandari**, *Use of infrared thermal imaging for estimating canopy temperature in wheat and maize*, Ms Thesis, West Texas A&M University, Canyon, Texas, August, 2016

[16] **Workswell**, *WIRIS Agro*, Available: https://www.drone-thermal-camera.com/detection-of-water-stress-cereals-crops-with-thermal-camera/#, (April 30, 2023)