Thermography to assess grapevine status and traits opportunities and limitations in crop monitoring and phenotyping – a review

Antonio La Fata

Dissertation to obtain a Master's Degree in

Viticulture and Oenology Engineering

Supervisor: Prof. J. Miguel Costa

Supervisor: Prof. Antonino Pisciotta

Jury:

President:

PhD Carlos Manuel Antunes Lopes, Associate Professor with Habilitation at Instituto Superior de Agronomia, Universidade de Lisboa.

Members:

PhD Joaquim Miguel Rangel da Cunha Costa, Assistant Professor at Instituto Superior de Agronomia, Universidade de Lisboa;

PhD José Manuel Couto Silvestre, Assistant Researcher at Instituto Nacional de Investigação Agrária e Veterinária, I. P. - Dois Portos.

2021

Acknowledgements

INTERPHENO - Uma Aproximação Interdisciplinar à Fenotipagem de Alto Débito em Plantas (PTDC/ASP-PLA/28726/2017)

Abstract

Climate change and the increasing water shortage pose increasing challenges to agriculture and viticulture, especially in typically dry and hot areas such as the Mediterranean and demand for solutions to use water resources more effectively. For this reason, new tools are needed to precisely monitor water stress in crops such as grapevine in order to save irrigation water, while guaranteeing yield. Imaging technologies and remote sensing tools are becoming more common in agriculture and plant/crop science research namely to perform phenotyping/selection or for crop stress monitoring purposes.

Thermography emerged as important tool for the industry and agriculture. It allows detection of the emitted infrared thermal radiation and conversion of infrared radiation into temperature distribution maps. Considering that leaf temperature is a feasible indicator of stress and/or stomatal behavior, thermography showed to be capable to support characterization of novel genotypes and/or monitor crop's stress. However, there are still limitations in the use of the technique that need to be minimized such as the accuracy of thermal data due to variable weather conditions, limitations due to the high costs of the equipment/platforms and limitations related to image analysis and processing to extract meaningful thermal data. This work revises the role of remote sensing and imaging in modern viticulture as well as the advantages and disadvantages of thermography and future developments, focusing on viticulture.

Keywords: Imaging, leaf temperature, sensors, precision viticulture, remote sensing

Resumo

As alterações climáticas e a progressiva escassez de água colocam desafios crescentes à agricultura e viticultura feitas especialmente em regiões tipicamente áridas e quente como as do Mediterrâneo. Por isso são necessárias novas ferramentas para melhor monitorizar o stress hídrico das culturas incluindo a vinha e usar o recurso água de uma forma mais eficiente. As tecnologias baseadas no uso de sistemas de imagem e na deteção remota são cada vez mais comuns na agricultura moderna e e na investigação agrária e incluem aplicações ao nível da fenotipagem/seleção de plantas, monitorização do stress das culturas e apoio à decisão..
A termografia é uma técnica que permite detectar a emissão da radiação térmica pelos objectos e convertê-la em imagens no visível mostrando a distribuição espacial da temperatura à sua superficie.. A termografia tem mostrado ser possível caracterizar genótipos e monitorizar o stress em diversas espécies e culturas como a da vinha e apoiar a programação da rega e seleção de culturas. Todavia existem ainda limitações no uso da imagem térmica que é necessário minimizar tais como a influência das condições meteorológicas, que afetam a precisão das medições. Há também limitações ao nível do preço dos equipamentos e no processamento de imagens para obtenção e uso de dados térmicos. Neste trabalho são apresentadas e discutidas as vantagens e desvantagens da termografia e apontam-se possíveis desenvolvimentos futuros em termos do uso da imagem térmica tendo como focus o seu uso em viticultura.

Palavras chave: Sistemas de imagem, temperatura da folha, sensores, viticultura de precisão, deteção remota.

Resumo alargado

As alterações climáticas e a progressiva escassez de água colocam desafios crescentes à agricultura e viticultura especialmente em regiões áridas como as do Mediterrâneo. São por isso necessárias novas ferramentas para monitorizar o stress de culturas como a vinha para se poupar e usar mais eficientemente os recursos hídricos.. Tecnologias baseadas no uso de deteção remota e no uso de sistemas de imagem são cada vez mais vulgares em agricultura e na investigação agrária e incluem aplicações que se estendem desde a fenotipagem e seleção de plantas até á monitorização do stress das culturas. A temperatura das plantas/culturas é um bom indicador da sua condição fisiológica e permite uma análise quantitativa sobre aspectos fisiológicos muito importantes como a transpiração e a condutância estomática. Por isso os sistemas de imagem térmica tornaram-se uma ferramenta útil para monitorizar remotamente o estado fisiológico de culturas como oda vinha. A termografia permite detectar a emissão da radiação no comprimento de onda do infra vermelho térmico e convertê-la em imagens no comprimento de onda do visível mostrando a distribuição espacial da temperatura à superfície dos corpos. Hoje em dia, existem diferentes tipos de equipamento com diferentes tipos e qualidades de detectores de imagem,com diferentes tamanhos/peso, portabilidade e preço. São também várias as plataformas que se podem usar (fixas, móveis, terrestres ou aéreas). Em viticultura e nodomínio da investigação agrária, a termografia tem vindo a ser usada principalmente na deteção de stress hídrico, apoio à programação da rega , seleção genotípica, detecção de doenças, monitorização da quantidade e qualidade dosdos frutos. Todavia ainda existem limitações no uso da termografia tais como a influência das condições meteorológicas na robustez dos resultados obtidos, custo excessivo de equipamentos e plataformas e também problemas ao nível do processamento das imagens para extração de informação válida . Neste trabalho são revistos varios aspectos das tecnologías de deteção remota e do uso da termografia na deteção de stress das culturas e em fenotipagem. São também apresentadas algumas das principais vantagens e desvantagens da termografía e apontam-se possíveis desenvolvimentos futuros desta técnica tendo como focus o seu uso em viticultura.

List of figures

Figure 11. Thermal images of the same citrus canopy acquired at different hours of the day, (Gan et al., 2018).

Figure 12. Thermal images detection system used for orange trees, the system is composed by a thermal camera, RGB camera and lights. The cameras are facing the canopy at a distance of 2 m and framing a Region of Interest (ROI) within the canopy, (Bulanon et al., 2008).

Figure 13. Digital images of Castelão and Moscatel bunches, and corresponding thermal images for *Vitis vinifera* cv Castelão (**A, B; C)** and cv Moscatel (**D,F**). Bunches and berries are outlined in circle and lasso in order to analyse them and exclude sky and soil, (Stoll & Jones, 2007).

Figure 14. Thermal image (grey scale), showing the "oilspot zone" where fungus has been inoculated in three different insertions on the main vine of the leaf, the inoculation zones presents a different temperature from the rest of the leaf, **A)** irrigated/inoculated leaf in **B)** non-irrigated/inoculated leaf, (Stoll et al., 2008).

List of tables

List of abbreviations:

ABA: Abscisic acid

AHRS: Altitude Heading Reference System

ATV: All-terrain vehicle

CO: Carbon monoxide

CO_2: Carbon dioxide

CSWI: Crop Water Stress Index

CTCP: Color-Thermal combined probability

DI: Deficit irrigation

DSS: Decision Support Systems

ETc: Cultural evapotranspiration

GPS: Global Positioning System

gs: Stomatal conductance to water vapour

Gt: Gigatons

H_2CO_3: Carbonic acid

HTP: High-throughput phenotyping

I_G: Stomatal conductance index

Ios: Apple mobile operating system

IR: Infra-red

IRT: Infra-red thermography

LAI: Leaf area index

LE: latent heat flux

LRF: Laser range finder

LW: Longwave radiation

MDS: Maximum daily shrinkage

MPa: Megapascal

MTD: Maximum temperature difference.

N: Nitrogen

NDVI: Normalized Difference Vegetation Index

NIR: Near infrared

Nwsb: Non-water-stressed baseline

pH: Potential of hydrogen

PIP: Phospholipase

PRD: Partial root drying

RDI: Regulated deficit irrigation

Rnet: Net radiation

ROI: Region of interest

SLAM: Simultaneous localization and mapping

SO_4: Sulfate

SW: Shortwave radiation

T_{air}: Air temperature

T_C: Canopy temperature

Twet

Tdry

T_{leaf}: Leaf temperature

UAV: Unmanned aerial vehicle

Ul: Upper limit

V: Volt

VPD: Vapour pressure deficit

WT: Wild type

WUE: Water use efficiency

ΔT (Tair-Tleaf) :Temperature difference between temperature of the air and leaf

ε: Emissivity

ψ_{stem} = Stem water potential

ψ_{leaf} = Leaf water potential

ψ_{MD}: Midday water potential

ψ_{PD}: Pre-dawn water potential

Ψ_W: Water potential

1. General introduction and aims

Viticulture is largely affected by climate conditions. In Southern Europe, precipitations tend to decrease and day and night temperatures tend to increase (Fraga et al., 2012). In addition more extreme climate conditions will tend to be more frequent in the future, with more persistent and severe heat waves, drought spells and more heavy precipitation events (IPCC, 2014; Lavrnić et al., 2017).

The viticulture sector must adapt and find solutions to the new and future situations. These can involve short- and long-term solutions (Costa et al., 2016). Improved crop, soil management and crop monitoring are crucial on the short term. In turn, grapevine phenotyping/characterization and selection are essential for future medium to long term solutions. Therefore, it is important to understand how grapevine varieties respond to stress, in particular to water and heat stress, and how they behave in response to changes and variations in air and soil temperatures and the related heat fluxes, in order to better develop breeding selection and management strategies for extreme climate adaptation (Costa et al., 2012; 2019). Plant phenotyping consists in the quantitative assessment of plant traits, including agronomic, morphological, eco-physiological and molecular traits, and it is a critical aspect towards more efficient and effective crop management and plant selections (Costa et al., 2019; Fiorani & Schurr, 2013; Milella et al., 2019). Currently, certain plant phenotyping measurements are done manually and are highly time-consuming (e.g. growth, leaf gas exchange) which involves human operators making measurements in the field, based on visual estimates or using hand-held devices (Milella et al., 2019).

Modern plant phenotyping and precision viticulture are based on sensor technology and imaging. In fact, remote and proximal detection sensors have become alternative tools to characterize plants and crop traits and monitor crop stress (e.g. water status, health) (Costa et al., 2019). Modern phenotyping and precision viticulture seek to exploit the use of remote sensing tools to describe vines traits in lab and field conditions, as well as to identify vineyard spatial variability with high resolution to support management decisions. In addition, imaging approaches permit physiological studies and/or stress monitoring to be carried at different levels (from an individual leaf, to an entire plant, field or region) (Costa et al., 2019; Sagan et al., 2019). Moreover, remote sensing approaches can also help to carry out large-scale characterization and selection of genotypes more resistant to abiotic stress. At the same time, a better monitoring will contribute to improved vineyard management and to more sustainable production (Costa et al., 2012; Kicherer et al., 2015; Matese & Di Gennaro, 2015).

The use of thermography as predictive monitoring tool in plant science and agriculture is not recent (Costa et al., 2013; Jones, 2004). However, the use of this technique is still limited in the agricultural sector which can be partially due to errors derived from variability in climate parameters (wind, radiation, precipitation), or to limitations due to the price of the equipment, or even to the unfriendly character of the instruments and/or complex image/data analysis and processing in real time that it is required (Costa et al., 2013). Thermal sensing has been shown to be a good tool to estimate plant water status in viticulture (Fuentes et al., 2012; Grant et al., 2007; Jones, 2002; Pou et al., 2014). In addition, the use of thermography has been extended not only to fixed and hand-held measurements but also to movable platforms, which permit to retrieve images along the vineyards row, namely by using tractors, UAVS or robots (Costa et al., 2013; Lopes et al., 2016; Zarco-Tejada et al., 2012).

The viticulture sector is facing an increasing lack of labour for vineyard operations, which makes it essential to find semi or total mechanized or robotized solutions for vineyard operations. This is the case of harvesting or pruning, but also other monitoring operations related to stress assessment, monitoring berry maturation, control drift of pesticide applications and yield prediction (Lopes et al., 2016). On the other hand, the use of robots and image-based solutions can be very important for grapevine phenotyping and selection purposes and field crop monitoring (Costa et al., 2019; INTERPHENO, 2019). There are still some limitations to be solved when using thermography and robots in agriculture and viticulture (Matese & Di Gennaro, 2015), namely related to image analysis and processing (e.g. image quality and further image processing and analysis, that are a very important part of the process (Matese & Di Gennaro, 2015). The present work provides an up-to-date review of the usefulness of current imaging technologies, focusing on thermography, and on its pros and cons, existing limitations, and future prospects with regards viticulture.

2. Literature review

2.1 Climate change and Mediterranean viticulture

The Mediterranean climate is constantly changing due to rising temperatures and extreme climate events intensity. The main cause is the increasing concentration of greenhouse gases in the atmosphere. CO_2 seems to be the gas with the biggest impact on the atmosphere, from 1750 to 2010 the carbon dioxide emissions were equal to 2040 + 310 $GtCO_2$ (IPCC, 2014). Greenhouse gases and their considerable concentration played a fundamental role in the increase of earth surface temperature, but also in the atmosphere and oceans of 0.85 [0.65-1.06] °C according to data considered for the period 1880-2012. (IPCC, 2014) In the most famous European wine regions as Italy, France, Germany, Portugal and Spain recent studies have already shown a shortening of the growing season and earlier phenological stages (Fraga et al., 2012).

Jones et al. (2005) found for 27 of the most important wine world regions that average temperatures increase of 1.3°C in the last 50 years but not in uniform way. According to the same author, the greatest increase in temperature was observed in the Iberian Peninsula, Southern France and California with warming average of 2.5°C (Jones, 2007). Growth and development of grapevine are influenced by climatic variability, they require temperatures suitable for the growth stage, water availability and solar radiation, which will influence the yield and wine quality (Magalhães, 2008; Makra et al., 2009). Nowadays, Mediterranean viticulture is more exposed to extreme climate events (heat waves, rainfall) but the most negative issue is the increase of the frequency of those events which may cause several problems in grapevine longevity, yield and berry quality (Costa et al., 2016).

According to the South Australian Regional Office of the Bureau of Meteorology (Hayman et al., 2012), an heat wave occurs when maximum daily temperature is above 35°C for 5 consecutive days or 40°C for 3 consecutive days. The damage that heatwaves can cause depends on the timing and the duration of the heat conditions and on the phenological stage of the vines (Hayman et al., 2012). For example, flowers are very susceptible to heat events which can affect the fruit set. In the berries they may cause a loss of yield and quality. The risk of sunburn is higher and dark berries can reach too high temperatures influencing quality and berry composition, as inhibits the synthesis of certain compounds such as anthocyanins or polyphenols, when the berry temperature is > 35°C (Costa et al., 2016; Hayman et al., 2012). In white berry varieties, high temperatures can affect the acids synthesis.

Soil temperature is another important factor of vine and berry growth, and too high soil temperatures could be negative for the canopy photosynthesis and can impact the root activity (Hayman et al., 2012).

2.2 Mediterranean viticulture and irrigation

Climate change, drought and heat stress associated with warmer conditions and the reduction of rainfall are major problems faced by Mediterranean viticulture. According to Giorgi & Lionello, (2008) Mediterranean region will be one of the most affected by climate change, and it is expected a general warming especially for summer season (+4-5°C in average Tair) and a reduction of rainfall about 25-30%, most in the southern part of the Mediterranean. In this context irrigation but also water savings will be the major goals of modern viticulture. Stressed plants show changes in physiological, biophysical and genetic mechanisms. (Simonneau et al., 2017)

The goal of precision viticulture is to manage water and heat stress with a specific irrigation to minimize climate risks, save water and berry quality. In the last 30 years different irrigation systems have been implemented, in particular, deficit irrigation strategies (Hayman et al., 2012; Medrano et al., 2015). These ones, such as regulated deficit irrigation (RDI), partial rootzone drying (PRD) and sustained deficit irrigation (DI), are used to control vegetative growth, fruit composition and optimize the water use efficiency (WUE) (Chaves et al., 2007; Lopes et al., 2011; Medrano et al., 2015). These strategies can save water but do require a more precise use of irrigation water and scheduling, which depend on more detailed monitoring of soil and plant water status in the vineyard and on a more detailed information on vineyard soil heterogeneity.

2.3 Grapevine stress physiology: short- and long-term responses to drought

Viticulture is generally located in dry areas. Several tools and methods are available to control the water deficit and to maintain a fair balance between quality and production. However, there may be numerous problems due to deficiency of watering.

As mentioned in the previous paragraph, the vine can develop short- and long-term symptoms in response given by water stress (Simonneau et al., 2017), and precise irrigation depends on more detailed information on vineyards condition and variability. To this extent, several methodologies are available to assess plant water status.

2.3.1 Water potential

Vine water status depends on the canopy size, evaporative demand and root system (Choné et al., 2001). The content of water in the vine affects the quality of the final products, a moderate water stress between flowering and veraison induces a smaller size of the berries with an increase of polyphenols compounds as anthocyanin and tannins. (Choné et al., 2001; Ojeda et al., 2001).

One of the primary consequences of water stress is the decrease in water potential (Ψ). This is an important parameter as it explains the movement of water from the soil to the plant to the atmosphere. Indeed, water transport in plants occurs according to a gradient of potential (from the less negative to the most negative) (Simonneau et al., 2017). Water flow inside the plants follows a gradient pressure that becomes increasingly negative from the roots up to the aerial part (Simonneau et al., 2017). During the day, and due to transpiration rate increase, water potential decreases. Evaporation and transpiration change the water status of the plants, including leaves. To better control the water supply during the growing season, the evaluation of plant water status is essential to monitor water stress in order to schedule irrigation (Simonneau et al., 2017). Pressure chamber is a tool to measure plany water status such as grapevine (Choné et al., 2001). This indicator of plant water stress may change depending on phenological stage, duration of the water stress, type of soil, type of irrigation, intensity of the water stress. In fact, it shows the combined effect of soil, plant and atmospheric conditions on the plant water status (McCutchan & Shackel, 2019; Ojeda et al., 2002). Thanks to the Scholander pressure chamber is possible to detect the Ψ of a plant using the following water stress index: dawn leaf water potential (Ψ_{dawn}), daily leaf water potential (Ψ_{leaf}) and stem water potential (Ψ_{stem}) (Choné et al., 2001). Predawn leaf water potential is measured before the sunrise when the stomata are closed and the plant has time to equilibrate its water potential with the most humid layer of the soil, so it's a detection of the recovered water during the night, in many cases is not the most used indicator of water stress. Due to the fact that the plant is in equilibrium with the most humid layer of the soil, this provide information about the soil water content near to the roots (Choné et al., 2001; Fernández, 2017; McCutchan & Shackel, 2019). By different researches is possible to see that the values of ψ_{dawn} in different cultivars as prune *(Prunus domestica)*, apple *(Malus domestica)* (McCutchan & Shackel, 2019) or grapes *(Vitis vinifera*) (Choné et al., 2001), are similar between well irrigated trees and trees grown under water limited conditions. This cause a wrong correlation between the symptoms and the values of the ψleaf. Besides the leaf water potential, ψ_{stem} has shown to be very useful as indicator of water stress, especially in almonds (Shackel et al., 1998), peach (Marsal & Girona, 1997) and vines (Choné et al., 2001). ψ_{stem} is less sensible to short-term environmental changes compared with ψlea); in peach trees, with 50% irrigation of ET, has values of ψ (stem) smaller than 100% irrigated trees. The difference between the two treatments was very little using the ψ (leaf). So ψ stem seems to be more accurate and related to soil-water conditions (Garnier & Berger, 1985; Meyer & Green, 1981). This is measured covering a leaf close to the stem with aluminium foil for at least 1 hour before measurement and normally is done between 11:00 and 15:00 so as to suppress transpiration until the leaf water potential is balanced with the adjacent tissue. Stem is an indicator of the ability of plants to move water from the soil to the atmosphere (Choné et al., 2001; Olivo et al., 2009). By the consideration of McCutchan & Shackel, (2019) Ψ_{Stem} is less variable than Ψ_{leaf} and closer to the variability of the daily evaporative demand, as VPD. In a plums farm taken in consideration by McCutchan & Shackel, (2019) the Ψ_{Stem} is able to show also small stress values where ψ_{leaf} could not. In detail, reductions of 50% in leaf and canopy water loss it's linked with reductions of 0.5-0.6 MPa in ψstem (McCutchan & Shackel, 2019). The Ψ_{Stem} is not the most accurate potential but it is the most practical one, as compared to the Ψ_{dawn} . The Ψ_{Stem} is much more used for practical reasons (less laborious, simple, fast, convenient time of the day) and is able to give satisfying results to assess grapevine water status.

2.3.2 Morphology and Growth

One of the primary and most evident responses of the plant to water stress is the modification of the growth, which goes towards a reduction in the length of the shoots and the leaf area, with the aim of reducing transpiration and therefore the loss of water (Taiz and Zeiger, 2002). The arrest of growth of the vegetative apex is a good indicator of water deficit (Wample & Smthyman, 2000). Imposition of water stress at budburst can reduce the number of shoots, their diameter and elongation resulting in a small size canopy to support fruit ripening (Wample & Smthyman, 2000; Fregoni, 2005). Also decreased individual leaf area has been observed for drier years compared to more rainy years (Costa et al., 2012). Limited vigour leads to a reduction of the transpiration area and to water tension in the xylem (Simonneau et al., 2017). Leaves are “very smart” organs, in case of drought or water limitations they tend to increase boundary layer resistance to decrease transpiration water loss and tend also to reduce the intercepted light as means to decrease the surface temperature and evaporative demand (Pellegrino et al., 2006; Simonneau et al., 2017). During fruit set stage the water stress can affect the number of flowers, in this case the water shortage can be very dangerous because can lead to an increase of the abortion and the abscission of the flowers by hormones change. It can involve repercussion on the fruit set percentage, with consequences in productivity and quality of grapes (Wample & Smthyman, 2000; Fregoni, 2005). Drought can affect berries size and the specific surface between skin and pulp, and consequently the quality of must. Berry composition is affected in terms of sugars, titratable acidity (tartaric and malic acids) and phenolic compounds (tannins, proanthocyanidins, flavonols, anthocyanins etc.) by plant water status associated with microclimate conditions of bunches and the architecture of the canopy (Carbonneau et al., 1978; Naor et al., 1997; Ojeda et al., 2002). One of the factors that influences the water status of a vine is the rootstock, which can result in the fact that the same variety may have differences in the water status during the growing season, notable after the veraison, with changes in the biochemistry of the berry, as anthocyanin biosynthesis (Deloire et al., 2004). Many studies showed the differences between rootstocks, as exposed by Deloire et al. (2004), a Carignan grafted in SO4 and 140 Ruggeri showed different resistance of the rootstock to the drought, in fact, it’s possible to classify the rootstock by its resistance to the drought.

- Very resistant: 140 Ru, 1103 P, 110 R
- Medium resistant: 41B, 420A, Rupestris du lot
- Poor resistance: K5BB, SO4, Riparia (Fregoni, 2005)

Root development is highly plastic, with typical shifts in the allocation of plants resources (carbohydrates) towards root growth at the expense of the shoots in dry conditions. This allows the plant to increase soil exploration for water uptake while reducing transpiration (Cramer et al., 2013; Sharp & Davies, 1985). Water movement in roots follows two directions, one axial and one radial. The axial direction includes the passage of water along the xylem up to the aerial part (Aroca et al., 2012), The radial movement of water from the soil solution to the xylem vessels follows three different paths, one apoplastic, one symplastic and one transmembrane. The union of the symplastic and transmembrane pathways takes the name of cell-to-cell path. Two forces regulate the absorption of water from the roots: osmotic and hydrostatic. The first is created by the active transport of solutes or biosynthesis of new osmolytes (root pressure). The second is generated by the breathable flow (Aroca et al., 2012). Normally, the vine is a species tolerant to drought, in the cases of soil water deficit its rooting apparatus develops, producing new roots in the deeper layers. This also facilitates absorption of nitrogen by roots (Bauerle et al., 2008; Keller, 2005; Mccarthy et al., 2000; Morlat & Jacquet, 2003). Plants, according to their water needs, can best manage water transport routes. Aquaporins, proteins responsible for the movement of water in the radial sense (Maurel et al., 2008), were studied by Vandeleur et al. (2009) in the cultivars of Chardonnay and Grenache comparing the expression of the two genes VvPIP1 and VvPIP2, the two PIP (phospholipase) coding for acquaporines. The first VvPIP1 gene increased during stress conditions in Chardonnay, increasing the transport of transcellular water by radial way, but not the second gene. This leads us to deduce that the roots of Chardonnay are able to cope better conditions of stress, maintaining a low water potential between soil and xylem (Alsina et al., 2007).

2.3.3 Leaf gas exchange and T_{leaf}

Normally plants under no water stress conditions leads to maintain a good regulation of stomatal closure/aperture in order to be able to apply at the metabolic process as photosynthesis or avoid heat damages (Chaves et al., 2016). Plants of *Citrullus colocynthis* grown in the desert, with air temperatures near to the survival limit, use higher rate of transpiration to cool down leaf temperature (Chaves et al., 2016). Under water deficit conditions, one of the short-term responses of plants is stomatal closure, to achieve an equilibrium between water loss, evaporative cooling and photosynthesis. This varies with the place but also on the genotypes/varieties (Chaves et al., 2010, 2016; Costa et al., 2012; Simonneau et al., 2017). During dry conditions or heat stress, stomata closed and transpiration rate decreases, resulting in higher WUE but also increasing leaf temperature (6-7 °C above air temperature) (Chaves et al. 2016). When this situation of closed stomata persists the plant may be damaged, and xylem embolism and plant death may occur (Chaves et al. 2016). Stomatal reduction and closure is linked to the abscisic acid (ABA). This phytohormone, is responsible for sending the signal from roots to the upper part of the plant inducing a turgor reduction by an osmotic flux from guard cells and, ultimately stomata closing.(Damour et al., 2010; Martorell et al., 2015). In *Arabidopsis thaliana* it was discovered that water stress induce a biosynthesis of ABA in the shoot and then a signal followed by stomatal closure (Chaves et al., 2011; 2016).

As reported by Martorell et al. (2015), variations of water potential are correlated with ABA concentration in the xylem: for the *V. vinifera* Grenache and Tempranillo in condition of no water stress, the level of ABA was below 200 g/mL. In turn, under conditions of water stress ABA concentration was higher than 300 g/mL. Under drought conditions, the evaporative demand by the atmosphere tends to increase due to the low air RH, This stimulate a response from the stoma to the VPD, that can show different mechanism to save water. In fact, depending on the cultivar, the stomata sensitivity to drought is variable and some are classified as isohydric (pessimistic) cultivars and others as anisohydric (optimistic) (Table 1). An anisohydric cultivar allows the opening of stomata with a reduction of the leaf water potential. On the contrary, the isohydric cultivar is able to close the stomata when the first signals of stress appear and keep higher leaf water potential (Damour et al., 2010; Simonneau et al., 2017; Tardieu & Simonneau, 1998).

Table 1: List of *Vitis vinifera* cultivars with a typical anisohydric or isohydric behaviour. (Chaves et al., 2010)

Cultivar	Stomatal Behaviour
Chardonnay	Anisohydric
Cabernet Sauvignon	Anisohydric
Grenache	Near-Isohidryc
Touriga Nacional	Anisohydric
Syrah	Anisohydric
Montepulciano	Anisohydric

Neverthless, a clear division between iso and anisohydric is difficult to establish due to the influence of growing conditions and as result of plant-invironnment interaction as reported by Chaves et al (2010).

Drought stress can induce stomatal closure in order to keep water inside the plant, preventing leaf water loss. However, the stomatal closure have another consequence, the warming of the leaf T of 6-8 °C and increase in WUE, that will lose many days before re-watering (Chaves et al., 2011; Pou et al., 2008). Stomatal closure and the gs are correlated to the content of ABA in the xylem, during water stress the re-watering is just correlated to hydraulic conductivity that is also lower (Pou et al., 2008).

Another metabolic pathway liable to changes due to stomata closure in case of water stress is photosynthesis that includes a complicated metabolic pathway to transport CO_2 from the atmosphere to the active site of ribulose 1-5 biphosphate carboxylase/oxygenase (Rubisco) in chloroplast (Chaves et al., 2011). The guard cells of the stomata are subject to endogenous and exogenous signals such as: Light, CO_2, VPD, hormones (ABA, auxins). Therefore, based on changes on atmospheric conditions stomata are able to open and close quickly (Chaves et al., 2011). With the control of the transpiration also the temperature of the leaf is influenced by the stomata, usually when the stomata are closed in moments of water stress to save water, the temperature of the leaves increases of 5-6°C, depending on the temperature of the air. (Chaves et al., 2011). As explained by Downton et al. (1987), in sunny conditions like in summer the assimilation of CO_2 decreases during the day under the increase in temperature. In the case of Downton et al. (1987), an increase of temperature of 10 °C leads to a decrease of about 6 μmol CO_2 m^{-2} s^{-1} absorbed. During the day, the photosynthesis faces a period of depression that coincides with midday (11:00 – 15:00); the closure of the stomata at midday is correlated to the accumulation of ABA in xylem and petioles, increasing pH in the xylem and to the decrease of the hydraulic conductance of the plant (Lovisolo et al., 2010).

Non-stomatal factors are also responsible for this decline. As reported by Lovisolo et al. (2010), gs in the afternoon is less sensitive to ABA and more sensitive to CO_2. The most important factors are feedback inhibition due to source–sink interactions, decreased mesophyll conductance to CO_2, photo inhibition and light (Lovisolo et al., 2010). Flexas et al. (2000) showed that the quantum efficiency of Photosystem1 (PSI) is lower during the afternoon at any light intensity. Air temperature also affects the photosynthetic rate. Downton et al. (1987) observed that with a temperature of 39°C, both the stomatal conductance and photosynthetic activity decrease and in the last hours of the afternoon leaves begin a photosynthetic recovery process.

2.3.4 Plant hydraulics and emboly and xylem cavitation

This phenomenon occurs mostly in dry soils with a high evaporative demand. In this case, the xylem, responsible for transporting water and solutes, is not able to exert an adequate tension force. This causes the formation of gas bubbles (caveats) inside the xylem vessels that obstruct the passage of water and cause emboli (Simonneau et al., 2017). The vessel embolism may cause several problems, if the leaf area doesn't decrease or in absence of stomatal closure this can lead to the loss of all the conducting system (Simonneau et al., 2017). The embolism leads to decrease in the water stem potential and therefore the lowering of the leaf water potential can increase the problem.

Cavitation is also influenced by genetics. Plants with small vessel size are less affected by this problem. In the case of grapevine, it has big vessel size, but this varies with the cultivar and adaptation to the dry environment (Simonneau et al., 2017). Within the same plant it is possible to find organs that are more or less susceptible (Choat et al., 2010). These authors showed that the stems, for example, are resistant to cavitation contrary to petioles. According to Zufferey et al. (2011) cavitation in petioles plays an important role in order to limit the leaf transpiration and the spread of embolism and make possible that other part of the plant as shoots and grapes could preserve their integrity in period of water stress or evapotranspiration. So this is linked to the hydraulic segmentation hypothesis where the distal organs, petioles and leaves of the plant are more sensible to cavitation and embolism events than stems, trunk and roots (Choat et al., 2005, 2010; Salleo et al., 2001; Tyree et al., 1993). The ratio between primary and secondary xylem of the organs has an important role in the sensibility to cavitation more than the diameter of vessels (Choat et al., 2005). The different cultivars can be more or less sensitive to cavitation, as shown by Chouzouri & Schultz, (2005) in trials made in *V. vinifera* cultivars of Silvaner, Airen, Grenache and Syrah under different conditions of water stress.

The most sensible to xylem embolism were Sylvaner and Airen due to the larger vessels size and the more uniform and large distribution, with the result of being more susceptible to embolism events. Plants have the capacity to restore this problem when the transpiration rate decreases during the night, which permits refilling the embolized xylem vessels in roots, shoots and leaves (Simonneau et al., 2017).

2.3.5 Osmotic adjustment

Plants which keep their physiological activity also in stress condition developed an osmotic adjustment. This permit to maintain the turgor of the cells also when water potential decrease in their vicinity. It consists in an increase of the solutes in order to create interactions between water and solutes, in this way the osmotic potential decrease and the turgor can be maintained. The osmotic potential is a component of the total hydraulic potential (Simonneau et al., 2017).

The substances implicated in the osmotic adjustment could be different, as sugar in wheat (Munns & Weir, 1981), in peaches (Escobar-Gutiérrez et al., 1998), sorghum (Jones & Turner, 1980) or amino acids in *Morus alba* cultivar. In the Mediterranean region grapevine usually grow in conditions of water stress due to the high evaporative demand and to the low water availability. In fact, grapevine is considered one of the best woody plant adapted to drought (Patakas et al., 2002).

Plants are able to maintain a cell turgor thanks to the osmotic adjustments that use different inorganic and organic compounds (Patakas et al., 2002). The increase in Ca^{++} in stressed plants was showed by Blatt & Gradmann, (1997) they are able to initiating stomatal closure where the concentration is very high and this reduce stomatal conductance, this Ca^{++} activity is still unknown. But the concentration of K^+, well-known as osmoticum ion, increase in stressed plants. On the contrary, an increase of K+ rise the stomatal conductance (Patakas et al., 2002). Also nitrate and SO_4 had an increase in stressed plant, that could be for the inhibition of reductase activity and to reduce the incorporation into amino acids (Kameli & Lösel, 1995). So, inorganic ions in contrast to organic solute seem to have a big potentiality to osmotic adjustments. During water stress the organic compound that suffer more is the starch, in fact, its concentration decrease a lot in stressed plant, as explained by Quick et al. (1992) due to the decrease in photosynthetic rate. Sugars such as glucose or fructose were shown not to be modified by drought, and presented a small decrease (Quick et al., 1992). Plants use inorganic ions because production of organic solutes is very expensive in terms of energy. Relevant quantity of carbon would be used for the osmotic adjustment instead of for growth (Patakas et al., 2002).

2.3.6 Phenology, leaf senescence and berry maturation

Water stress can cause a decrease of flowers number, in this time water deficit can be very dangerous because can increase the abortion and the abscission of the flowers by hormones changes with impact on fruit set, and further yield and berry quality. Drought can affect berries size and the specific surface between skin and pulp, and as consequence the quality of must (Zarrouk et al., 2016). Berry composition is affected in terms of sugars, titratable acidity (tartaric and malic acids) phenolic compounds (tannins; proanthocyanidols, flavonols, anthocyanins etc.) by plant water status associated with microclimate of grape bunches and the architecture of the canopy (Deloire et al., 2004). Severe water stress can cause the apex abscission; if followed by rehydration, it can cause the emission of secondary shoots, which determine competition phenomena and cause an alteration of the ripening processes (Wample & Smthyman, 2002). In this phase, excessive stress significantly worsens the quality of the product and, in the most serious cases, leads to a halt in the ripening and dehydration of the grape. In general, however, the vegetative development is more sensitive than that of the berry to water stress (Mccarthy et al., 2000).

2.4 Thermal regulation in plants and the leaf energy balance

Leaves, interact with the surrounding environment via energy – exchange processes (Costa et al., 2013) (Fig. 1). Leaf and plant temperature depend on different factors, such as meteorological conditions (time of day, clear or cloudy sky, air temperature, wind speed), soil conditions (soil type, soil water content, etc.) and leaf/canopy properties (morphology, density, height).

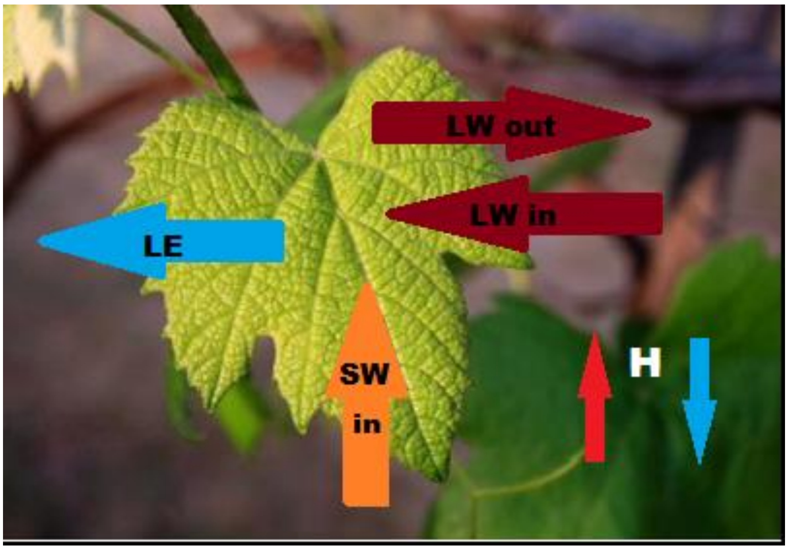


Figure 1: Energy leaf exchange for a young grapevine leaf, where LE = Latent heat flux, cooling of the leaf by transpiration, LWin = Longwave radiation, that represent the LW radiation absorbed by the leaf, LWout = Longwave radiations that are emitted by the leaf at Tleaf, SW = Shortwave radiation that represent the incoming SW radiation absorbed by the leaf, H=Sensible heat, the blue and red color means the cooling and warming respectively of the leaf relatively to the surrounding environment (Still et al., 2019).

All these parameters could influence the ratios and dimension of the sensible and latent heat fluxes (Costa et al., 2013). Sensible heat (H) is directly conditioned by leaf boundary layer conductance, with lower values increasing T_{leaf} for a given H. The latent heat flux (LE), is conditioned by plant water status, stomatal conductance. For a specific R_{net} (Eq. 1) increasing water stress can decrease stomatal conductance and LE that can be resumed in decreased leaf transpiration and higher Tleaf. In contrast, the ΔT (T_{air}-T_{leaf}) and H will increase (Still et al., 2019)

$$R_{net} = \alpha SW_{in} + \varepsilon IR\ (LW_{in}) - 2\ \varepsilon IR \sigma\ (T_{leaf})^4 \qquad \text{(Eq. 1)}$$

Incoming and out coming energy from a leaf is regulated by the so called leaf energy balance equation (Still et al., 2019), which is composed by the short wave adsorbed radiation (SW) by the leaf, the long wave radiation (LW) divided in incoming and out coming LW. Leaf absorptivity for LW is represented by εIR that correspond to its emissivity (assumed 0.96). α is the leaf absorptivity for SW radiation. The last term of the equation is the LWout that consider the Tleaf and include the Stefan-Boltzmann constant σ

($5.67 \cdot 10^{-8}$ W · m^{-2} · K^{-4}) that represents the constant of proportional of Stefan-Boltzmann law.

2.5 The importance of genotype characterization and precise crop monitoring

The species *Vitis vinifera* is characterized by a large genetic diversity which needs to be better defined in terms of phenotypic response to biotic and abiotic stress (e.g. response to drought) (Mittler, 2006; Zarrouk et al., 2016). Such large variability represents an opportunity to support breeding, in order to create or to select superior genotypes better adapted to both biotic and abiotic stresses.
Abiotic stress, such as high salinity, drought and heat are major topics of research in agriculture and viticulture, in particular the combination of their effects (Mittler, 2006).

Each grapevine variety has a different response to environmental stress and depends on the behaviour and traits of both the rootstock and variety genotypes (Mittler, 2006). Grapevine varieties can differ in their response to water stress and with regard to water use efficiency (Bota et al., 2016). The response before mentioned is linked to some parameters such as stem water potential, leaf petiole, hydraulics and also leaf stomatal regulation (Zarrouk et al., 2015). Stomatal conductance is an important trait that influences the behaviour of varieties and their correct allocation under more adverse climate change conditions. In a study carried out by Rogiers et al. (2009) Grenache variety showed during all day and night a lower stomatal conductance (gs), while Semillon variety exhibited an anisohydric behaviour with a high gs during the day, failing to rehydrate the plant prior to Dawn (Zarrouk et al., 2016). Also, Costa et al. (2012) showed that grape varieties have different strategies to dissipate heat via evaporative cooling. Some varieties keep their stomata more open during the day, as in the case of Touriga Nacional under no water supply limitations. This strategy is typical of an “optimistic” variety, which may lead to earlier leaf senescence and abscission causing problems to berry quality especially under dry and heat wave condition. Varieties with high WUE and good stomatal control may have limitations in terms of heat dissipation that may favour sunburn under warm and dry conditions (Chaves et al., 2016; Costa et al., 2012). Therefore, a better characterization of the grapevine varieties response to drought and abiotic stress conditions can be an important tool to improve grapevine adaptation to more adverse climate scenarios, and optimize vineyards performance. More studies are needed to better understand the role of aquaporins in grapevine. *V. vinifera* genome has 28 genes coding for aquaporins, proteins that allow the passage of water between biological membranes (cell-to-cell pathway) and control the water flow. They seem to be very relevant in response to biotic and abiotic stress (Fouquet, 2005; Leitão et al., 2012).

In a context of more extreme conditions and scarcer resources, improved phenotypic characterization is crucial to understand the response of grapevine to abiotic and biotic stress and to optimize grapevine selection and breeding. Moreover, other phenotypic traits may also be relevant for breeding and selection, like fruit traits (e.g., berry size and colour) (Kicherer, 2015) or bunch compactness (Kicherer et al., 2015). Phenotypic acquisition is normally done by visual way, but this kind of evaluation is limited by time, cost and subjectivity of records (Kicherer et al., 2015; Costa et al., 2019). To overcome the difficulties related to visual assessment, imaging tools based on the visible and IR thermal, chlorophyll fluorescence, multispectral imaging are being used to support monitoring and characterization of traits related to roots, shoots, canopy, leaf or even fruits.

Precision viticulture is making use of non-destructive phenotyping methods as well (García-Tejero et al., 2016; Grant et al., 2007; Stajnko et al., 2004; Matese et al., 2015). New techniques to monitor plant growth and physiological status are available based on image tools and image analysis techniques, high-throughput phenotyping (HTP) systems.

These systems increase accuracy, precision and throughput of measurements with a reduction of costs and less hand labour by means of automation, remote sensing, data integration and experimental design (Briglia et al., 2019)

2.6 Traits and methodologies used in grapevine phenotyping and crop monitoring

Conventional methods to assess plant water status of crops like grapevine are often destructive and laborious. Table 2 presents some of the most used methodologies in grapevine to water status monitoring. All are time-consuming, some are destructive and all provide no idea on the field spatial variability nor in the plant. Therefore, these approaches have limitations when considering large-scale trials and measurements and automatization.

Table 2: Non-exhaustive list of common parameters and measuring technologies to monitor water stress in plants, with focus in grapevine (Bota et al., 2016; Loveys, 1998; Cruz et al., 2013)

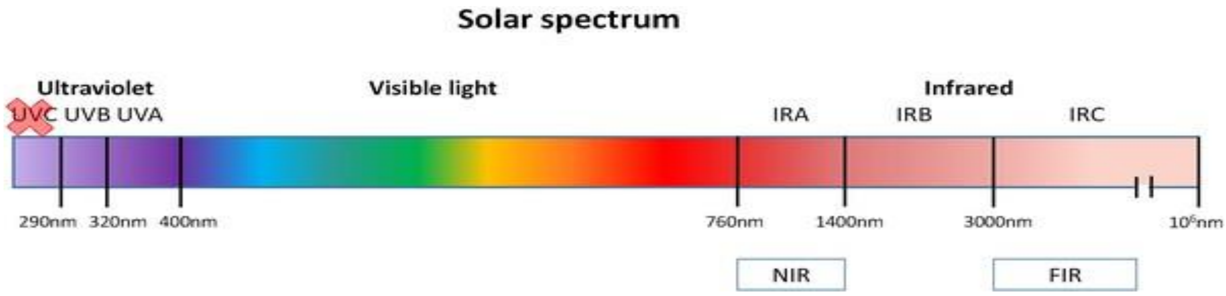
TRAITS	METHODS AND RELATED EQUIPMENT
Leaf and shoot growth (area, length, weight), leaf colour, leaf senescence	RGB imaging NDVI imaging
Water potential at pre-dawn $_{D}$), Midday (ψ_{MD})	Pressure chamber or psychrometer Easy to use, fast but disruptive method and time consuming Measurement of xylem's negative hydrostatic pressure Variation during the day due to the environment, soil water content, resistance from root to leaves. Manual and time-consuming measurements.
Leaf gas exchange	Porometer and Infrared (IR) gas analyser (IRGA) Sensitive measure of vine performance but subject to rapid change in response to ambient conditions. It requires multiples measurements in single points to have a panoramic of the variability of the canopy. Measurements can take 3-5 minutes per leaf
Leaf temperature	Infrared thermography (punctual measurements) Leaf and canopy temperature depend on the transpiration rate Affected by climate conditions variations (wind, radiation, etc)
Stem morphology (Trunk diameter)	Measure trunk diameter (dendrometry) is indirectly linked to plant water status. Maximum Daily trunk Shrinkage (MDS) was proposed as a suitable tool to support irrigation schedule as it senses soil water variation and is relates to water plant status; MDS is influenced by weather conditions (larger MDS under warm days due to high evaporative demand). However, under deficit irrigation where the degree of intensity of water stress is moderate to strong, MDS is not a good indicator because the trunk does not completely rehydrate overnight, daily growth is negative; After veraison MDS is not more representative of plant water status
Carbon isotope composition	Provides information on long term WUE and is based based on the CO2 present in the environment; The ^{13}C represents 1.1 % of carbon in the CO_2 atmospheric concentration and $1^{2}C$ is used in photosynthesis.; Diminution of leaf ψ reduces CO_2 exchanges between leaf and environment; The Ratio $^{12}C/^{13}C$ describes the condition compared to the environment.. One sampling time is able to monitor different fields. The major limitations for practical usage is the fact it is time highly consuming and expensive
Sap flow	Provides information of plant hydraulic functions dysfunction in a given environment and provides an estimation of plant transpiration; Sap flow is the it is typically measured in the xylem (sapwood portion of xylem); Some sap flow based methods are complicated (Heat – pulse, Granier and Stem Heat Balance method); Equipment required for sap flow measurements is still expensive and data interpretation is difficult.

2.7 Thermal imaging and the electromagnetic spectra

In order to understand imaging approaches including thermography we need to know the different bands of the electromagnetic spectra (Figure 2). The electromagnetic spectrum has different wavelengths. The ultraviolet (UV) region starts at 290 nm until 400 nm, the visible light from 400 nm to

760 nm, the NIR from 760 nm to 1400 nm, the infrared (IR) from 760 nm to 1,000,000 nm. Sun light that reaches the earth consists of 50% of visible light wavelength and 42% from IR, and the other part from UV. The near IR falls about 760 nm and 1400 nm. IR is not visible by the human eye, but it is possible to detect it as heat (Costa et al, 2010)

Figure 2: The electromagnetic spectrum showing the ultraviolet (100-400 nm), visible (400-760 nm) and



infrared spectra (760-10^6 nm) (Barolet et al., 2016).

IR thermal cameras operate in the range of 1000 nm to 14000 nm. The most used wavelengths for thermal imaging are 3000–5000 nm(3-5 μm) or 7000–14000 nm (7.14 μm) (Costa et al, 2010).

Another important aspect to consider when talking about IR thermal radiation is emissivity (ε) which indicate the amount of the energy that radiates from a target at a specific wave length as a fraction of radiation emitted by a blackbody (Jones and Vaughan, 2010). A blackbody is able to absorb the total emitted radiation that hits it and doesn't reflect anything, so it appears black. The emissivity for a blackbody is 1, but in the real-world objects are grey, it means that the emissivity is less than 1 (Costa et al, 2010). Therefore, in practice we use values of about 0.96 for plants. The radiant energy of a body is determined by two major components: 1) the absolute temperature of the body and 2) its emissivity of the object (Eq. 2). These two elements are represented in the Stefan Boltzmann law, where the total energy radiated by a blackbody per surface area in unit time is directly proportional to the 4^{th} power of its temperature (Costa et al, 2010). So, and according to the Stephan Boltzman law, when the emitted radiation and the emissivity of a body are known, is possible to determine the surface temperature of the object.

$$W = \varepsilon * B * T^4 \qquad \text{(Eq. 2)}$$

W = Spectral exiting radiation (W cm^{-2})

ε = Emissivity

B = Stefan Boltzmann constant ($5.67 \cdot 10^{-8}$ W · m^{-2} · K^{-4})

T = Temperature (K)

2.7.1 Indices based on IR radiation

Several stress indices are based on IR radiation. One of the most common is the reflectance index the Normalised Difference Vegetation Index (NDVI) (Eq. 3) (Jones, 2004). Images are created by transforming each multi-waveband image pixel according to the relation:

$$\text{NDVI} = \frac{(\text{near infrared}) - (\text{red})}{(near\ infrared) + (red)} \qquad \text{(Eq. 3)}$$

where ‘near IR’ and ‘red’ are respectively the reflectance in each band (Hall et al., 2002). Green vegetation has a high reflectance in the NIR. The values of this index can go from -1 to +1, High values of NDVI can indicate a complete vegetation cover. The advantages of this ratio are that the light reflected from a target will not influence the calculation (Hall et al., 2002).

Regarding the indices based on thermal IR radiation (thermal indices), they have been developed to optimize the use of thermal data and to reduce the influence of environmental fluctuations in the canopy temperature measurements (Costa et al., 2013; Garcia-Tejero et al. 2016; Gutierrez et al., 2017). One of the most used is he Crop Water Stress Index (CWSI) (Eq. 4).. A non-transpiring crop is insensitive to vapour pressure deficit and the difference between Tc and Tair can be estimated if wind speed and net solar radiation are known. With this consideration, Jackson (1981) developed a CWSI:

$$\text{CWSI} = \frac{((\text{Tcanopy}-\text{Tair})-(\text{Tcanopy}-\text{Tair})\text{nwsb}}{(Tcanopy-Tair)ul-(Tcanopy-Tair)nwsb} \qquad \text{(Eq. 4)}$$

where Tcanopy – Tair is the measured difference in temperature, (Tcanopy – Tair) is the estimated difference at the same VPD under non-limiting soil water conditions (non-water-stressed baseline), and (Tcanopy – Tair) is the non-transpiring upper limit (measured if wind speed and net solar radiation are known). Under clear sky conditions this index permit to establish a relation between crops temperature with maximum and minimum values possible below similar climate conditions. Higher is the CWSI, more stressed is the crop (Costa et al., 2013). These baselines represent the lower temperature limit that a particular crop would attain if it were transpiring at its full potential, which provides a simple method to normalize thermal images, both for incoming solar radiation (irradiance) and for measurement error within the sensor itself (Loseke, 2018).

Another important thermal index is based on the equation developed by an arrangement of Leaf energy balance. The Linear thermal index, also called the Stomatal conductance index (IG), was firstly reported by Jones in 1999.

$$\text{IG} = (\text{Tdry} - \text{Tcanopy})\ (\text{Tcanopy} - \text{Twet}) \qquad \text{(Eq. 5)}$$

IG index (Eq. 5) use the same terms of CWSI, but gives low values in stressed crops and higher values with increasing water vapour (Costa et al., 2013). Another thermal index consists in the difference between the canopy and air temperature ΔT. . If Tcanopy (Tc) is lower than Tair, then plants are assumed to be well watered. If Tc is higher than Tair, then plants are assumed to be under drought stressed (Costa et al., 2013).

$$\Delta T = \text{Tcanopy-Tair} = \text{TC}-\text{Tair} \qquad \text{(Eq. 6)}$$

The difference between Tc and Tair (Eq. 6) depends on meteorological conditions as vapour pressure, rnet, wind. Under non-limiting soil water conditions, a crop transpires at a potential rate. Under non-limiting conditions, there is a linear relation between Tc – Tair and the air VPD. This linear relationship was called the non-water stressed based line (Costa et al., 2013; Jackson, 1981) and means.that for a given VPD the difference between Tc and Ta gives the minimum possible value. On the other hand, the ΔT for a non-transpiring crop is insensitive to VPD; this is considered as "upper limit" that, as reported before, is possible to measure just when wind speed and radiation are known (Costa et al., 2013).

2.8 Remote sensing for phenotyping and crop monitoring

The increasing demand for non-destructive, fast and easy to manage technologies led to develop powerful tools in precision viticulture to provide a general view of grapevine shape, size, vigour and water conditions over entire vineyards in order to improve grape quality and yield (Hall et al., 2002) (Table 3). Remote sensing of crops based on measurements of the total amount of reflected and emitted radiation by the canopy at different spectral wavelengths (e.g. ultraviolet, visible, infrared (IR), and microwave) canopy reflectance depend by leaf area index (LAI) and leaf biochemical properties, as well as leaf optics (Jones and Vaughan, 2010).

Table 3: List of methodologies and respective plant/crop phenotyping traits (Großkinsky et al., 2015; Jones & Grant, 2016; Metzner et al., 2015; Szigeti, 2008

IMAGING METHODS	WAVELENGTH (nm)	TRAITS	PLANT ORGANS	PROS & CONS
RGB	564-580 red 534-545 green 420-440 blue	Growth Senescence Biotic and abiotic stress Plant morphology Colour Compactness	Roots Leaves Clusters Shoots	Low cost Illumination Exposure. Limited output on physiology. 2D.
Thermal IR	3000-5000 nm 7000-14000 nm	Stomatal behaviour Stress	Canopy Leaf Berries Bunches	Illumination Wind Temperature Plant structure. RH
Hyperspectra l	Full spectrum	Chlorophyll content Carotenoids content Xanthophylls Epoxidation (PRI) Choloris/necrosis	Leaf Canopy Berries	Difficult analysis. Plant growth and illumination influence analysis. Non-exhaustive info on biochemistry tissue
Fluorescence	440-460 nm 520-530 nm	Phenolic content biotic and abiotic stress photosynthesis measure.	Leaf and berries	Complex to image full and deep canopies necessitate for illumination difficult implement in dark conditions.
Laser, stereo (LIDAR)	180-400 nm	Plant biomass Plant structure.	Leaf area Leaf angle Leaf composition	No exhaustive info about plant physiology. 3D images

2.9 Aerial and terrestrial platforms

Both the academy and the industry keep studying new technologies to achieve faster and more robust field measurements at preferentially low or affordable costs (Costa et al., 2019). On-the-go sensing tools are also now becoming important for precision viticulture; combining sensor with GPS-equipped vehicles is one of the new challenges for the future (Gutiérrez, et al., 2018). Imaging is a faster, non-destructive method that can provide information on spatial variability. This is especially relevant to study physiological processes and traits in plants (Costa et al., 2013). Imaging can be carried out in multiple ways at multiple levels of detail. The most common involves the traditional manual operation of the equipment and image acquisition at a ground level, whereas other involves the use of mobile platforms (terrestrial or aerial) that permit e.g. on-the-go image acquisition with vehicles modified by humans or UAV or autonomous vehicles (Gago et al., 2015;Gutiérrez, et al., 2018).

2.9.1 Aerial platforms

Precision viticulture can also involve the use of aerial platforms to estimate relevant parameters during the growing season for crop classification, mapping–crop forecasting, yield predictions, crop status and condition, weed detection, disease detection, nutrient deficiency and photosynthetic pigment content (Berni et al., 2009). UAV (Unnamed aerial vehicle) could be differentiate by size, weight, scope: for example, there are UAV used for endurance or aerodynamics or just for unprofessional uses. Table 4 shows UAV classification according to size and operating characteristics of equipment. To understand how these platforms work is better to speak about Unnamed aerial Systems (UAS) because these systems are composed no only by the aerial vehicle but also there is a Ground control station and a communication data link (Colomina & Molina, 2014)

Table 4, UAV classification according to the size of the equipment and its operating characteristics (U.S. Army, 2010)

Category	Size	Weight (kg)	Altitude (m)	Airspeed (km/h)
Group 1	Small	0-9	<365	<185
Group 2	Medium	10-25.	<1066	<463
Group 3	Large	<600	<5486	<463
Group 4	Larger	>600	<5486	Any airspeed
Group 5	Largest	>600	>5486	Any airspeed

UAV (Figure 3) have been used to define vineyard spatial variability and to obtain a vineyard map thanks to the implement of NDVI index that make possible to classify regions by vigour, yield and vine water status (Baluja et al., 2012). In the last decade the use of airborne sensing tools is increasing because of the higher resolution imagery (spectral and spatial resolution), compared with satellite platforms (Matese & Di Gennaro, 2015). These platforms can be driven by remote control, pilots or autonomously thanks to GPS implement. These platforms have a very high spatial resolution (1-2m/pixel and corresponding image footprints of the order of 100 ha (Hall et al., 2002). In addition, these are equipped with sensors that allows the implementation of different operations. Besides, in the last years a regulation of UAV flights is requested by the stakeholders in order to use this technologies in all the application fields (Matese & Di Gennaro, 2015). Moreover, UAVs are becoming more interesting for some technical reasons as: cost, with some hundred euro is possible to buy a small UAV, they are enable to buy an automated flight planning and image reconstruction and is possible to use it when is required. On the other hand, the battery could be a problem, due to the duration.

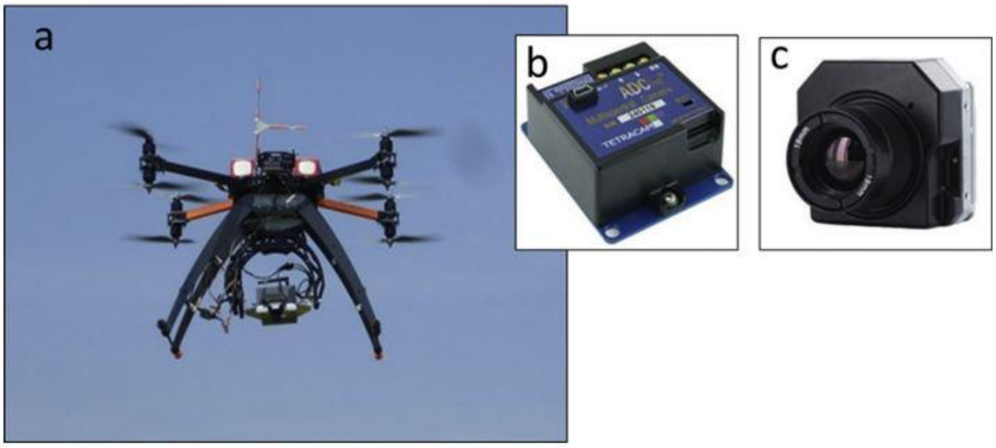


Figure 3: UAV platform for data acquisition, **A)** Complete platform composed by Unmanned aerial vehicle, multispectral camera and thermal camera **B)** multispectral camera and **C)** thermal camera (Santesteban et al., 2017).

In terms of field sensing, the difference existing between a tractor, a quad or a robot is on image resolution. Indeed, a UAV can provide a spatial resolution of 1 m, which is not able to distinguish a leaf. On the contrary, in-field sensing is able to provide a spatial resolution of 1 cm, that can distinguish a leaf and in the study of grapevine traits normally is required a spatial resolution of at least 1 m in order to provide good information and avoid the interference by the soil back-ground (Jones and Grant, 2016). UAV are able to transport different tools that could be connected to the aerial vehicle, a wide range of camera (RGB, Thermal, hyper spectral, multispectral), many progresses have been done in this field. FLIR, develop a small and low-weight thermal camera that at the beginning was used for military scope and then for fire monitoring in forest. Nowadays we may find more applications in precision agriculture (Colomina & Molina, 2014). A major difference between airborne sensing and in field (ground based) sensing is data collection. Satellite or airborne operate with a "Push-broom" mode, which means that the sensors scan a single line of pixels at each time point and thanks to the moving of the platform in the ground field a complete image (crop map) is generated (Jones & Grant, 2016). Another difference is about the width of the swath and the homogeneity of view angle, wide-angle sensors are required to view a wide swath. Table 5 shows a list of satellite platform used in the past.

Table 5. Non-exhaustive list of satellite platforms used in the last 25 years divided by Satellite, Spatial resolution, frequency to return (days), suitability for precision agriculture. P = purple, G = green, B = blue, R = red, NIR = Near-infrared, MIR = mid to infrared, TIR = thermal infrared. L = low suitability class, M= medium suitability class, H = High suitability class (Mulla, 2013).

Satellite	Spatial resolution	Frequency return	Suitable for PA
Landsat 1 (1972)	G,R, IR (56 x 79 m)	18	L
Landsat 5 (1984)	B,G,R, NIR, MIR, TIR (30m)	16	M
Spot 1 (1986)	G,R,NIR (20 m)	2 - 6.	M
LiDar (1995)	VIS (Vertical RMSE 10 cm)	N/A	H
RadarSat (1995)	C-banda radar (30 m)	1 - 6.	M
IKONOS (1999)	Panchromatic B,G,R, NIR (1-4 m)	3	H
QuickBird (1999)	Panchromatic B,G,R, NIR (0.61 - 2.4 m)	1 - 4.	H
RapidEye (2008)	B,G,R, red edge, NIR (6.5 m)	5.5	H
GeoEye-1 (2008)	Panchromatic B,G,R, NIR1, NIR2 (1.6 m)	2.8	H
WorldWiev-2 (2009)	P,B,G,Y,R, red edge, NIR (0.5 m)	1.1	H
Landsat 8 (2013)	Visible, NIR, SWIR (100 m) Thermal (30 m) Panchromatic (15 m)	16	H

Normally, field sensors uses a view in the crop or low view angle, while airborne or satellites systems use frequently a nadir view (Jones & Grant, 2016). In grapevine, such type of platforms has been used to mainly monitor vine water status. Santesteban et al (2017) used an UAV coupled with a thermal camera to evaluate plant water status and their variation during the season in a vineyard.

Remote sensing involves different tools to manage crop/plant productions and status, aerial remote sensing detect and record sunlight reflected from the surface of objects (Hall et al., 2002). The utility of a sensor is based on 3 parameters: Spatial resolution, revisit frequency or frequency return and radiometric resolution. Spatial resolution is a measure of the smallest object detectable by the sensor on the ground (Hall et al., 2002). The distance from the ground and the number of available pixels in the sensor, determine the pixel-size on the ground and the overall image footprint (Hall et al., 2002). The spectral resolution is the number of wavebands of data that can be simultaneously recorded at each pixel (Hall et al., 2002). As is possible to see in table 5, each satellite has his own spatial, spectral and temporal resolution. A fact that all sensors have in common is that plants do not reflect light on red or blue wavelengths but they adsorb incident energy in these wavebands in order to use it for photosynthesis (Hall et al., 2002). This reflected energy is important to leaf cell structure and is influenced by water status (Hall et al., 2002; Tanda & Chiarabini, 2019). Frequency return or temporal resolution is the resolution of a measurement with respect to the time (Hall et al., 2002).

During the last 30 years many satellites were improved and used for agricultural scopes. One of the first implementation of satellites for agriculture was used by US with Landsat 1, in 1973, to differentiate Midwest USA landscape in maize or soybeans with an accuracy of 83%. In 1986, France launched his satellite, called SPOT1, with the possibility to collect 20 m images with a return frequency in 6 days in the IR, NIR, green, blue and red wavebands (Mulla, 2013). As it is possible to see in Tab. 5, the most recent satellites are RapidEye, GeoEye and WorldView. RapidEye is the first satellite able to collect images in the spectrum region of 690 - 730 nm that is the chlorophyll sensitive spectrum region (Mulla, 2013). GeoEye was launched in 2008 in Herdon, USA, this is very similar to RapidEye with a spatial resolution of 40x60 cm in the blue, green, red, IR and NIR and a revisit frequency of 3 days. GeoEye is used to provide images for Google Earth or Maps, a revolution for every person in this world (Mulla, 2013). Images from RapidEye in viticulture are used mostly to zoning coupled with vegetation index as NDVI. Hoff et al., (2017) used RapidEye for zoning landscape and to differentiate Brazilian vineyards by NDVI, in order to give the producer a tool that can help him in his decisions. Also Santangelo et al., (2013) used RapidEye to correlate NDVI images to production parameters as anthocyanin and sugar in different phonological stages in Nero d'Avola, autochthonous grape variety in Sicily. WorldView 2 has been launched by DigitalGlobe in 2009, this one collects images in the same bands of the last two with the difference that collects image at 50 cm resolution and just 1 day of revisit cycle (Mulla, 2013). From Landsat to this new and last satellites, science and people have made considerable progress. Imaging resolution systems has been improved from 80 m to 40 cm, and are able to collects images in important wavebands, as for example RapidEye. From 1983 to date the number of spectral bands has been improved from 4 to 8 or more with Worldview and the return visit frequency pass from 18 days to 1 (Mulla, 2013). This development in satellites imagery has been a warning for precision agriculture because with the use of this data the efficiency and the precision of agricultural practices increased. Dependently on the agricultural practices, the spatial and spectral resolution needs can be different, it depends on: crop management objectives, capacity of farm equipment to vary farm inputs, and farm unit area (Mulla, 2013). Many authors used IKONOS images (Johnson et al., 2001; 2003), this satellite was launched in California in 1999. Multispectral and panchromatic sensors are able to differentiate objects less than a square meter from the ground (Mulla, 2013). IKONOS satellite images, it's used with the purpose to monitor vineyards canopies with the use of NDVI index and its correlation with vegetation index as LAI (Johnson et al., 2001). It's also used to study soil surface variability (Wassenaar et al., 2001) or to correlate the images with production data, as Brancadoro et al., (2006) did in Franciacorta (Lombardy). The use of satellites by the agricultural industries, it is a step into the future, the potentiality of satellite imagery for site-specific agriculture is not just agronomical but also economic and ecological. With the good information about the conditions of the land, using, for example vegetation indexes as NDVI, farmers can plan their expenses more precisely, they can save their money and use less tractors and machines with the use of variable rate technology (VRT). At least, satellite crop monitoring requires fewer human resources and it is more convenient and easier to control a big area, so no use of cars, tractors and less gas consumed.

2.9.2 Terrestrial platforms

Ground based platforms are also used for site-specific viticulture. The system, normally a sensor, is mounted on the tractor and the measurements on the canopy can be done during a cultural operation. Moreover, the information collected via the tractors together with GPS can be used to define a high-resolution map to use for precision management (Jones & Grant, 2016). In addition to thermal data, sensors installed in tractors can provide also information on canopy and based on NDVI index (Jones & Grant, 2016). Some digital platforms can be used namely in tractors as a proximal sensing platform, especially to detect grapevine yield and quality. Arnó et al., (2013) mounted a laser scanner (LiDAR) on a tractor to detect vegetation parameters in a vineyard. This system works in a transverse direction along the rows and is able to elaborate and generate geometric and structural parameters of plants, such as: height of the vines (H), the cross-sectional area (A), the canopy volume (V) and the tree area index (TAI). New proximal sensing technologies allows to find the most non-invasive way to collect information with a high-spatial resolution, to map and characterize vineyards' variability. Gutiérrez et al. (2018) used an on-the-go system, composed by all-terrain-vehicle (ATV) with a thermal camera mounted on it. The problem of on-the-go sensing is that during the raw gaps, wood, metal, other component of the canopy and sky frame are captured by the cameras. In this case the images are filtered and just the middle section of the image was taken for the analysis, creating a region of interest (ROI). After that, pixels with a temperature who ranged between Twet and Tdry were used to calculate the CWSI (Fernández-Novales et al., 2018; Gutiérrez et al., 2018). Also Diago et al., 2017 reported the use of an on-the-go system for NIR spectroscopy to determine vineyards' variability in terms of water status of vines by using a Mule (Kawasaki Mule 610), and concluded that NIR spectroscopy can be a valuable tool to use with on-the-go proximal sensing.

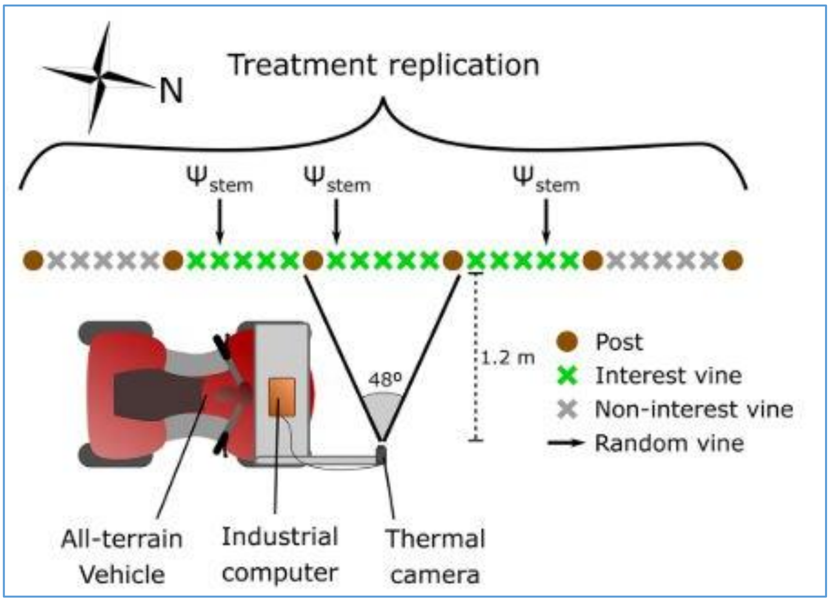


Figure 4, Thermal platform developed by Gutierrez et al. (2018) composed by ATV controlled by driver, thermal camera, industrial computer connected to the camera. The ATV was GPS equipped and the thermal camera had a vision angle of 48°.

In the last decades, robotics and agriculture are developing a strictly relationship in order to give the farmers a tool that can help them in the management of the vineyard. Many projects are now developing as VinBot, Wall-Ye, Vineguard, Vitirover , U-go robot (Longo et al., 2013) or Phoenix (Reiser et al., 2019).Not all of them are suitable for the use of themal imaging in agriculture/ viticulture but they support the work of growers in vineyards. The robots AgrobV14 and U-go Robot (Unnamed Ground Outdoor Robot) are similar in their scope; both were made for steep-slope soil conditions as the Douro region in Portugal and the Etna region in Sicily, Italy. U-go allows remote operations thanks to the use of a joypad, can be mounted different sensors webcam, attitude and heading reference system (AHRS), laser range finder (LRG), and Global navigation satellite systems in order to provide different informations. The biggest difficulty in these regions is the position accuracy; to solve this problem dos Santos et al. (2016) built an accurate approach of SLAM (Simultaneous localization and mapping) called VineSLAM in order to work in a steep-slope area with low GPS availability. In agricultural and natural conditions, sensors are exposed to many different climatic situations as wind or rain that can affect the accuracy of the localization. VineSLAM uses hybrid maps to solve this problem. The hybrid maps are composed by one topological and one feature-based. The topological map is made up of three important data: a metric featured-based map, the RFID tags associated with the row and the altitude range of the row. Thanks to these data, the robustness of the map is increased and so the robot. Test made in a truly natural context showed that Agrob V14 is able to move in steep slope vineyards with rocks and incline of 30%, and it can autonomously conduce crop monitoring as crop yield, soil/air temperature/humidity and crop water stress index (Dos Santos et al., 2016). Another ATV able to help the growers is the one developed by Reiser et al., (2019) at the Hohenheim university in Germany, Phoenix, the rotating electrical tiller weeder robot (Figure 5). In the test made by the authors the main goal was to evaluate the use of the robot with two different system control for detecting trunks: a sonar sensor and a feeler. The sonar was used to detect the trunks because it could be placed at any position on the robot. The signal could directly replace the input signal of the feeler without any additional software changes (Reiser et al., 2019). This is correlated with the distance of the sensor from the object. According to Reiser et al., (2019) the sonar treatment has a better performance than the feeler. The percentage of the tilled area between the trunks was the parameter used for the efficiency of weed control, the tilled area by the feeler was about 65%, on the contrary, the one of the sonars was the 82%.

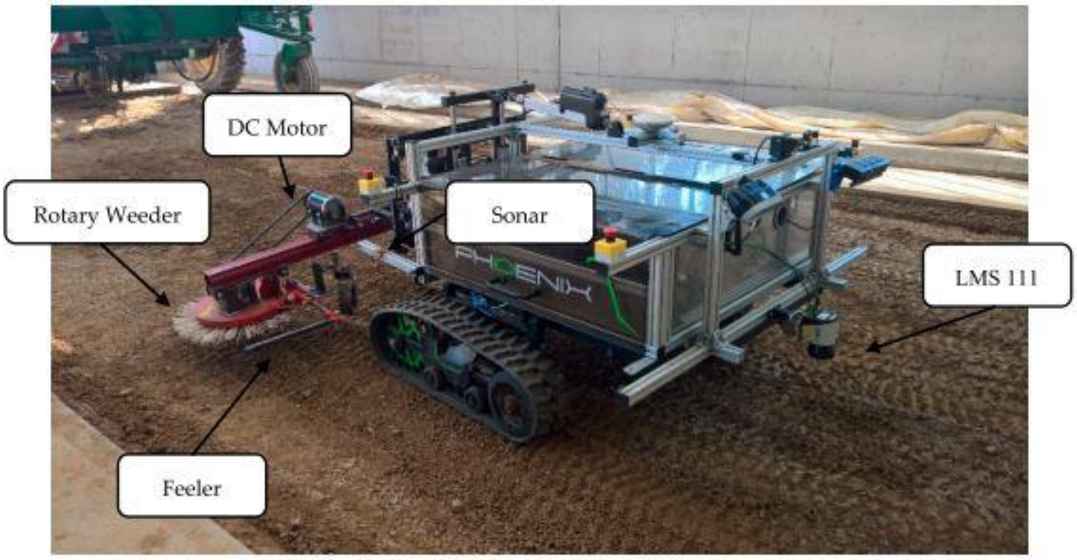


Figure 5. ATV Phoenix create for intra-row weeding control. The robot is autonomous and composed by rotary weeder fixed on a metallic bar, feeler, sonar, LMS-111 2D laser scanner used to follow vine rows and DC motor, a hydraulic motor redesigned electric (Reiser et al., 2019).

The challenge is to develop an agricultural robot equipped with non-invasive sensing technologies and sensors (RGB for machine vision, thermal infrared, and GPS) to make the robot more autonomous and robust in measurements. Many robots were developed for precision agriculture, Wall-Ye, the robot created to map the vineyard, to prune the vine and eventually harvest grapes. It's equipped with a monitoring system based on optical sensors, so, it can move autonomously in the rows in the vineyard (Matese & Di Gennaro, 2015; Shamshiri et al., 2018). The VineGuard, is another artificial intelligence machine that can move itself around the vineyard and the rows thanks to a movement system optimized for rough soils. It is able to do many operations as localization, monitoring of maturation state and to detach and take grape sample from the vine, this thanks to a robotic arm designed for harvesting but still it's in development (Matese & Di Gennaro, 2015). Other one is the Vitirover, a sustainable mower, this robot has the function to control the height of the grass in the vineyard, it is equipped with a solar system that permit to recharge. So, this is an alternative to tillage and herbicide for control grassing in the vineyard. The project ''VVINNER" (Vigilant Vineyard &INNovative Ecological Rover) wants to expand the scope of this robot, due to the coupling with a RGB camera and a NIR camera in order to be used for disease detection, monitoring the ecosystem in the vineyard and to have accurate meteorological data for yeld estimation (Keresztes et al., 2014; Matese & Di Gennaro, 2015). According to Keresztes et al., (2014) is possible to couple Vitirover with other sensors. VinBot is an example of an all-terrain autonomous mobile robot with a set of sensors capable of capturing and analysing vineyard images and 3D data by means of cloud computing applications, in order to obtain yield maps representing the spatial variability of the vineyard plots (Lopes et al., 2016). The capabilities of the VinBot can be enhanced by the incorporation of a thermal sensor that can help on water stress monitoring purposes. In Portugal, Lopes et al., (2017) used the VINBOT (Figure 6) to estimate grape yield in an experimental vineyard trained on vertical shoot position. The Vinbot permits to scan plants by a 2D laser and from a RGB camera positioned on the head of the robot to estimate canopy features and predict yield. (Lopes et al., 2017;Guzmán et al., 2016). The future will encompass the incorporation of a thermal camera to extract thermal data to support water stress monitoring.

Robotics is the new challenge of the precision viticulture and several prototypes of robots have been proposed in the last decades. A consortium formed by the University of Milan, Vitirover and Eurecat, have developed a robot called Grape, capable of put pheromones in the vineyard, thanks to the use of a robotic arm (Roure et al., 2018).

Figure 6, Representation of the VINBOT robot, the all-terrain autonomous mobile robot equipped with: RTK-DGPS antenna, Laser 2D, Wifi router, RGBD camera, Radio (Guzmán et al., 2016).

2.10 Low cost thermographic sensors

Expensive thermal image equipment discourages users to buy and use them, namely in agriculture sector. In fact, the high cost may result in that companies prefer to irrigate in a more empirical way or to make use of other methods, such as NDVI or water potential. As a consequence, development of cheaper tools and sensors opens new perspectives for the use of imaging in crop phenotyping and monitoring (INTERPHENO, 2019; Costa et al., 2020). This applies to the case of thermography.

Smartphones have become a “close friend” of humans and they can be used to support growers to make decisions for their crops together with other additional tools (Petrie et al., 2019). For example, the FLIR One camera (Flir Systems, USA) can be connected to the smartphone and it can provide analysis and results in real-time. In a study carried out by Petrie et al. (2019), this camera with a resolution of 160x120 pixels and an additional RGB camera (640 x 480 pixel) was used. The camera has a long wave infrared sensor with a range from 8 to 14 mm, a thermal sensitivity better than 0.1° C and the lens has a field of view of 46° horizontally and 35° vertically. The camera will measure over a temperature range of 20 °C to 120 °C with an accuracy of ±3 °C (of the average of the difference between the ambient and the scene temperature) (Petrie et al., 2019). This study was carried out for *V. vinifera* Cabernet Sauvignon and Chardonnay varieties and the Tc was determined by a software which is possible to download in smartphones with a common mobile operating system as iOS or Android. The images collected permitted to estimate CWSI and IG indices which have the advantage to that they do not require meteorological data input (weather station) as they are normalized data (Petrie et al., 2019).

Other companies besides FLIR Systems are also developing low-cost cameras for a wider use (professional and not professional) (Skewes et al., 2018).Other studies using smartphones were carried for other crops such as almond trees (Poirier-Pocovi et al., (2020). More recently Fuentes et al., (2019) also used such technology to evaluate smoke contaminations in grapevine. Smoke cause reduction in stomatic conductance and so the variability between gs of a non-smoked leaf and a smoked-leaf was used to detect differences in leaf temperatures. Thermal images of the canopy were acquired with a FLIR T-series (B360) thermal camera, with a resolution of 320 x 240 pixels, the camera is able to detect temperature between -20 and +1200 °C.

An algorithm was developed by the authors with a 10x10 sub-division of the images to extract canopy data as IG, Tcanopy and CWSI (Fuentes et al., 2019). Many sub-divisions were taken in account but the 10x10 was the most useful with an accuracy of 96%. This model developed by Fuentes et al., (2019) to detect smoke contaminations in canopies can be implemented in mobile tools as smartphones or tablet connecting this one with an infrared thermal camera (i.e., FLIR One®, FLIR Systems, Portland, OR, USA).

Noguera et al. 2020 developed a new low-cost device based on a thermal infrared (IR) sensor for the measurement of canopy temperature and monitoring of water status on olive tree. The performance of the developed device was compared to a commercial thermal camera in a commercially managed olive orchard, where two different irrigation treatments were established: a full irrigation treatment and a regulated deficit irrigation.

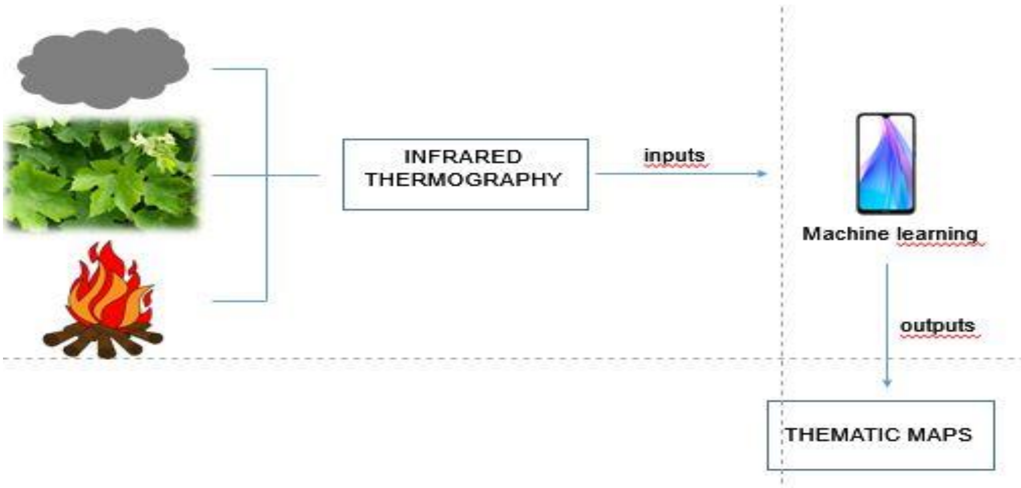


Figure 7. Diagram showing how thermography can detect smoke contamination in grapevine leaf and berries. Smoke contaminations is detected by a thermal sensor, the data are processed by a smart platform and after that a thematic map is produced (Fuentes et al., 2019).

A field evaluation was carried out, which included the validation of the acquired canopy temperature and the calculation of CWSI against two widely accepted water stress indicators, namely gs and Ψ_{Dawn}. The crop water stress index (CWSI) resulting in a coefficient of determination R2 ≥ 0.79. CWSI calculated from the IR measurements showed high correlation when compared to two standardized water stress assessment methods: Ψ_{Dawn} and gs. Although the results were promising, further work is needed to expand the experimental setup to different environmental conditions and plant water statuses. Nevertheless, the aim of this research was to develop a low-cost alternative for plant water status estimation based on thermal IR measurements.

The low-cost of the developed device, along with its ease of use (it does not need to be operated by expert personnel), labour cost savings, and high precision, paves the way for the implementation of an olive orchard water status appraisal system as an alternative to more costly current technologies, and consequently, to increased efficiency and production. This tool was not already applied on the vine, in the future could be very interesting to analyse the performance of this new low cost device on this plant. Table 6 resumes some examples of thermal cameras used in agriculture and viticulture field.

Table 6.Non-exaustive list of thermal cameras used in agriculture and viticulture field (Costa et al., 2013; 2019; Fuentes et al., 2019; Salvador Gutiérrez et al., 2018; Jones & Grant, 2016; Livingston et al., 2018; Sagan et al., 2019; Vadivambal & Jayas, 2011).

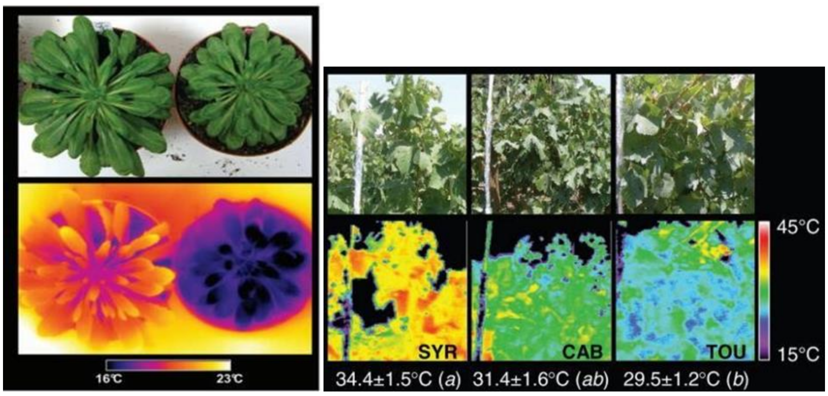
Camera model	Manufacturer	Spectral Range (µm)	Temperature range (°C)	Thermal sensivity	Thermal resolution
AGEMA 570	FLIR Systems, USA	8–12	−20°C to 500°C; −20°C to 1,500°C (with filter)	0.1°C at 30°C	320×240
AGEMA 880	FLIR Systems, USA	8−12	−20°C to 1,500°C	0.7 K at 30°C	NA
Infra-Eye 102 A	Fujitsu, Tokyo, Japan	8−14	NA	NA	NA
Inframetrics 760	Inframetrics, Massachusetts, USA	8−12	20°C to 400°C; 20°C to 1,500°C (with filter)	0.1°C at 30°C	NA
IR snapshot 525	Alpine Components,East Sussex, UK	8−12	0°C to 350°C; −50°C to 650°C	0.1°C at 30°C	120×120
Model D500	Raytheon Inc., Waltham, MA	7-14.	NA	NA	320×240
ThermaCam P25	FLIR Systems, USA	7,5-13	-40°C to 120°C; 0°C to 500°C; optional 2000°C.	0.08°C at 30°C	320×240
ThermaCam P65 HS	FLIR Systems, USA	7,5-13	-40°C to 120°C; 0°C to 500°C; optional 2000°C.	0.5 K at 30°C	320×240
ThermaCam SC500	FLIR Systems,	7,5-13	-20°C to 500°C; optional 2000°C.	0.07 K at 30°C	320×240
ThermaCam SC2000	FLIR Systems, USA	7,5-13	−40°C to 2,000°C	0.1°C at 30°C	320×240
Thermovision A40M	FLIR Systems, USA	7,5-13	−40°C to 120°C; 0°C to 500°C; optional 2000°C	0.08°C at 30°C	320×240
Varioscan 2011	Jenoptic laser, Jena, Germany	10	1,500°C (with filter)	0.1 K at 30°C	NA
Varioscan 3021 ST	Jenoptic laser, Jena, Germany	8−12	−40C to 1,200°C	0.03 K at 30°C	360×240
VIGOcam v50	Vigo Systems, Warsaw, Poland	8−14	10°C to 100°C or 0 to 350°C, optional: 1,500°C	0.08°C at 30°C	384×288
One Pro LT	Flir Systems, USA	8 -14 µm	-20°C to 60°C	NA	80 × 60
SC660	Flir Systems, USA	7-13 µm	–40°C to +1500°C	NA	640 × 480
A35	Flir Systems, USA	7.5–13 µm	-25°C - 100°C; –40°C - 550°C	NA	320 × 256
ICI 8640 P	Infrared Cameras Inc, USA	7–14 µm	20 °C - 120 °C; optional 0°C-500°C	0.02 °C at 30 °C	640 x 512
Vue Pro R 640	Flir Systems, USA	7.5–13.5 µm	-20°C to +50°C	NA	NA
B360	Flir Systems, USA	7.5 - 13µm	-20 C to + 120 C	0.05°C at 30°C	320 x 240
ThermaCAM B20	Flir Systems, USA	7.5–13 µm	-40°C to +55°C	NA	320 x 240
ThermaCAM P640	Flir Systems, USA	7–13 µm	-40°C to +500°C; optional 2000 °C	0.04°C at 30°C	640 x 840
T620	Flir Systems, USA	7.5 - 14µm	-40°C to 650°C	0.06°C at 30°C	640 × 480

2.11 The use of thermography in phenotyping and crop monitoring

2.11.1 Plant phenotyping & selection regarding stomatal behavior

Thermal imaging has been often used in genetics and mutant characterization, namely when mutations were affecting stomatal behaviour and responses to the environment. In this case, thermography has been used in large scale screenings to select and isolate different mutants and consequently signalling pathways as means to understand the genetic and physiological bases of stomatal response to the environment, leaf surface can be measured continuously non-destructively thanks to thermography (Costa et al., 2013; Merlot et al., 2002). Thermography has enabled to screen and select different stomatal mutants (Costa et al., 2013; Merlot et al., 2002) and to find different molecular stomatal regulators of transpiration in *A. thaliana* species. Different mutants with abnormal stomatal response to drought, air, CO_2, light and ozone were identified, and can be good research tools to better understand stomatal response and signalling pathways (Chaves et al., 2016).

So, in the last decade thermography was an accurate tool to differentiate different stomatal regulation behaviour and it was used to screen genotypes not only in *Arabidopsis thaliana,* but also other species such as in rice or maize (García-Tejero et al., 2017; Hirayama et al., 2006), garlic (Sánchez-Virosta et al., 2020) or in grapevine (Costa et al., 2012). In another study carried out by Costa et al. (2012) thermography was used to compare grapevine varieties (Syrah, Cabernet Sauvignon and Touriga Nacional) which showed different T_{leaf} for similar water status (similar Ψ_{pd}). Moreover, gs was not correlated with stomatal density, suggesting that these varieties had different stomatal control. More recently, thermal measurements were also used to compare the response of different grapevine genotypes to water stress, as part of a selection program of Portuguese grapevine selection.



A) **B)**

Figure 8. A) False coloured thermal images of *Arabidopsis thaliana* genotypes at two different growth stage. Images show different temperature behaviour of *A. thaliana* plants at mature stage. The Wild type (WT) plants show a typical stomatal closure under darkness. As result they show higher leaf temperature than mutant plants with open stomata under dark conditions (OST2 mutants) (**B)**, Visible and false coloured thermal images of different varieties of *V. vinifera* (cv Syrah) (SYR), Cabernet (CAB) and Touriga Nacional (TOU) (Costa et al., 2012; 2013).

2.11.2 Thermography and crop water status

Thermography, or thermal imaging, is one of the most successful techniques to assess water stress in field conditions (Costa et al., 2013; Grant et al., 2007; Jones, 2004).

Many vineyards now in the world are suffering the global warming and the lack of water. When and how much water to use for irrigation are now important decisions that the growers have to take and it will influence quality and yield of production, but also costs and input resources to use (Shellie & King, 2020). Leaf emissivity detected by thermal cameras in the infrared spectral region allows to create a maps of leaf temperature. Starting from these values is possible to estimate the CWSI, a valuable tool for irrigation-scheduling, to map an agricultural zone and understand the behaviour of the plant in front of a water deficit condition (Figure 8).

Santesteban et al., (2017) use thermal information to build a CWSI map in a vineyard located in Navarra region, Spain, where a large range of values were found (Figure 9). In this case, the values of CWSI obtained by thermography that was compared with instantaneous measurements in the field of Ψstem and gs and a good correlation between them was found (R^2>0.65). Also (Belfiore et al., 2019; Fuentes et al., 2012; Möller et al., 2007; Pou et al., 2014; Shellie & King, 2020) found higher correlations between CWSI and field measurements of Ψstem and gs.

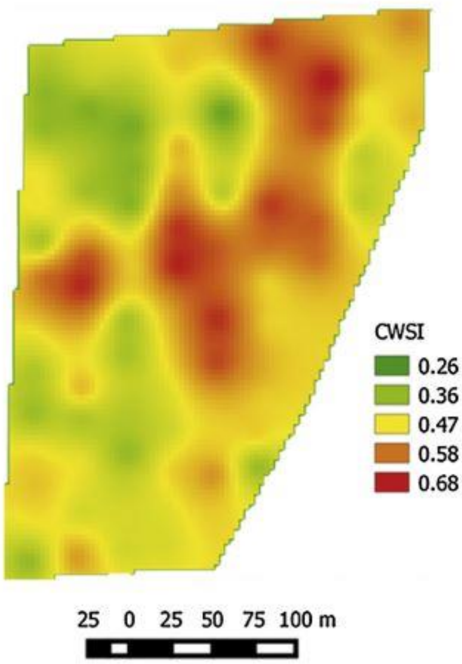


Figure 9. A CWSI map built with the use of thermal images (Santesteban et al., 2017).

Despite the great potential of thermography to assess the water status of the vine, some limits need to be considered (Costa et al., 2013): 1) sensibility to climatic factors, such as solar radiation and wind, which can influence the detection and the use of thermal data due to the changes in the stomatal conductance to water vapour (gs); 2) non-leaf material could be considered in measurements (stems, branches, soil, sky) ; 3) the heterogeneity of vine canopy compared to other crops. To minimize this effect, only the shaded side of the canopy is used to obtain thermal images (Fuentes et al., 2012).

On what concerns the reference parameters to use in the implementation of CWSI, the Twet and Tdry can be obtained by painted leaves with petroleum jelly and water or artificial leaves could be used, as exposed by Pou et al. (2014), where a platinum artificial leaf was used for the Tdry reference and a wet artificial leaf was used for Twet maintained wet by a cotton piece that adsorb water continuously from a reservoir.

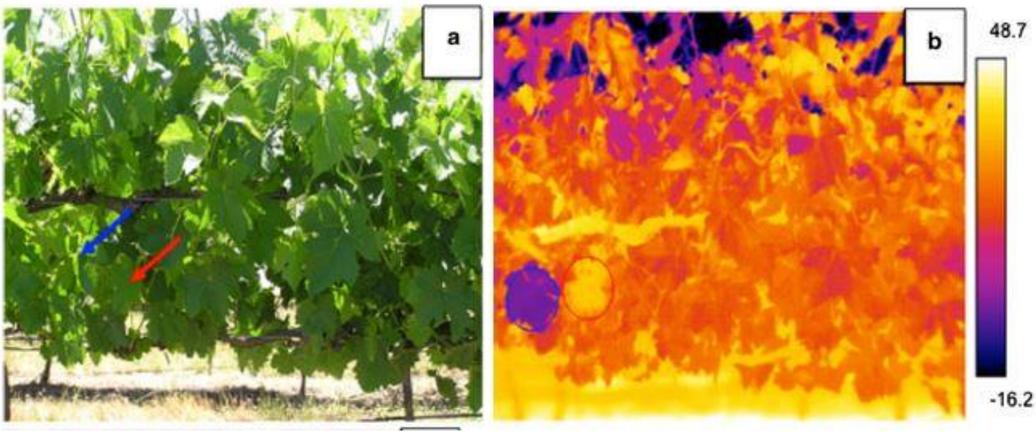


Figure 10, **a**) Example of canopy with reference leaves signed in blue (wet) and red (dry); **b**) Corresponding thermal images with reference leaves rounded (Fuentes et al., 2012).

Leaf and canopy temperature can show different values during the day depending on canopy exposure, plant water status, time of the measurements causing differences also in the CWSI. According to Pou et al., (2014) in a trial made in a vineyard with two different slopes, plants with a high-water status shows low values of temperature and, on the contrary, plants with low water status shows higher temperatures. On what concerns canopy exposition, sunlit parts of the canopy show higher values of temperature (Table 7).

Table 7, Crop Water Stress Index (CWSI canopy, CWSI leaf) and Temperature (Tcanopy and T leaf) for a vineyard in a lower and upper zone of a slope (Pou et al., 2014).

Thermal data	**Lower zone (Higher water status)**		**Upper zone (Low water status)**	
	Sunlit	**Shaded**	**Sunlit**	**Shaded**
CWSI canopy	0.40 ± 0.01	0.56 ± 0.01	0.70 ± 0.02	0.98 ± 0.01
CWSI leaf	0.62 ± 0.02	0.54 ± 0.02	0.83 ± 0.02	0.86 ± 0.02
T canopy	27.5 ± 0.2	24.5 ± 0.3	30.6 ± 0.3	29.1 ± 0.2
T leaf	30.0 ± 0.3	24.1 ± 0.2	32.9 ± 0.4	28.6 ± 0.6

For CWSI canopy, side of measurements and water status influence the values obtained. Higher values for the shaded part and low values for the sunlit oriented part. According to Möller et al., (2007) plants increase their variability on canopy temperature with crop stress and this relationship can be used to indicate water stress. In a study carried out by Pou et al., (2014) temperature of canopy and leaf were higher in the sunlit side and as expected by Pou at al., (2014), higher in the upper zone with a low water status. On what concern the side of thermal measurements, according to Pou at al., (2014) it is better to use the shaded part of the canopy because more consistent correlations were found between thermal indices as CWSI, Ig and gs. Also Jones, (2002) agrees with this statement, he used the shaded side to minimize thermal variability between grapevine canopies.

Anyway, from these results is understandable that thermal indices could be used as implementation of CWSI under low or high-water status. This relationship is more accurate at midday when maximum differences between stressed and unstressed plants occurred (Pou et al., 2014).

2.11.3 Thermography and yield prediction

Thermography has been used also in yield prediction in different types of fruits, such as: apple (Stajnko et al., 2004) and citrus (Gan et al., 2018). Gan et al., (2018) developed a system composed by: A) RGB and thermal system to register accurate images; B) algorithms able to bind registration, information fusion and detection in order to be able to have a real-time processing system; C) fusion of thermal and RGB images to get a high quality-accuracy image on citrus fruit (Figure 11). A specific image analysis algorithm was used to detect fruits in thermal image, this algorithm is based on the difference of temperature between the fruits and the rest of the canopy, because normally this parts are warmer due to the sun exposure (Gan et al., 2018). According to the same authors, morning and late afternoon are the best times for thermal images, the difference between canopy and fruit temperature was about 0.5 – 2.0° C and in the afternoon the difference was larger, because sunlight and atmosphere had crucial impact on leaves and fruit temperature. This model uses a circle detection method to find the fruit in the thermal image, when the model found the circle it uses the diameter and the pixel intensity as average fruit diameter and pixel intensity, this information will be used in the fusion with colour images. In the case that the circle was not detect, a temperature control is able to find the fruit comparing the temperature, keeping the areas with lower temperature, because fruits have lower temperature. After that, the images are used for information fusion with RGB images and the fruit area is calculated on the base of the CTCP (Color-Thermal combined probability) if the area of the circle is higher than 0.5 the fruit is confirmed (Gan et al., 2018). So, this system for fruit detection could be a possible future development for precision viticulture. Its limitations are the difficulty to register good quality images during the day in natural conditions and the information fusion when the quality of the images is low. The advantages of this new approach are that the fruit detection in thermal images is more accurate due to the best distinguish of the fruits in the canopy and because is able to go deeper in the canopy compared with colour images.

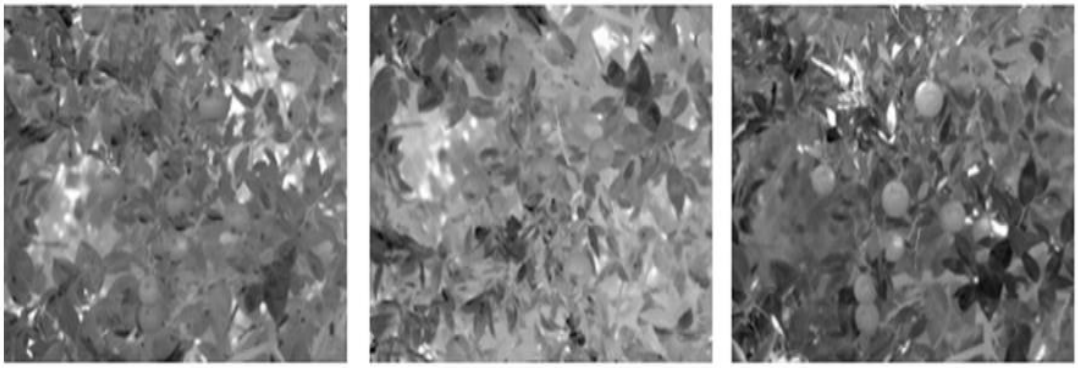


Figure 11, Thermal images of the same citrus canopy acquired at different time of the day (Gan et al., 2018).

Smith et al., (1985) used thermal differences between canopy and air temperature to study the relationship with wheat yield. This was investigated by using two irrigated wheat crops, sown in different times. Experiments were conducted in 1982 and 1983 on a red-brown soil in Australia. Measurements of canopy temperature were made around solar noon. In both years, measurements started from the time of jointing before irrigations begun. Transpiration and CO_2 assimilation rates were very close in the year but not between years. A new algorithm to estimate number of apple and diameter was implemented by Stajnko et al., (2004), a thermal camera captured images in an apple orchard during the vegetation period in 2001. More than 120 images were recorded each time and were processed using different algorithms.

In this experiment the thermal camera could not differentiate the fruits properly. Soil, RGB intensity and leaves disturb the fruit detection. To solve this problem, data from the images were transformed in a form that reduces the intensity colour variation. In this trial, a relevant correlation was found between the fruit number manually measured and the estimated number (R^2 0.83 – 0.88). Concerning fruit detection, the correlation was a bit lower (R^2 0.67 – 0.70) because the algorithm underestimates the diameter of the apple based on the detection of the longest segment. Fruit borders can show lower temperatures or are hidden by leaves, so the lower fruit diameter is detected and the lower correlation is obtained (Stajnko et al., 2004).

Bulanon et al., (2008) studied the thermal temporal variation in orange canopy as tool for fruit detection for harvesting orange (Figure 12), thermal images of orange fruit canopy were acquired during 24h cycles, fruit surface temperature, ambient temperature and RH was measured. Temperature variation of the canopy was measured using a special software for processing thermal images. Canopy and fruits were divided in 4 ROI.

Figure 12, Example of the experimental seet up to obtain thermal images of orange trees. The system is composed by a thermal camera, RGB camera and artificial light source for night image acquisition. The cameras are facing the canopy at a distance of 2 m and framing a Region of Interest (ROI) within the canopy. Source: (Bulanon et al., 2008)

The fruit temperature was higher in the morning until afternoon and it dropped from the late afternoon until morning. Regarding air temperature, Tair was higher during the morning than fruit temperature, causing a heat transfer from the ambient to the fruits. During the afternoon, fruits temperature showed higher values than air temperature with a difference between them of 1.6 °C. ROI 1 and 2 showed temperature fluctuations along the day due to the different exposure to the sun (Bulanon et al., 2008). In conclusion, according to (Ishimwe et al., 2014) the difference between fruit and canopy facilitates fruit detection from afternoon till midnight.

2.11.4 Thermography as tool to detect berry temperature

Berries like leaves are subject to stress, the set of different factors determines the temperature of the bunch, which can influence the final characteristics of the wine. Different authors confirmed that T>35°C affects negatively the synthesis of polyphenol compounds and flavours, based on light and temperature effects. However, light and temperature are very important for a complete and full maturation of bunches. In fact, these two climatic variables are responsible for the accumulation of anthocyanin, tannins, flavors, acids and sugars, all components that lead to determine the fruit quality (Haselgrove et al., 2000; Spayd et al., 2002; Stoll & Jones, 2007). In a study carried out by Stoll & Jones, (2007) the temperature of Castelão and Moscatel (*V. Vinifera*) bunches has been detected in order to evaluate the usefulness of thermal imaging in the detection of the stress and the incidence of solar radiation on berry temperature (Figure 13). Of course, this is an aspect influenced by the composition, orientation and architecture of the canopy.

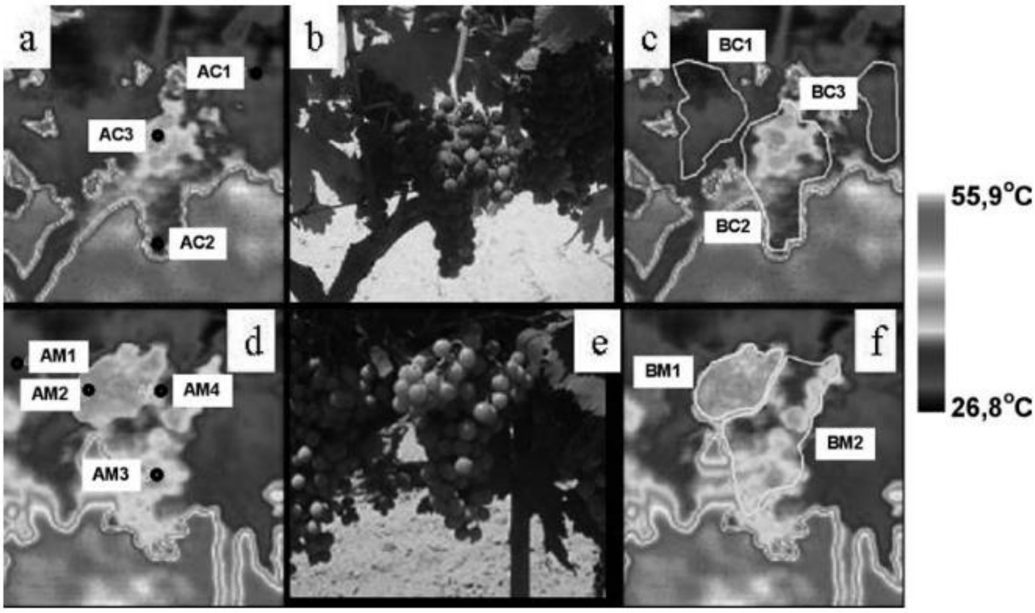


Figure 13. RGB images of bunches **(B, E),** and corresponding thermal images for *Vitis vinifera* cv Castelão **(A, C)** and cv Moscatel **(D, F).** Bunches and berries are outlined in circle and lasso in order to analyse them and exclude sky and soil (Stoll & Jones, 2007).

In the figure 14, the bunches show a temperature above 11°C from the environment for Castelão and 12°C for Moscatel, in addition, a higher temperature was founded in bunches from non-irrigated grapevines comparing to the irrigated ones. Thermography is a suitable tool for the canopy and the bunches heat stress monitoring, but also for studies about the dynamic of degradation of certain compounds affected by heat stress (Stoll & Jones, 2007).

2.11.5 Thermography to detect biotic stress

Thermography has been used to detect pathogens diseases and it has been found as a useful tool, able to predict fungal disease such as *Plasmopora viticola* (Allègre et al., 2007; Stoll et al., 2008).
Stoll et al., (2008) confirmed that it is possible to detect the disease in the leaves 3 days before can be visible to human eyes. *Plasmopora viticola*, is a oomycete fungus, that present the first symptoms in the leafs in April/May with the characteristic yellow spot (oilspot) (Figure 14) the entity of the disease depends from the climatic conditions and leafage. In condition of sporulation, it means with high rate of humidity, rain and temperature higher than 10°C is possible to see in the intercellular space of the mesophyll the hyphae that will compose the mycelium, this attack the abaxial leaf side, with the formation of sporangiophores (Belli, 2006). According to Allègre et al., (2007) different pathogens could affect transpiration rate. Grapevines affect by *P. viticola*, mantains open stomatas also under dark conditions, in consequence, transpiration deregulating occurs (Stoll et al., 2008). In another study carried out by Stoll et al., (2008) with irrigated/inoculated, non-irrigated/non-inoculated, non-irrigated/inoculated Riesling *(V. vinifera)* vine plants in Geisenheim research center. Thermography was able to show the variation of temperature in the leaf, the MTD (maximum temperature difference) is a

valid index able to differentiate an infected leaf tissue from a healthy tissue (Lindenthal et al. 2005; Oerke et al. 2006).

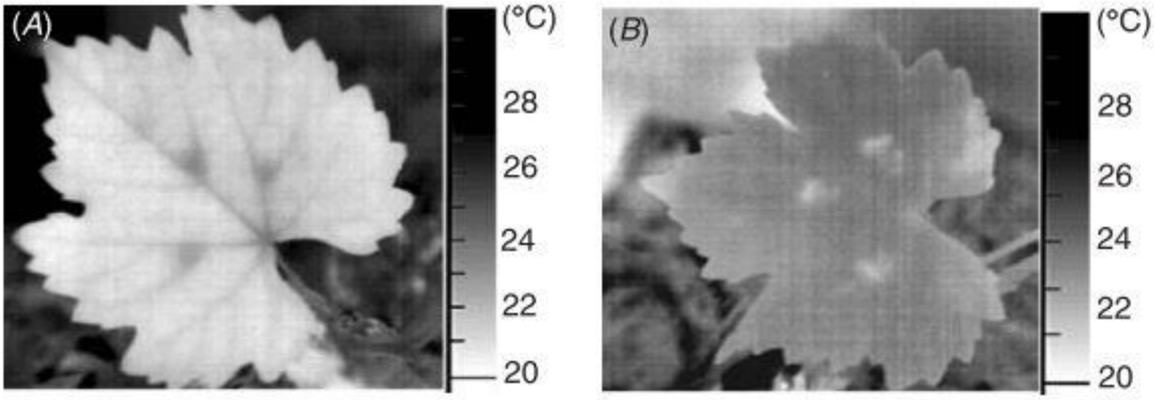


Figure 14. Thermal image (grey scale), showing the “oilspot zone” where fungus has been inoculated in three different insertions on the main vine of the leaf, the inoculation zones presents a different temperature from the rest of the leaf. In **A)** irrigated/inoculated leaf in **B)** non-irrigated/inoculated leaf (Stoll et al., 2008).

Thanks to thermography interaction between the pathogen and grapevine was detected 3 days after inoculation, after 5 days from inoculation just the 3% of the leaves showed symptoms. Just after 8 days clear symptoms were detectable on the leaves (Stoll et al., 2008).

This was clear also in the MTD detection, in fact, for inoculated plants irrigated and non-irrigated the MTD of both was higher than the controls plants showing a change in leaf temperature at the inoculation point. On day 4 and 7 after the inoculation, irrigated\inoculated plants have shown between 39.7 and 46.1% of pixels outside the threshold of ±0.2 °C compared with the control vines of 14.4 and 14.1 of pixels outside the threshold. This show us that the sensitivity of the temperature clearly indicates differences caused from the pathogen (Stoll et al., 2008).

Other examples report the use of thermography for detection of different pathogens attack as such events modify stomatal regulation and promote closure, for example with *Pseudomonas syringae* (Di Giorgio et al., 1996) Tobacco Mosaic Virus (Chaerle et al., 2001), or instead promote stomatal aperture and cause necrosis, e.g. *Puccinia striiformis* West. Stripe rust of wheat (Smith et al., 1986) and *Cercospora beticola* Sacc. (Chaerle et al., 2004)

There are also some limitations in the use of thermography for disease detection as: not clearly detection of specific stress, weather changing conditions, sensitive to leaf coverage and highly dependent on illumination (Lee et al., 2010). According to Lee et al., (2010) in wheat affected by yellow rust the detection of the specific stress can be solved with the use of other new technologies as hyperspectral imaging method for crop disease, using image analysis algorithms to discriminate the canopy from the background and after that the classification of combinations of spectral wavebands to differentiate healthy leaf tissue and yellow rust disease

2.11.6 Thermography to detect freezing damage

Normally freezing damage is studied by the use of thermocouples on parts of a plant and recording the temperature when the exothermal event occurs. This method has a big limitation: is not able to identify the site of nucleation of freezing and the freezing pathway in the plant (Pearce & Fuller, 2001). When a plant or one of its tissues freeze, an exothermic event occurs and it can be detected as a rise in temperature; when the freezing event ends, the temperature fall (Pearce & Fuller, 2001).

Many authors use thermography to study the site of nucleation and the pathway of freezing in tomato, bean, oat, wheat, barley (Hacker & Neuner, 2007; Livingston et al., 2006; Pearce & Fuller, 2001; Wisniewski et al., 1997; Workmaster et al., 1999).

Grapevine is susceptible to freezing but their organs can differ in the tolerance to freezing temperature. Organs with higher water content are more frost susceptible. Temperatures of –2 to –3 °C can cause several problems to leaves, shoots and green buds. However, in order to adapt at this situation plants can increase their freezing tolerance, this phenomenon is called cold acclimation. Anyway, if grapevine is exposed for long time at low temperature it lose hardiness because the process of cold acclimation can be stopped, reversed or restarted depending on temperature (Carbonell-Bejerano et al., 2015; Sawicki et al., 2015). It's known that there are some species of *Vitis amurensis*, with a specific genetic resistance, that are able to live with -50°C (Carbonell-Bejerano et al., 2015; Morando et al., 2013). Other species like *V. labrusca* or *V. aestivalis* are also more resistant than *V. vinifera* to freezing temperatures (Carbonell-Bejerano et al., 2015). According to Pearce & Fuller (2001) the ice enters the leaves via stomata, so the first frozen tissue is the leaf, but in some woody plants it first occurs inside plants. Intense cold can be fatal for the foliar tissues, which become discoloured, whitish and then dried up. Lower temperatures can affect the normal growth of grapevine, before flowering can cause problems on ovule and pollen development with the consequence to lead at negative effects in fruit set and seeds. But in grapevine freezing tolerance at flowering is genotype dependent, for example Chardonnay is more susceptible than Syrah and Cabernet Sauvignon (Meyer-Regueiro et al., 2015; Sawicki et al., 2015). Long-time exposed to freezing temperature can lead to the formation of a large crystal from many small crystals, this process is called recrystallization. It can deform cells and damage plant tissue, anyway, it not always kill the vine but the tension inside the wood can lead to a crack of woody organs (Sawicki et al., 2015).

Thermography has been used also to monitor and manage frost stress, Fwater reezing generates an exothermic process that heats up the vegetal tissue, so thermography is able to detect the variation of temperature (Prashar & Jones, 2014). In this way, it is possible to monitor the freezing process, to screen and characterize different genotypes on the base of their frost sensitiveness. Fuller & Wisniewski (1998), used thermography in potato (*Solanum tuberosum*) and cauliflower (*Brassica oleracea* var. Botrytis) to follow the freezing behaviour. In their study, the cauliflower showed 10 different ice-nucleation process in 50 minutes of time, with the first one occurring at -6.5°C and the last one at -9.5°C. At the end, cauliflowers that early frozen showed some frost damage as a discolouration which evolved to a water-soaked appearance. This depends also on the frozen timing. In fact, no damage has been shown in cauliflower when frozen for 15 minutes (Fuller & Wisniewski, 1998). Thermography was also used to control freezing events in wheat (Livingston et al., 2018).

Workmaster et al. (1999) use video thermography to study ice formation in cranberry (*Vaccinium macrocarpon*), in particular in leaves, stems and fruit. Samples were cooled at -8°C and leaves froze just when ice was present on the surface, after that the ice propagate in the stem and other leaves. On the fruit, ice nucleation occurs when the ice is in the calyx. A difference has been found between ripe and unripe fruits, in particular ripe berries supercool early compared to unripe berries that needed more time to cool down. Fruits supercool because extrinsic ice propagation is blocked in the pedicel and fruit surface (Workmaster et al., 1999). This study provides additional evidence that IR video thermography has great potential to study of ice nucleation and propagation in plants.

Wisniewski et al., (1997) used video thermography to evaluate ice nucleation and propagation in plants. Images were analysed by an image analysis software. In this experiment, the presence of a nucleation active bacteria was detected and it could be the one that start the nucleation process. This experiment was carried out in species as bean, peach, apple. An imaging radiometer was used to image the thermal response of plants during freezing. In a bean leaf a droplet of 2.0 uL of ice + ice nucleation bacteria were placed on the left side with a temperature of 2 °C. It was possible to differentiate the frozen part from the unfrozen one because areas with a lower temperature were black and the ones with higher temperature were white. The droplet was the first one to freeze.

3. Remote sensing and High-throughput phenotyping (HTP) technologies in crop monitoring and phenotyping: relevance for grapevine

Several EU projects are now in development focused on large scale phenotyping and phenotyping technologies, For example the European Infrastructure for Multi-scale Plant Phenotyping and Simulation for Food and Security in Changing Climate (EMPHASIS) (Pieruschka et al., 2021) is aiming to share and make possible the use of HTP technologies to European users. With this new approach it will be possible to avoid the large gap between genomic, physiology and agronomy and overcome the limitations of less developed countries in what concerns HTP (Costa et al., 2019).

HTP approaches are involve accurate and fast technology based on imaging and computer vision for large scale screens. Normally, phenotyping in viticulture is done by visual estimation following the description rules/standards provided by the BBCH scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) and OIV descriptors (OIV, 2001) (Lorenz et al., 1995).

However, this type of characterization and estimation is expensive and can be also subjective. Moreover, acquisition of phenotypic data on large areas (many hectares) could be highly time consuming and difficult in conditions of fast plant growth.

New technologies systems in vineyards are now able to detect morphological – plant variety features, in a simple and rapid way. HTP systems are composed by different technologies, in order to minimize the errors and increase the quality of recording (Herzog et al., 2014). Spachos (2020) built up a system composed by a series of small and low-cost devices connected between them, these are new systems based on the linking of different smart tools linked by wireless. This system uses images captured by a drone in conjunction with the sensors nodes that check if the data match the past data or if there has been some change (Spachos, 2020). The system is composed by two sensors nodes. The first nodes, collect data from the sensors and send the data to the relay nodes, the second type of nodes are the relay nodes and they just receive packets of data and send to the control room. The system is composed by 3 mains parts, the first one includes the wireless monitoring nodes, each of them contains four soil moisture and four soil temperatures sensors, the nodes are rechargeable thanks to a solar panel. The second one, very important, is the wireless network that leads all the data from the sensors to the control room. The third one is composed by a computer and a drone, here all the data are processed and if some data exceed the threshold parameters the control room send a signal to the drone and this one moves to the point of interest to collect more data (Spachos, 2020).

Rilling et al., (2017), presents a project for crop monitoring, a new method formed by different type of sensors data, methods to create 3D maps and to maximize map accuracy in order to give more fast and accurate response to the farmers. The system is composed by a multi-sensor system: hyper spectral imaging, 3D Lidar scanner and thermal imaging and can be mounted on different platform as UAV, ATV etc. So, the combination between different images methods is a key for the future precision viticulture in order to overcome image analysis problems.

In the last decade it was a big interest to build automated system based on remote sensing to monitor LST (land surface temperature) and SST (soil surface temperature) (Frodella et al., 2020). Monitoring SST of the soil can be an important tool because the soil temperature drive soil physiochemical and biological process and may help to estimate evapotranspiration. The use of IR technologies allows to overcome some limitations that the common soil probes at varying soil depth causes. In fact the heterogeneity of the soil not allow to have a representative soil monitoring. Thermography permits to overcome this limitation thanks to its stability and can help to understand the soil by its temperature (Frodella et al., 2020)

4. Conclusions and future prospects

One of the priorities for modern agriculture and viticulture is the optimization of inputs use (e.g. water). Under the pressure of climate change, optimization of natural resources uses, such as water, is obligatory. Thermography is a valid technology for both the industry and agriculture, and it can support growers namely in terms of crop stress monitoring and more precise crop and soil management.

Thermal imaging has still some limitations that need to be solved. One of the first is the price of this equipment although nowadays it is possible to find thermal cameras with a price starting from 400 € but with a limited resolution (Baluja et al., 2012; Belfiore et al., 2019; Costa et al., 2020; Fuentes et al., 2019; Sagan et al., 2019; Stoll & Jones, 2007). To choose the best quality\price thermal camera some key features must be considered such as: spatial resolution, focus, temperature range, lens options, battery life. Companies are trying to develop new devices that provide better quality image at more accessible prices. The FlirOne PRO, for example can provide good quality thermal images with a thermal resolution of 160x120 and an average price of 400 €. Also, the new camera FLIR C5, Flir Systems, tascable, easy to use with 160 x 120 IR detector. Besides equipment limitations, also the software is a limiting factor, especially because the most efficient are expensive. This is very important because for practical usage in agriculture because we need a fast and precise interpretation of the thermal data.

The last generation thermal cameras can reach high ground resolution, providing high accuracy for canopy extraction data in discontinuous row crops such as grapevines and fruit trees, making it a promising tool for field and irrigation management applications in agriculture/horticulture. And in order to be more efficient, thermal imaging should be easily portable and movable. Therefore future tendencies for viticulture should involve the use of on-the-go systems (Gutiérrez et al., 2017; 2018; Diago et al., 2019). In this case, the thermal camera should be coupled to a tractor, an ATV, a robot or even UAV and will make possible monitoring of large areas. The use of UAV at different altitudes can make possible to gather information from the entire field or single plants (Maes & Steppe, 2012). However, and in my opinion, the other major challenge is to couple thermography with robots. The possibility to create a smart tool to automatically collect and process thermal images is one of the aims to monitor the vineyards of the future. A robot that is able to compare new thermal images with old ones and intervene/decide if something changes or if some threshold thermal parameters are exceeded (air temperature, soil T or leaf T) can be the future. In my opinion, robotics will be the right arm of agronomists in decision making.

Future developments for thermography will also involve combination of imaging methods in other spectral wavelengths as visible and chlorophyll fluorescence, multispectral imagery (Costa et al., 2013). Combination with hyperspectral imaging for example can help to discriminate the background from the canopy. High resolution imagery, with pixels < 0.5 m^2 can be used to detect additional morphological information as canopy thickness and missing vines count (Tisseyre & Taylor, 2006).
Supporting decision to choose the best cultural operation, the right time and intensity is needed for more efficient and sustainable viticulture and agriculture. Therefore, integrated high-tech systems and devices, such as drones, soil or leaf sensors and satellites allow to have a vegetative, sanitary, productive real-time situation of the vineyard and are the major tools of Decision Support Systems (DSS) and they will tend to be more used to control vineyard managements. The DSS can support ''prescription maps'' to intervene in a different way depending on crop needs (Progetto SUVISA- AGRIDIGIT, 2018). Policy makers in Europe should also promote investments in precision agriculture approaches and in the use of non-invasive technologies by the industries in order to encourage partnership between universities, researchers (public sector) and wineries, farms, agricultural companies, IT companies (private sector), in order to reduce the impact of the climate change and to optimize the inputs of natural resources and improve the crop productivity (Costa et al., 2019).

In parallel with improvements in the technologies the sector needs to invest in human skills and more advanced training of technical personnel who can support the efficient use of those technologies and software or in the training of agronomists or other engineers capable of supporting knowledge and innovation transfer into the viticultural sector. The European Union should also invest more in training (technical seminars, networking where these technologies are explained to the farmers and entrepreneurs in order to develop the agricultural sector). A good example is the NEFERTITI project network (https://nefertiti-h2020.eu/pt/homept/), that aims innovation via demonstration. This type of projects should be enlarged and sustained on the long term. Inclusion of young and more technologically educated graduates will help to integrate novel technologies while creating more jobs and rejuvenating the wine supply chain. Nowadays private companies are also offering solutions and services on this topic. For example a project named "*The Vineyard of the Future (VoF)*"**https://www.abc.net.au/news/2016-09-01/vineyard-of-the-future-project-to-secure-australia-wine** wants to create a multinational platform aimed at establishing a full-equipped vineyard using IoT for data detection and elaboration that can be used by viticulturist and agronomist to investigate in the potential effects of the climate change in viticulture and enology. In conclusion, the viticulture sector is facing an increasing challenge due to climate change, consumer trends and labor shortage for vineyard operations, which makes it essential to find semi or total mechanized or robotized solutions. Imaging and remote sensing tools can be a solution that need to be optimized. Imaging can support crop monitoring besides harvesting or pruning,

5. References

ADVICLIM (2016). Adapting viticulture to climate change guidance manual to support winegrowers' decision-making .
http://www.adviclim.eu/wp-content/uploads/2015/06/B1-deliverable.pdf

Allègre, M., Daire, X., Héloir, M.-C., Trouvelot, S., Mercier, L., Adrian, M., & Pugin, A. (2007).
Stomatal deregulation in Plasmopara viticola-infected grapevine leaves. *New Phytologist*, *173*(4), 832–840.

Alsina, M. M., Herralde, F. De, Biel, C., & Savé, R. (2007). Water relations and vulnerability to embolism in eight grapevine cultivars. *Vitis*, *46*(1991), 1.

Arnó, J; Escolà, A; Vallès, J. M; Llorens, J.; Sanz, R.; Masip, J.; Palacín, J.; Rosell-Polo, J. . (2013). Leaf area index estimation in vineyards using a ground-based LiDAR scanner. *Precision Agriculture Springer US*, *14*(3), 290–306.

Aroca, R., Porcel, R., & Ruiz-Lozano, J. M. (2012). Regulation of root water uptake under abiotic stress conditions. *Journal of Experimental Botany*, *63*(1), 43–57.

Baluja, J., Diago, M. P., Balda, P., Zorer, R., Meggio, F., Morales, F., & Tardaguila, J. (2012). Assessment of vineyard water status variability by thermal and multispectral imagery using an unmanned aerial vehicle (UAV). *Irrigation Science*, *30*(6), 511–522.

Bauerle, T. L., Smart, D. R., Bauerle, W. L., Stockert, C., & Eissenstat, D. M. (2008). Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate. *New Phytologist*, *179*(3), 857–866.

Belfiore, N., Vinti, R., Lovat, L., Chitarra, W., Tomasi, D., de Bei, R., Meggio, F., & Gaiotti, F. (2019). Infrared thermography to estimate vine water status: Optimizing canopy measurements and thermal indices for the varieties Merlot and moscato in northern Italy. *Agronomy*, *9*(12), 821.

Belli, G. (2006). *Elementi di patologia vegetale*. Piccin-Nuova Libraria, second edition, Milano

Berni, J. A. J., Zarco-Tejada, P. J., Suárez, L., & Fereres, E. (2009). Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle. *IEEE Transactions on Geoscience and Remote Sensing*, *47*(3), 722–738.

Blatt, M. R., & Gradmann, D. (1997). K+-Sensitive Gating of the K+ Outward Rectifier in Vicia Guard Cells. *The Journal of Membrane Biology*, *158*(3), 241–256.

Bota, J., Tomás, M., Flexas, J., Medrano, H., & Escalona, J. M. (2016). Differences among grapevine cultivars in their stomatal behavior and water use efficiency under progressive water stress. *Agricultural Water Management*, *164*, 91–99.

Brancadoro, L., Failla, O., Dosso, P., & Serina, F. (2006). Use of satellite in precision viticulture: the Franciacorta experience. *6th International Terroir Congress,* Bordeaux - Montpellier, 2006. 276–279.

Briglia, N., Montanaro, G., Petrozza, A., Summerer, S., Cellini, F., & Nuzzo, V. (2019). Drought phenotyping in Vitis vinifera using RGB and NIR imaging. *Scientia Horticulturae*, *256*, 108555.

Bulanon, D. M., Burks, T. F., & Alchanatis, V. (2008). Study on temporal variation in citrus canopy using thermal imaging for citrus fruit detection. *Biosystems Engineering*, *101*(2), 161–171.

Carbonneau, A., Casteran, P., & Leclair, P. (1978). *Essai de determination en biologie de la plante entiere de relations essentielles entre le bioclimat naturel, la physiologie de la vigne et la composition du raisin: methodologie et premier resultats sur les systemes de conduite*. Ann. Amelior. Plantes, 28(2), 195 - 221.

Chaerle, L., De Boever, F., Van Montagu, M., & Van der Straeten, D. (2001). Thermographic visualization of cell death in tobacco and Arabidopsis. *Plant, Cell and Environment*, *24*(1), 15–25.

Chaerle, L., Hagenbeek, D., De Bruyne, E., Valcke, R., & Van Der Straeten, D. (2004). Thermal and Chlorophyll-Fluorescence Imaging Distinguish Plant-Pathogen Interactions at an Early Stage. *Plant and Cell Physiology*, *45*(7), 887–896.

Chaves, M. M., Costa, J. M., Zarrouk, O., Pinheiro, C., Lopes, C. M., & Pereira, J. S. (2016). Controlling stomatal aperture in semi-arid regions—The dilemma of saving water or being cool? *Plant Science*, *251*, 54–64.

Chaves, M. M., Santos, T. P., Souza, C. R., Ortuño, M. F., Rodrigues, M. L., Lopes, C. M., Maroco, J. P., & Pereira, J. S. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology*, *150*(2), 237–252.

Chaves, M. M., Zarrouk, O., Francisco, R., Costa, J. M., Santos, T., Regalado, A. P., Rodrigues, M. L., & Lopes, C. M. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany*, *105*(5), 661–676.

Chaves, M., Miguel Costa, J., & Madeira Saibo, N. J. (2011). Recent Advances in Photosynthesis Under Drought and Salinity. In *Advances in Botanical Research*, 57:49-104.

Choat, B., Drayton, W., Brodersen, C., Matthews, M., Shackel, K., Wada, H., & Mcelrone, A. (2010). Measurement of vulnerability to water stress-induced cavitation in grapevine: A comparison of four techniques applied to a long-vesseled species. *Plant, Cell & Environment*, *33*, 1502–1512.

Choat, B., Lahr, E., Melcher, P., Zwieniecki, M., & Holbrook, N. (2005). The spatial pattern of air seeding threshold in mature sugar maple trees. *Plant, Cell and Environment*, *28*, 1082–1089.

Choné, X., Van Leeuwen, C., Dubourdieu, D., & Gaudillère, J. P. (2001). Stem water potential is a sensitive indicator of grapevine water status. *Annals of Botany*, *87*(4), 477–483.

Chouzouri, A., & Schultz, H. R. (2005). Hydraulic anatomy, cavitation susceptibility and gas-exchange of several grapevine cultivars of different geographic origin. *Acta Horticulturae*, *689*, 325–332.

Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *92*, 79–97.

Costa, J. M, Grant O.M., Chaves M. (2010). Use of Thermal Imaging in Viticulture: Current Application and Future Prospects. *Methodologies and Results in Grapevine Research, Springer*, 10:135–146.

Costa, J. M., Egipto, R., Sánchez-Virosta, A., Lopes, C. M., & Chaves, M. M. (2019). Canopy and soil thermal patterns to support water and heat stress management in vineyards. *Agricultural Water Management*, *216*, 484–496.

Costa, J. M., Garcia-Tejero, I., Egipto, R., Tomás, M., Vaz, M., Lopes, C. M., & Chaves, M. (2014). Assessing Canopy Temperature Patterns in Two Grapevine Varieties Subjected To Deficit Irrigation : a Tool To Optimize Water Management ? *In 19 Th International Meeting of Viticulture GiESCO, Peach*

Rouge-Montpellier, 31 May - 5 June 2015. 130–133.

Costa, J. M., Grant, O. M., & Chaves, M. M. (2013). Thermography to explore plant-environment interactions. *Journal of Experimental Botany*, *64*(13), 3937–3949.

Costa, J. M., Marques da Silva, J., Pinheiro, C., Barón, M., Mylona, P., Centritto, M., Haworth, M., Loreto, F., Uzilday, B., Turkan, I., & Oliveira, M. (2019). Opportunities and Limitations of Crop Phenotyping in Southern European Countries. *Frontiers in Plant Science*, 10:1125, 1–16.

Costa, J. M., Ortuño, M. F., Lopes, C. M., & Chaves, M. M. (2012). Grapevine varieties exhibiting differences in stomatal response to water deficit. *Functional Plant Biology*, *39*(3), 179–189.

Costa, J. M., Vaz, M., Escalona, J., Egipto, R., Lopes, C., Medrano, H., & Chaves, M. M. (2016). Modern viticulture in southern Europe: Vulnerabilities and strategies for adaptation to water scarcity. *Agricultural Water Management*, *164*, 5–18.

Costa, Vaz, M., Escalona, J. M., Egipto, R., Medrano, H., & Chaves, M. M. (2020). Water as a critical issue for viticulture in southern Europe: sustainability vs competiveness. *IVES Technical Reviews, Vine and Wine*, 2016 - 2017.

Cramer, G. R., Van Sluyter, S. C., Hopper, D. W., Pascovici, D., Keighley, T., & Haynes, P. A. (2013). Proteomic analysis indicates massive changes in metabolism prior to the inhibition of growth and photosynthesis of grapevine (Vitis viniferaL.) in response to water deficit. *BMC Plant Biology*, *13*(1), 49 - 70.

Damour, G., Simonneau, T., Cochard, H., & Urban, L. (2010). An overview of models of stomatal conductance at the leaf level. *Plant, Cell and Environment*, *33*(9), 1419–1438.

Deloire, A., Carbonneau, A., Wang, Z., & Ojeda, H. (2004). Vine and water a short review. *Journal International Des Sciences de La Vigne et Du Vin*, *38*(1), 1–13.

Delrot, S., Medrano, H., Or, E., Bavaresco, L., & Grando, S. (2010). Methodologies and results in grapevine research. Springer, 1 - 448.

Diago M.P., Aquino A., Millan B., Palacios F., Tardaguila J., (2019). On-the-go assessment of vineyard canopy porosity, bunch and leaf exposure by imaging analysis

Diago, M. P., Bellincontro, A., Scheidweiler, M., Tardaguila, J., Tittmann, S., & Stoll, M. (2017). Future opportunities of proximal near infrared spectroscopy approaches to determine the variability of vineyard water status. *Australian Journal of Grape and Wine Research*, *23*(3), 409–414.

Di Giorgio, D., Camoni, L., Mott, K. A., Takemoto, J. Y., & Ballio, A. (1996). Syringopeptins, Pseudomonas syringae pv. syringae phytotoxins, resemble syringomycin in closing stomata. Plant Pathology, 45(3), 564–571.

Dos Santos, F. N., Sobreira, H., Campos, D., Morais, R., Paulo Moreira, A., & Contente, O. (2016). Towards a Reliable Robot for Steep Slope Vineyards Monitoring. *Journal of Intelligent and Robotic Systems: Theory and Applications*, *83*(3–4), 429–444.

Downton, W. J. S., Grant, W. J. R., & Loveys, B. R. (1987). Diurnal Changes in the Photosynthesis of Field-Grown Grape Vines. *New Phytologist*, *105*(1), 71–80.

Escobar-Gutiérrez, A. J., Zipperlin, B., Carbonne, F., Moing, A., & Gaudillére, J. P. (1998). Photosynthesis, carbon partitioning and metabolite content during drought stress in peach seedlings.

Functional Plant Biology, *25*(2), 197–205.

Fernández-Novales, J., Tardaguila, J., Gutiérrez, S., Marañón, M., & Diago, M. P. (2018). In field quantification and discrimination of different vineyard water regimes by on-the-go NIR spectroscopy. *Biosystems Engineering*, *165*, 47–58.

FLIR (2020). https://www.flir.com/browse/professional-tools/thermography-cameras/

Fernández, J. E. (2017). Plant-based methods for irrigation scheduling of woody crops. *Horticulturae*, *3*(2), 35.

Fiorani, F., & Schurr, U. (2013). Future Scenarios for Plant Phenotyping. *Annual Review of Plant Biology*, *64*(1), 267–291.

Flexas, J., Briantais, J. M., Cerovic, Z., Medrano, H., & Moya, I. (2000). Steady-state and maximum chlorophyll fluorescence responses to water stress in grapevine leaves: A new remote sensing system. *Remote Sensing of Environment*, *73*(3), 283–297.

Fouquet, R. (2005). *Les aquaporines de vigne : identification, études d'expression en conditions de contraintes abiotiques et approches de caractérisation fonctionnelle*. *(Doctoral dissertation*, *Bordeaux 1).*

Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., & Santos, J. A. (2012). An overview of climate change impacts on European viticulture. *Food and Energy Security*, *1*(2), 94–110.

Frodella, W., Lazzeri, G., Moretti, S., Keizer, J., & Verheijen, F. G. A. (2020). Applying infrared thermography to soil surface temperature monitoring: Case study of a high-resolution 48 h survey in a vineyard (Anadia, Portugal). *Sensors*, *20*(9), 2444.

Fuentes, S., de Bei, R., Pech, J., & Tyerman, S. (2012). Computational water stress indices obtained from thermal image analysis of grapevine canopies. *Irrigation Science*, *30*(6), 523–536.

Fuentes, S., Tongson, E. J., De Bei, R., Viejo, C. G., Ristic, R., Tyerman, S., & Wilkinson, K. (2019). Non-invasive tools to detect smoke contamination in grapevine canopies, berries and wine: A remote sensing and machine learning modeling approach. *Sensors*, *19*(15), 3335.

Fuller, M. P., & Wisniewski, M. (1998). The use of infrared thermal imaging in the study of ice nucleation and freezing of plants. *Journal of Thermal Biology*, *23*(2), 81–89.

Gago, J., Douthe, C., Coopman, R. E., Gallego, P. P., Ribas-Carbo, M., Flexas, J., Escalona, J., & Medrano, H. (2015). UAVs challenge to assess water stress for sustainable agriculture. *Agricultural Water Management*, 153, 9–19.

Gan, H., Lee, W. S., Alchanatis, V., Ehsani, R., & Schueller, J. K. (2018). Immature green citrus fruit detection using color and thermal images. *Computers and Electronics in Agriculture*, 152, 117–125.

García-Sánchez, F., Galvez-Sola, L., Martínez-Nicolás, J. J., Muelas-Domingo, R., & Nieves, M. (2017). Using Near-Infrared Spectroscopy in Agricultural Systems. *Developments in Near-Infrared Spectroscopy*, *1*, 97-127.

García-Tejero, I. F., Costa, J. M., Egipto, R., Durán-Zuazo, V. H., Lima, R. S. N., Lopes, C. M., & Chaves, M. M. (2016). Thermal data to monitor crop-water status in irrigated Mediterranean viticulture. *Agricultural Water Management*, *176*, 80–90.

García-Tejero, I. F., Hernández-Cotán, A., Apolo, O. E., Durán-Zuazo, V. H., Portero, M. A., & Rubio-

Casal, A. E. (2017). Infrared thermography to select commercial varieties of maize in relation to drought adaptation. *Quantitative InfraRed Thermography Journal*, *14*(1), 54–67.

Garnier, E., & Berger, A. (1985). Testing water potential in peach trees as an indicator of water stress. *Journal of Horticultural Science*, *60*(1), 47–56.

Giorgi, F., & Lionello, P. (2008). *Climate change projections for the Mediterranean region*. *63*, 90–104.

Gomes, V. M., Fernandes, A. M., Faia, A., & Melo-Pinto, P. (2017). Comparison of different approaches for the prediction of sugar content in new vintages of whole Port wine grape berries using hyperspectral imaging. *Computers and Electronics in Agriculture*, *140*, 244–254.

Grant, O. M., Tronina, Ł., Jones, H. G., & Chaves, M. M. (2007). Exploring thermal imaging variables for the detection of stress responses in grapevine under different irrigation regimes. *Journal of Experimental Botany*, *58*(4), 815–825.

Großkinsky, D. K., Svensgaard, J., Christensen, S., & Roitsch, T. (2015). Plant phenomics and the need for physiological phenotyping across scales to narrow the genotype-to-phenotype knowledge gap. *Journal of Experimental Botany*, *66*(18), 5429–5440.

Gutiérrez, S., Diago, M. P., Fernández-Novales, J., & Tardaguila, J. (2017). On-the-go thermal imaging for water status assessment in commercial vineyards. *Advances in Animal Biosciences*, *8*(2), 520–524.

Gutiérrez, S., Diago, M. P., Fernández-Novales, J., & Tardaguila, J. (2018). Vineyard water status assessment using on-the-go thermal imaging and machine learning. *PLoS ONE*, *13*(2), 1–18.

Gutiérrez, S., Fernández-Novales, J., Diago, M. P., & Tardaguila, J. (2018). On-the-go hyperspectral imaging under field conditions and machine learning for the classification of grapevine varieties. *Frontiers in Plant Science*, *9*, 1–11.

Guzmán, R., Ariño J., Navarro R., L. C. M. (2016). Autonomous hybrid GPS/reactive navigation of an unmanned ground vehicle for precision viticulture-VINBOT. *62nd German Winegrowers Conference,* Stuttgart, 16 *November 2016*.

Hacker, J., & Neuner, G. (2007). Ice propagation in plants visualized at the tissue level by infrared differential thermal analysis (IDTA). *Tree Physiology*, *27*(12), 1661–1670.

Hall, A., Lamb, D. W., Holzapfel, B., & Louis, J. (2002). Optical remote sensing applications in viticulture - A review. *Australian Journal of Grape and Wine Research*, *8*(1), 36–47.

Haselgrove, L., Botting, D., Van Heeswijck, R., Høj, P. B., Dry, P. R., Ford, C., & Land, P. G. I. (2000). Canopy microclimate and berry composition: The effect of bunch exposure on the phenolic composition of Vitis vinifera L cv. Shiraz grape berries. *Australian Journal of Grape and Wine Research*, *6*(2), 141–149.

Hayman, P., McCarthy, M., Thomas, D., & Longbottom, M. (2012). Managing Grapevines During Heatwaves Factsheet. *Australian Grape and Wine Authority*, 1–9.
https://www.wineaustralia.com/getmedia/90cf20af-1579-462d-b06e-35f343cbe129/201201_Managing-vines-during-heatwaves.pdf

Herzog, K., Roscher, R., Wieland, M., Kicherer, A., Läbe, T., Förstner, W., Kuhlmann, H., & Töpfer, R.

(2014). Initial steps for high-throughput phenotyping in vineyards. *Vitis - Journal of Grapevine Research*, *53*(1), 1–8.

Hirayama, M., Wada, Y., & Nemoto, H. (2006). Estimation of drought tolerance based on leaf temperature in upland rice breeding. *Breeding Science*, *56*(1), 47–54.

Hoff, R., Ducati, J. R., & Farias, A. R. (2017). GIS and Remote Sensing to Support Precision Viticulture for Analysis of Vineyards in the Campanha Wine Region , Brazil. *Journal of Environmental and Agricultural Sciences*, *10*, 20–32.

INFOWINE (2007). https://www.infowine.com/intranet/libretti/libretto4594-01-1.pdf

INTERPHENO (2019). https://ciencias.ulisboa.pt/pt/noticia/18-05-2021/luzes-c%C3%A2maras-a%C3%A7%C3%A3o-o-fasc%C3%ADnio-das-plantas-n%C3%A3o-tem-fronteiras

IPCC. (2014). Climate Change 2014 Part A: Global and Sectoral Aspects. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Ishimwe, R., Abutaleb, K., & Ahmed, F. (2014). Applications of Thermal Imaging in Agriculture—A Review. *Advances in Remote Sensing*, 03, 128–140.

Johnson, L. F., Roczen, D. E., Youkhana, S. K., Nemani, R. R., & Bosch, D. F. (2003). Mapping vineyard leaf area with multispectral satellite imagery. *Computers and Electronics in Agriculture*, *38*(1), 33–44.

Johnson, Lee F, Roczen, D., & Youkhana, S. (2001). Vineyard Canopy Density Mapping With Ikonos Satellite Imagery. *The Third International Conference on Geospatial Information in Agriculture and Forestry*, 10 November, 2001.

Jones, H. G. (2002). Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *Journal of Experimental Botany*, *53*(378), 2249–2260.

Jones, H. G. (2004). Thermal imaging and infrared sensing in plant ecophysiology. *Advances in Plant Ecophysiology Techniques*, 41, 107–163.

Jones, H. G., & Grant, O. M. (2016). Remote sensing and other imaging technologies to monitor grapevine performance. *Grapevine in a Changing Environment: A Molecular and Ecophysiological Perspective*, Wiley Blackwell, Oxford, 179–201.

Jones, M. M., & Turner, N. C. (1980). Osmotic Adjustment in Expanding and Fully Expanded Leaves of Sunflower in Response to Water Deficits. *Functional Plant Biology*, *7*(2), 181–192.

Jones G. V., (2007). Climate Change: Observations, projections, and general implications for viticulture and wine production. Unpublished work, 1–13.

Jones, G. V, White, M. A., Cooper, O. R., & Storchmann, K. (2005). Climate Change and Global Wine Quality. *Climatic Change*, *73*(3), 319–343.

Kameli, A., & Lösel, D. M. (1995). Contribution of Carbohydrates and other Solutes to Osmotic Adjustment in Wheat Leaves Under Water Stress. *Journal of Plant Physiology*, *145*(3), 363–366.

Keller, M. (2005). Deficit Irrigation and Vine Mineral Nutrition. *American Journal of Enology and Viticulture*, *56*(3), 267–283.

Keresztes, B., Grenier, G., Germain, C., Da Costa, J. P., & Beaulieu, X. D. (2014). VVINNER: An autonomous robot for automated scoring of vineyards. *Proceedings of the International Conference of Agricultural Engineering, 2014, Zurich, Switzerland*.

Kicherer, A., & Kühn-institut, J. (2015). *High-throughput phenotyping of yield parameters for modern grapevine breeding Disser tationen aus dem Julius Kühn-Institut*, 7, 22.

Lavrnić, S., Zapater-Pereyra, M., & Mancini, M. L. (2017). Water Scarcity and Wastewater Reuse Standards in Southern Europe: Focus on Agriculture. *Water, Air, & Soil Pollution*, *228*(7), 251 - 262.

Lambers H, Chapin S. F., Pons T.L., (1998) Plant Physiological Ecology, first edition. Springer.

Lebot, V., Malapa, R., & Jung, M. (2013). Use of NIRS for the rapid prediction of total N, minerals, sugars and starch in tropical root and tuber crops. *New Zealand Journal of Crop and Horticultural Science*, *41*(3), 144–153.

Lee, W. S., Alchanatis, V., Yang, C., Hirafuji, M., Moshou, D., & Li, C. (2010). Sensing technologies for precision specialty crop production. *Computers and Electronics in Agriculture*, *74*(1), 2–33.

Leitão, L., Prista, C., Moura, T. F., Loureiro-Dias, M. C., & Soveral, G. (2012). Grapevine aquaporins: Gating of a tonoplast intrinsic protein (TIP2;1) by cytosolic pH. *PLoS ONE*, *7*(3).

Livingston, D. P., Tallury, S. P., Owens, S. A., Livingston, J. D., & Premkumar, R. (2006). Freezing in nonacclimated oat: Thermal response and histological observations of crowns during recovery. *Canadian Journal of Botany*, *84*(2), 199–210.

Livingston, D. P., Tuong, T. D., Murphy, J. P., Gusta, L. V., Willick, I., & Wisniewski, M. E. (2018). High-definition infrared thermography of ice nucleation and propagation in wheat under natural frost conditions and controlled freezing. *Planta*, *247*(4), 791–806.

Longo, D., Pennisi, A., Bonsignore, R., Schillaci, G., & Muscato, G. (2013). A small autonomous electrical vehicle as partner for heroic viticulture. *Acta Horticulturae*, *978*, 391–398.

Lopes, C. M., Graça, J., Sastre, J., Reyes, M., Guzmán, R., Braga, R., Monteiro, A., & Pinto, P. A. (2016). Vineyard yeld estimation by VINBOT robot - preliminary results with the white variety Viosinho. *Proceedings 11th Int. Terroir Congress. Jones, G. and Doran, N.(Eds.), Pp. 458-463. Southern Oregon University, Ashland, USA.*

Lopes, C. M., Santos, T. P., Monteiro, A., Rodrigues, M. L., Costa, J. M., & Chaves, M. M. (2011). Combining cover cropping with deficit irrigation in a Mediterranean low vigor vineyard. *Scientia Horticulturae*, *129*(4), 603–612.

Lopes, C., Torres, A., Guzman, R., Graca, J., Reyes, M., Victorino, G., Braga, R., Monteiro, A., & Barriguinha, A. (2017). Using an unmanned ground vehicle to scout vineyards for non-intrusive estimation of canopy features and grape yield. *20th GiESCO International Meeting*, *2*, 16–21.

Lorenz, D. H., Eichhorn, K. W., Bleiholder, H., Klose, R., Meier, U., & Weber, E. (1995). Phenological growth stages of the grapevine (Vitis vinifera L . ssp . vinifera) Codes and descriptions according to the extended BBCH scale. *Australian Journal of Grape and Wine Research, 1*(2), 100–103.

Loseke, B. A. (2018). Replacing Herbicides with Groundcovers to Enhance Vineyard Sustainability. A dissertation Presented to the Faculty of The Graduate College at the University of Nebraska In Partial Fulfillment of Requirements for the Degree of Doctor of Philosophy, Major: Agronomy and Horticulture, Under the Supervision of Professor Paul E. Read. Lincoln, Nebraska: May, 2018.

Lovisolo, C., Perrone, I., Carra, A., Ferrandino, A., Flexas, J., Medrano, H., & Schubert, A. (2010). Drought-induced changes in development and function of grapevine (Vitis spp.) organs and in their hydraulic and non-hydraulic interactions at the whole-plant level: A physiological and molecular update. *Functional Plant Biology*, *37*(2), 98–116.

Maes, W. ., & Steppe, K. (2012). In Posidonia oceanica cadmium induces changes in DNA Estimating evapotranspiration and drought stress methylation and chromatin patterning with ground-based thermal remote sensing in agriculture: a review. *Journal of Experimental Botany*, *63*(13), 4671–4712.

Magalhães, N. (2008). A Vinha e o Vinho em Portugal. *IVV - Instituto Da Vinha e Do Vinho, I.P.*, 9000.

Makra, L., Vitányi, B., Gál, A., Mika, J., Matyasovszky, I., & Hirsch, T. (2009). Wine quantity and quality variations in relation to climatic factors in the Tokaj (Hungary) winegrowing region. *American Journal of Enology and Viticulture*, *60*(3), 312–321.

Martorell, S., Diaz-Espejo, A., Tomàs, M., Pou, A., El Aou-ouad, H., Escalona, J. M., Vadell, J., Ribas-Carbó, M., Flexas, J., & Medrano, H. (2015). Differences in water-use-efficiency between two Vitis vinifera cultivars (Grenache and Tempranillo) explained by the combined response of stomata to hydraulic and chemical signals during water stress. *Agricultural Water Management*, *156*, 1–9.

Matese, A., & Di Gennaro, S. F. (2015). Technology in precision viticulture: a state of the art review. *International Journal of Wine Research*, *7*(1), 69–81.

Maurel, C., Verdoucq, L., Luu, D.-T., & Santoni, V. (2008). Plant Aquaporins: Membrane Channels with Multiple Integrated Functions. *Annual Review of Plant Biology*, *59*(1), 595–624.

Mccarthy, M., Loveys, B. R., Dry, P. R., & Stoll, M. (2000). Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. *Deficit Irrigation Practices*, *22*, 79–87.

McCutchan, H., & Shackel, K. A. (2019). Stem-water Potential as a Sensitive Indicator of Water Stress in Prune Trees (Prunus domestica L. cv. French). *Journal of the American Society for Horticultural Science*, *117*(4), 607–611.

Medrano, H., Tomás, M., Martorell, S., Escalona, J. M., Pou, A., Fuentes, S., Flexas, J., & Bota, J. (2015). Improving water use efficiency of vineyards in semi-arid regions. A review. *Agronomy for Sustainable Development*, *35*(2), 499–517.

Merlot, S., Mustilli, A. C., Genty, B., North, H., Lefebvre, V., Sotta, B., Vavasseur, A., & Giraudat, J. (2002). Use of infrared thermal imaging to isolate Arabidopsis mutants defective in stomatal regulation. *Plant Journal*, *30*(5), 601–609.

Metzner, R., Eggert, A., van Dusschoten, D., Pflugfelder, D., Gerth, S., Schurr, U., Uhlmann, N., & Jahnke, S. (2015). Direct comparison of MRI and X-ray CT technologies for 3D imaging of root systems in soil: Potential and challenges for root trait quantification. *Plant Methods*, *11*(1), 1–11.

Meyer, W. S., & Green, G. C. (1981). Plant indicators of wheat and soybean crop water stress. *Irrigation Science*, *2*(3), 167–176.

Milella, A., Marani, R., Petitti, A., & Reina, G. (2019). In-field high throughput grapevine phenotyping with a consumer-grade depth camera. *Computers and Electronics in Agriculture*, *156*, 293–306.

Mittler, R. (2006). Abiotic stress, the field environment and stress combination. *Trends in Plant Science*, *11*(1), 15–19.

Möller, M., Alchanatis, V., Cohen, Y., Meron, M., Tsipris, J., Naor, A., Ostrovsky, V., Sprintsin, M., & Cohen, S. (2007). Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *Journal of Experimental Botany*, *58*(4), 827–838.

Morando, A., Lavezzaro, S., & Ferro, S. (2013). Danni da gelo invernale su vite. *Vitenda*, *18*.

Morlat, R., & Jacquet, A. (2003). Grapevine Root System and Soil Characteristics in a Vineyard Maintained Long-term with or without Interrow Sward. *American Journal of Enology and Viticulture*, *54*(1), 1–7.

Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, *114*(4), 358–371.

Munns, R., & Weir, R. (1981). Contribution of Sugars to Osmotic Adjustment in Elongating and Expanded Zones of Wheat Leaves During Moderate Water Deficits at Two Light Levels. *Functional Plant Biology*, *8*(1), 93–105.

Naor, A., Gal, Y., & Bravdo, B. (1997). Crop load affects assimilation rate, stomatal conductance, stem water potential and water relations of field-grown Sauvignon blanc grapevines. *Journal of Experimental Botany*, *48*(9), 1675–1680.

NEFERTITI project network (2020). https://nefertiti-h2020.eu/pt/homept/

Noguera M., Millán B., Pérez-Paredes J. J., Ponce J. M. Aquino A., & Andújar J. M. (2020). A New Low-Cost Device Based on Thermal Infrared Sensors for Olive Tree Canopy Temperature Measurement and Water Status Monitoring. Remote Sensing, 12(4), 723 - 742.

OIV (2001) List descripteurs OIV. https://www.oiv.int/public/medias/2274/code-2e-edition-finale.pdf

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A., & Deloire, A. (2002). Influence of pre and post-veraison water deficit on synthesis and concentration of skin. *American Journal of Enology and Viticulture*, *53*, 261–267.

Ojeda, H., Deloire, A., & Carbonneau, A. (2001). Influence of water deficits on grape berry growth. *Vitis*, *40*(3), 141–145.

Olivo, N., Girona, J., & Marsal, J. (2009). Seasonal sensitivity of stem water potential to vapour pressure deficit in grapevine. *Irrigation Science*, *27*(2), 175–182.

Patakas, A., Nikolaou, N., Zioziou, E., Radoglou, K., & Noitsakis, B. (2002). The role of organic solute and ion accumulation in osmotic adjustment in drought-stressed grapevines. *Plant Science*, *163*(2), 361–367.

Pearce, R. S., & Fuller, M. P. (2001). *Freezing of Barley Studied by Infrared Video Thermography*. *125*, 227–240.

Pellegrino, A., Gozé, E., Lebon, E., & Wery, J. (2006). A model-based diagnosis tool to evaluate the water stress experienced by grapevine in field sites. *European Journal of Agronomy*, *25*(1), 49–59.

Petrie, P. R., Wang, Y., Liu, S., Lam, S., Whitty, M. A., & Skewes, M. A. (2019). The accuracy and utility of a low cost thermal camera and smartphone-based system to assess grapevine water status. *Biosystems Engineering*, *179*, 126–139.

Pieruschka, R., Fahrner, S., and Schurr, U.: EMPHASIS: European infrastructure for multi-scale plant phenotyping and simulation for food security in a changing climate, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1372, https://doi.org/10.5194/egusphere-egu21-1372, 2021.

Poirier-Pocovi, M., Volder, A., & Bailey, B. N. (2020). Modeling of reference temperatures for calculating crop water stress indices from infrared thermography. *Agricultural Water Management*, *233*, 1060- 1070.

Pou, A., Diago, M. P., Medrano, H., Baluja, J., & Tardaguila, J. (2014). Validation of thermal indices for water status identification in grapevine. *Agricultural Water Management*, *134*, 60–72.

Pou, A., Flexas, J., Alsina, M. D. M., Bota, J., Carambula, C., De Herralde, F., Galmés, J., Lovisolo, C., Jiménez, M., Ribas-Carbó, M., Rusjan, D., Secchi, F., Tomàs, M., Zsófi, Z., & Medrano, H. (2008). Adjustments of water use efficiency by stomatal regulation during drought and recovery in the drought-adapted Vitis hybrid Richter-110 (V. berlandieri x V. rupestris). *Physiologia Plantarum*, *134*(2), 313–323.

Prashar, A., & Jones, H. G. (2014). Infra-red thermography as a high-throughput tool for field phenotyping. *Agronomy*, *4*(3), 397–417.

Quick, W. P., Chaves, M. M., Wendler, R., David, M., Rodrigues, M. L., Passarinho, J. A., Pereira, J. S., Adcock, M. D., Leegood, R. C., & Stitt, M. (1992). The effect of water stress on photosynthetic carbon metabolism in four species grown under field conditions. *Plant, Cell & Environment*, *15*(1), 25–35.

Reiser, D., Sehsah, E. S., Bumann, O., Morhard, J., & Griepentrog, H. W. (2019). Development of an autonomous electric robot implement for intra-row weeding in vineyards. *Agriculture (Switzerland)*, *9*(1), 1–12.

Rilling, S., Nielsen, M., Milella, A., Jestel, C., Frohlich, P., & Reina, G. (2017). A multisensor platform for comprehensive detection of crop status: Results from two case studies. *2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance, AVSS 2017*.

Rogiers, S. Y., Greer, D. H., Hutton, R. J., & Landsberg, J. J. (2009). Does night-time transpiration contribute to anisohydric behaviour in a Vitis vinifera cultivar? *Journal of Experimental Botany*, *60*(13), 3751–3763.

Rossa, Ü. B., Angelo, A. C., Nisgoski, S., Westphalen, D. J., Frizon, C. N. T., & Hoffmann-Ribani, R. (2015). Application of the NIR Method to Determine Nutrients in Yerba Mate (Ilex paraguariensis A. St.-Hill) Leaves. *Communications in Soil Science and Plant Analysis*, *46*(18), 2323–2331.

Roure, F., Serrano, D., Astolfi, P., Bardaro, G., Gabrielli, A., Bascetta, L., & Matteucci, M. (2018). GRAPE : Ground Robot for vineyArd. *Iberian Robotics Conference*, *1*, 249–260.

Sagan, V., Maimaitijiang, M., Sidike, P., Eblimit, K., Peterson, K. T., Hartling, S., Esposito, F., Khanal, K., Newcomb, M., Pauli, D., Ward, R., Fritschi, F., Shakoor, N., & Mockler, T. (2019). UAV-based high resolution thermal imaging for vegetation monitoring, and plant phenotyping using ICI 8640 P, FLIR Vue Pro R 640, and thermomap cameras. *Remote Sensing*, *11*(3).

Salleo, S., Lo Gullo, M. A., Raimondo, F., & Nardini, A. (2001). Vulnerability to cavitation of leaf minor veins: Any impact on leaf gas exchange? *Plant, Cell & Environment*, *24*, 851–859.

Sánchez-Virosta, A., Léllis, B. C., Pardo, J. J., Martínez-Romero, A., Sánchez-Gómez, D., & Domínguez, A. (2020). Functional response of garlic to optimized regulated deficit irrigation (ORDI) across crop stages and years: Is physiological performance impaired at the most sensitive stages to water deficit? *Agricultural Water Management*, *228*, 105886.

Santangelo, T., Di Lorenzo, R., La Loggia, G., & Maltese, A. (2013). On the relationship between some production parameters and a vegetation index in viticulture. *Remote Sensing for Agriculture, Ecosystems, and Hydrology XV*, *8887*, 888715.

Santesteban, L. G., Di Gennaro, S. F., Herrero-Langreo, A., Miranda, C., Royo, J. B., & Matese, A. (2017). High-resolution UAV-based thermal imaging to estimate the instantaneous and seasonal variability of plant water status within a vineyard. *Agricultural Water Management*, *183*, 49–59.

Shamshiri, R., Weltzien, C., Hameed, I., Yule, I., Grift, T., Balasundram, S., Pitonakova, L., Ahmad, D., & Chowdhary, G. (2018). Research and development in agricultural robotics: A perspective of digital farming. *International Journal of Agricultural and Biological Engineering*, *11*, 1–14.

Sharp, R. E., & Davies, W. J. (1985). Root Growth and Water Uptake by Maize Plants in Drying Soil. *Journal of Experimental Botany*, *36*(9), 1441–1456.

Shellie, K. C., & King, B. A. (2020). Application of a daily crop water stress index to deficit irrigate malbec grapevine under semi-arid conditions. *Agriculture*, 10(11), 1–17.

Simeone, M. L. F., Parrella, R. A. C., Schaffert, R. E., Damasceno, C. M. B., Leal, M. C. B., & Pasquini, C. (2017). Near infrared spectroscopy determination of sucrose, glucose and fructose in sweet sorghum juice. *Microchemical Journal*, *134*, 125–130.

Simonneau, T., Lebon, E., Coupel-Ledru, A., Marguerit, E., Rossdeutsch, L., & Ollat, N. (2017). Adapting plant material to face water stress in vineyards: Which physiological targets for an optimal control of plant water status? *Oeno One*, *51*(2), 167–179.

Skewes, M., Petrie, P. R., Liu, S., & Whitty, M. (2018). Smartphone tools for measuring vine water status. *Acta Horticulturae*, *1197*, 53–58.

Smith, R. C. G., Barrs, H. D., Steiner, J. L., & Stapper, M. (1985). Relationship between wheat yield and foliage temperature: theory and its application to infrared measurements. *Agricultural and Forest Meteorology*, *36*(2), 129–143.

Smith, R. C. G., Heritage, A. D., Stapper, M., & Barrs, H. D. (1986). Effect of stripe rust (puccinia striiformis west.) and irrigation on the yield and foliage temperature of wheat. *Field Crops Research*, *14*, 39–51.

Spachos, P. (2020). Towards a Low-Cost Precision Viticulture System Using Internet of Things Devices. *IoT*, *1*(1), 5–20.

Spayd, S. E., Tarara, J. M., Mee, D. L., & Ferguson, J. C. (2002). Separation of Sunlight and Temperature Effects of *Vitis vinifera* cv. Merlot berries. *American Journal of Enology and Viticulture*, *53*(3), 171–182.

Stajnko, D., Lakota, M., & Hočevar, M. (2004). Estimation of number and diameter of apple fruits in an orchard during the growing season by thermal imaging. *Computers and Electronics in Agriculture*, *42*(1), 31–42.

Still, C., Powell, R., Aubrecht, D., Kim, Y., Helliker, B., Roberts, D., Richardson, A., & Goulden, M. (2019). Thermal imaging in plant and ecosystem ecology: applications and challenges. *Ecosphere*, *10*(6), 1 - 16.

Stoll, M., & Jones, H. G. (2007). Thermal imaging as a viable tool for monitoring plant stress. *Journal International Des Sciences de La Vigne et Du Vin*, *41*(2), 77–84.

Stoll, M., Schultz, H. R., & Berkelmann-Loehnertz, B. (2008). Exploring the sensitivity of thermal imaging for Plasmopara viticola pathogen detection in grapevines under different water status. *Functional Plant Biology*, *35*(4), 281–288.

Szigeti, Z. (2008). Physiological status of cultivated plants characterised by multi-wavelength fluorescence imaging. *Acta Agronomica Hungarica*, *56*(2), 223–234.

Tanda, G., & Chiarabini, V. (2019). Use of multispectral and thermal imagery in precision viticulture. *Journal of Physics: Conference Series*, volume 1224, 36th UIT Heat Trasnfer Conference 25-27 June 2018, Catania, Italy.

Tardieu, F., & Simonneau, T. (1998). Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modelling isohydric and anisohydric behaviours. *Journal of Experimental Botany*, *49*, 419–432.

Tisseyre, B., & Taylor, J. (2006). An overview of methodologies and technologies for implementing precision agriculture in viticulture. *XII Congresso Brasileiro de Viticultura e Enologia*, *March 2016*, Bento Gonçalves, Brazil, 45–54.

Tyree, M., Cochard, H., P, C., B, S., & Améglio, T. (1993). Drought-induced leaf shedding in walnut: Evidence for vulnerability segmentation. *Plant Cell and Environment*, *16*, 879–882.

U.S. Army. (2010). Unmanned Aircraft Systems Roadmap 2010-2035. *Federation Of American Scientists*, 1–140.

Vadivambal, R., & Jayas, D. S. (2011). Applications of Thermal Imaging in Agriculture and Food Industry-A Review. *Food and Bioprocess Technology*, *4*(2), 186–199.

Wample, R. L., & Smthyman, R. (2002). Regulated deficit irrigation as a water management strategy in Vitis vinifera production. In *Deficit Irrigation Practices*, 89–100, FAO Water reports 22 ISBN 92-5-104768-5: 89-100.

Wassenaar, T., Baret, F., Robbez-Masson, J.-M., & Andrieux, P. (2001). Sunlit soil surface extraction from remotely sensed imagery of perennial, discontinuous crop areas; the case of Mediterranean vineyards. *Agronomie*, *21*(3), 235–245.

Wisniewski, M., Lindow, S. E., & Ashworth, E. N. (1997). Observations of ice nucleation and propagation in plants using infrared video thermography. *Plant Physiology*, *113*(2), 327–334.

Workmaster, B. A. A., Palta, J. P., & Wisniewski, M. (1999). Ice nucleation and propagation in cranberry uprights and fruit using infrared video thermography. *Journal of the American Society for Horticultural Science*, *124*(6), 619–625.

VINEBOT (2021) https://robotnik.eu/projects/vinbot-en/

Zarrouk, O., Costa, J. M., Francisco, R., Lopes, C., & Chaves, M. M. (2016). Drought and water management in Mediterranean vineyards. *Grapevine in a Changing Environment: A Molecular and Ecophysiological Perspective*, 38–67.

Zufferey, V., Cochard, H., Ameglio, T., Spring, J. L., & Viret, O. (2011). Diurnal cycles of embolism formation and repair in petioles of grapevine (Vitis vinifera cv. Chasselas). *Journal of Experimental*

Botany, *62*(11), 3885–3894.