Thermography in Viticulture

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SUMMARY

Infrared Precision agriculture matches inputs to crop demands, enhancing crop yields and product quality, of-fering economic benefits to the producer, and reducing resource wastage and pollution. Dwindling water resources make precision irrigation an area of particular interest. Precision irrigation is especially appealing in viticulture, where precise regulation of vine water status is necessary to optimize yield and grape (and hence wine) quality simultaneously. Precision irrigation requires monitoring of both spatial and temporal variation in vine water status.

Closure of stomata, the pores on the leaf surface through which gas exchange takes place, is a rapid response to water deficit. Detection of stomatal closure could alert the viticulturist to the need to irrigate. Monitoring stomatal aperture, however, until recently was a very slow process. When stomata are open, transpiration cools the leaves, but when the stomata close, there is no longer any stomatal cooling. As a result, leaf temperature is a good indicator of transpiration rate or stomatal conductance, or conversely of water stress, when environmental conditions are constant. Much progress has been made in determining the impact of a range of variables (meteorological, leaf surface radiative properties etc.) on leaf temperature. This means that even under varying environmental conditions, stomatal conductance can now be estimated from leaf temperature.

Thermal imaging means that the temperature of large numbers of leaves, plants, rows of crops, or even whole fields can be assessed rapidly. Therefore in theory it should be possible to use thermal imaging to detect individual vines that require irrigation, and to determine changing irrigation requirements over time. In practice, there is still some way to go before thermal imaging is used routinely for irrigation scheduling. Whole crops do not behave identically to individual leaves, variation in temperature caused by variability in crop structure can be difficult to separate from variation caused by differences in transpiration, and the best means of removing the effect of variation in meteorological conditions is still unclear. There are additional challenges relating to grapevine. Firstly, it is not a continuous crop, meaning that in overhead images leaf temperatures need to be separated from the temperatures of the soil or ground herbage in corridors between vine rows. Secondly, for many cultivars understanding of grapevine physiology has been derived from measurement on the vertical leaves facing into the corridors, whereas aerial or satellite imaging captures horizontal leaves at the top of vine canopies. Nonetheless, grapevine is one of the best studied crops with respect to thermal imaging under field conditions, and the potential of thermal imaging for detection of spatial variation in vine water status has been amply proven. With sufficient focusing of effort and collaboration between disciplines, the remaining technical problems should not be insurmountable.

There has recently also been some interest in utilizing thermal imaging to better understand different physiological responses in different cultivars, and there is no reason why thermal imaging could not be used for large-scale screening of different genotypes under particular environmental conditions, as is being undertaken as part of genetic improvement programs in other crops. Thermal imaging has also been shown to be useful for pre-visualization detection of pathogen infection and for monitoring the temperature of developing grapes (an important determinant of final grape, and wine, quality). Diverse uses of thermal imaging in other disciplines, such as ecology, may also be found to be relevant to enhancing modern viticulture. Additionally, it is likely that thermography will increasingly be combined with other imaging techniques (near infra-red, chlorophyll fluorescence, multi/hyperspectral, laser-induced) for a more complete understanding of vine, or vineyard, behaviour.

1. INTRODUCTION

Precision agriculture

Precision agriculture matches inputs to crop demands, enhancing crop yields and product quality, offering economic benefits to the producer, and reducing wastage and pollution. Matching inputs to demands means prevention of the range of biotic and abiotic factors that can lead to sub-optimal growing conditions. Since crops do not grow in uniform environments, some sections of crop will need more of certain inputs than others. Requirements will also vary with the stage of crop development, season etc. To prevent a reduction or adverse changes in a crop's growth or development, it is important that alterations in crop requirements can be detected rapidly.

Dwindling water resources make precision *irrigation* an area of particular interest. Climate change will exacerbate water shortages: in the Mediterranean Basin, for example, the summer drought period will lengthen, and heat waves are expected to be more frequent and severe (4, 32), while spring and summer precipitation will decrease by 20-40% (15). Summer droughts are already more frequent in this region than they were 30 years ago (31). Compounded with climate change is increasing demand for water from the domestic and industrial sectors, reducing the quantity of freshwater available for use in agriculture (36). Water use is becoming increasing regulated (e.g. EU Water Framework Directive), with an onus on growers to demonstrate efficient use of water resources.

Precision irrigation is especially appealing in viticulture, where precise regulation of vine water status is necessary to optimise yield and grape (and hence wine) quality simultaneously. Too much irrigation leads to excessive vegetative growth and although yields under these conditions can be very high, this is to the detriment of grape quality (12). On the other hand, where irrigation is not applied, yields can fluctuate dramatically between years. In some vine-growing regions, such as the Alentejo in southern-Portugal, summer precipitation is very limited, while evaporative demand is high, making efficient use of available irrigation water a priority. Moreover, there is increasing interest in using deficit irrigation techniques in order to impose a degree of water stress that enhances grape quality. The risk with such techniques, however, is that too severe a stress could accidentally be imposed, causing a drastic reduction in yield. Sensing plant water status (as opposed to soil or meteorological conditions) is considered the most accurate means of determining irrigation requirements. Thus in viticulture, precision irrigation requires monitoring of both spatial and temporal variation in vine water status.

Stomatal closure

Closure of stomata, the pores on the leaf surface through which gas exchange takes place, is a rapid response to water deficit. Detection of stomatal closure could alert the viticulturist to the need to irrigate. Monitoring stomatal aperture, however, until recently was a very slow process. In research, it is usually monitored with porometers or leaf-chamber methods (Fig. 1A). While these are very sensitive means of measuring stomatal conductance, they are not suitable for routine application in crop production, because their use is too time-consuming: stomatal conductance follows a diurnal course and is also sensitive to changes in the weather, so there is a relatively narrow window in which plants can be assessed, if their stomatal conductance is to be compared.

When stomata are open, transpiration cools the leaves, but when the stomata close, there is no longer any stomatal cooling (Fig. 1B). As a result, leaf temperature is a good indicator of transpiration rate or stomatal conductance, or conversely of water stress, when environmental conditions are constant. We can use this approach to relatively rapidly assess spatial variation in stomatal conductance.

2. APPLICATIONS OF THERMAL IMAGING IN VITICULTURE

Application to irrigation scheduling

Thermal imaging means that the temperature of large numbers of leaves (Fig. 1C), plants, rows of crops, or even whole fields can be assessed rapidly. This has been applied in the vineyard to monitor the impact of water deficit. Grant et al. (18) showed that on several dates in summer in the Alentejo, at different times of day, leaf canopy temperatures were higher in non-irrigated grapevines than in those vines irrigated to match all the water they lost in transpiration.

Moreover, thermal imaging showed canopy temperature differences not only between those extremes, but also between vines that were exposed to different levels of deficit irrigation (not all the water they lost in transpiration was replaced) (Fig. 2). Vines receiving less irrigation had higher leaf canopy temperatures, indicating lower stomatal conductance. Therefore it should be possible to use thermal imaging to detect individual vines that require irrigation. Thermal imaging of ornamental crops for example has successfully indicated areas of the crop inadvertently subjected to water stress (10). This possibility of assessing plant water status over large areas is hugely appealing in viticulture: one vineyard can consist of numerous fields, with different varieties, variation in soil depth, a range of row orientations etc., and to be able to assess water status over such a diverse area from an aerial thermal image would be extremely advantageous for the irrigation manager.

Unfortunately, the approach is not in fact so straightforward to apply in viticulture. Firstly, grapevine is not a continuous crop, meaning that in overhead images leaf temperatures need to be separated from the temperatures of the soil or ground herbage in corridors between vine rows. Secondly, in a commonly used growing system, vertically shoot positioned (VSP), the majority of leaves face into the corridors between vine rows rather than upwards. Thus, for many cultivars understanding grapevine physiology has been derived from measurements on the vertical leaves facing into the corridors, whereas aerial or satellite imaging captures horizontal leaves at the top of vine canopies. For this reason, some recent research has focused on exploring whether thermal images taken from above the vine canopy, from a grape-picker (Fig. 3) provide information on the stomatal conductance of the majority of leaves. Preliminary results have been encouraging (33).

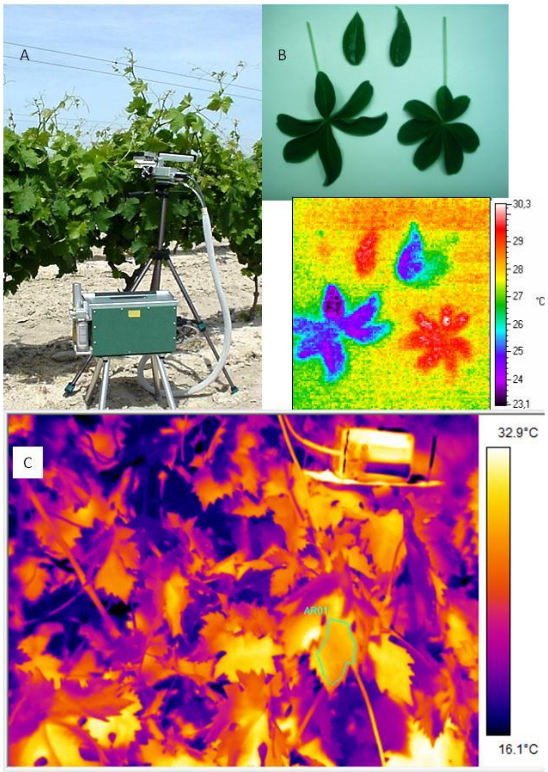

Fig. 1 - An infra-red gas analyser with a vine leaf inserted in the leaf chamber so as to measure stomatal conductance and other features of leaf gas exchange (A), digital (top) and ther-mal (bottom) images of lupin leaves, where the leaf on the right of the images is from a plant that had been subjected to drought, and the leaf on the left is from a plant that had been watered daily (B), and a thermal image of a section of grape-vine, showing a number of leaves (C).

Another problem is that some of the very causes of variation in water status within a vineyard also complicate the application of thermal imaging. Different row orientations mean that some vines are more exposed to solar radiation than others, and different cultivars may have different canopy structures, leading to variation in shading. Even within a cultivar, we have found that variation in soil depth leads to variation in vigour, which in turn results in variation in shading, and hence the relationship between leaf canopy temperature and vine water status is not always consistent. This can be particularly problematic where it is difficult to separate soil and leaf components of a thermal image - for example from an aerial thermal image with relatively low resolution. Soil temperature can vary hugely depending on shading (Fig. 4A-B). Despite this reservation, aerial thermal imaging, even with relatively poor resolution (each pixel equated to about 1 m^2 on the ground) has been shown to very clearly identify areas of a vineyard with greater or lesser soil water availability (11). Moreover, the size and weight of thermal imagers has fallen so much in recent years that it is now possible to install them in micro-aircraft, including unmanned aerial vehicles (3, 5), which fly at lower altitudes, allowing higher resolution imaging.

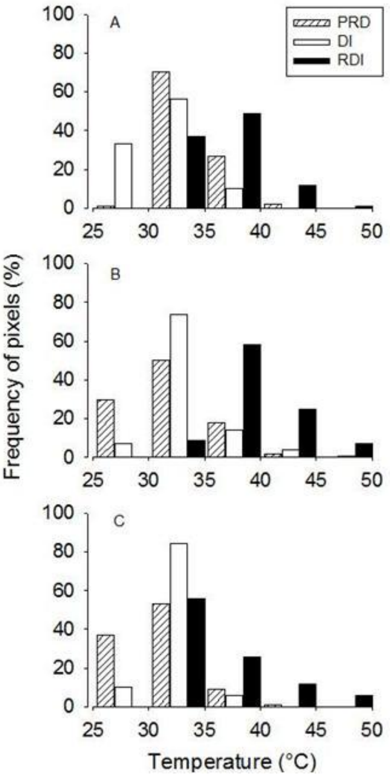

Fig. 2 - The percentage of pixels in thermal images of Aragonêz vines subjected to different levels of deficit irrigation (PRD, DI, and RDI), in three separate sections of a vineyard (A-C). At the time of imaging, less irrigation was applied under the RDI regime than the under the other two irrigation regimes. Hence pixels of images of vines given RDI tended to have higher temperatures. These data were collected in the Alentejo with Ł. Tronina.

In theory, thermal imaging could be applied not only to detecting areas of the crop that need irrigation at a particular point in time, but also to determining changing irrigation requirements over time. In practice, there is still some way to go before thermal imaging can be used routinely for irrigation scheduling. Initially, a major constraint was separation of the impact of changing meteorological conditions from the impact of changing stomatal conductance.

Fig. 3 - H. Ochagavía capturing thermal images of the top of Tempranillo grapevines in Rioja.

Much research has therefore been devoted to separating the impact of environment e.g. air temperature from the impact of stomatal conductance on leaf temperature. One approach is to include reference surfaces within each image. The temperature of the leaves of interest is then calibrated against that of the reference surfaces.

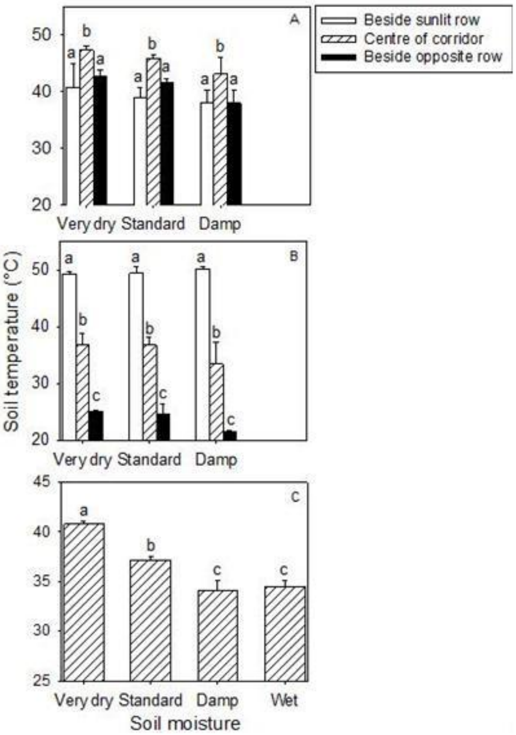

Fig. 4. Temperatures of soils in different classes of soil moisture (A-C) and in different parts of the corridor between vine rows (A-B). A refers to one crop and B-C to a different crop; the two crops differed in row orientation; data in A and B were gathered in August, whereas data in C were obtained later in the season, in September. Within a graph, different letters indicate significant differences at $P < 0.001$. These data were collected in Rioja with H. Ochagavía, M.P. Diago, and J. Baluja (3).

Particularly popular is to use two references, one wet and one dry, representing the extremes of no stomatal resistance and no stomatal conductance, respectively. Various indices are in use, including an adaptation of Idso's (24) Crop Water Stress Index (CWSI), where

$$\mathrm{CWSI} = (T_{\mathrm{leaf}} - T_{\mathrm{wet}})/(T_{\mathrm{dry}} - T_{\mathrm{wet}})$$

where T_{leaf} is the temperature of the leaf/leaves of interest, T_{wet} is the temperature of wet reference surface, and T_{dry} is the temperature of the dry reference. Another increasingly used index (21, 22, 33) is the index I_G (an index of stomatal conductance) (27), where

$$I_G = (T_{\mathrm{dry}} - T_{\mathrm{leaf}})/(T_{\mathrm{leaf}} - T_{\mathrm{wet}}).$$

What to actually use as the reference surfaces, however, is not so straightforward. Firstly, the radiative properties of the reference surfaces need to be similar to those of leaves. Wet and dry filter papers are easy to install within a canopy (28), but the temperature of the wet filter paper has sometimes been found to be higher than that of the leaves of interest (19), even though the leaves would be expected to show intermediate temperatures. Even where the references surfaces have identical properties to the leaves of interest (for example if real leaves are used), differences in the angle of the reference surfaces towards the sun compared to that of the leaves of interest will mean that the reference and the leaves of interest are effectively not in fact in the same environment: a surface will be hotter if exposed to more radiation. Particularly as stomata close, the impact of slight changes in leaf angle on leaf temperature can become large (19). In some work this problem can be solved by forcing the leaves of interest and the reference leaves to the same angle. Grant et al. (21, 22) when screening different strawberry cultivars for variation in response to water deficit, for example, used narrow gauge fishing line to keep leaves flat. Where the average temperature of a large section of vine canopy, rather than the temperature of individual leaves, is used, variation in leaf angle is likely to be less problematic (18). However, forcing a large section of vine to behave as a wet or dry reference is not so straightforward, as preparing such references would be too time-consuming. Grant et al. (18) therefore took the approach of using the temperatures of fully irrigated and non-irrigated vines as references, when interested in vines subjected to deficit irrigation. Although the fully irrigated and non-irrigated vines may not have been perfect extremes (the fully irrigated vines could have had partial stomatal closure for example at midday, and the non-irrigated vines may not have had complete stomatal closure), they were nonetheless suitable references against which the vines of interest could be compared. The difficulty in that case, however, was that it was not possible to include fully irrigated and non-irrigated vines at sufficient spatial replication within the crop so that they could be included in thermal images of each vine of interest. Therefore, the fully irrigated and non-irrigated vines were imaged at intervals, and their temperatures *extrapolated* so as to obtain reference temperatures for *the same time* as each thermal image of the vines of interest was obtained. Although fully irrigated and non-irrigated vines have been used as references in other work (7, 9), to my knowledge this approach of extrapolating the temperatures has never been used since. This, in my opinion, is disappointing, since we know that vine temperature can change substantially within a short period of time e.g. over the morning. Extrapolating the temperatures therefore seems to me to be the only way to ensure that the reference temperatures really relate to the same conditions as the temperatures of the vines that are of interest in the study/monitoring.

Despite the above complications, the expected relationship between I_G and stomatal conductance, measured with a porometer or in a leaf chamber, has been validated under laboratory (26), greenhouse (17) and field conditions (18, 19, 30), and in some cases thermal imaging has been shown to be *more* sensitive than porometry (19, 30). The use of thermal indices rather than leaf temperature alone can accentuate differences (21), aiding their detection, and absolute values of the indices can be quite consistent even over large differences in air temperature. Standardisation of reference surfaces would seem desirable, allowing comparison of different studies, and increasing confidence in a protocol amongst irrigation managers. Research is underway to explore the potential of sensors with wet and dry artificial leaves - the wet 'leaf' in this case being kept wet by means of a wick into a small reservoir of water. Even if such an approach was standardised, however, the size of the artificial leaves would probably need to be adjusted for different species, but the standard model could probably be used for all grapevine work.

In aerial thermal imaging, small reference surfaces such as mentioned above will not be detected within the image, and anyway would not be appropriate. What *is* appropriate, however, is difficult to determine. Some authors have used air temperature + 5°C (1) as the upper (dry) reference, but this is an arbitrary value. The temperature of water in a basin, or of wet material, has been used as the wet reference (1). Water, however, has different radiative properties to leaves, and we have found (data not shown) that the temperature of different materials, even though of the same colour, can vary hugely. Moreover the structure of these flat surfaces is completely different to that of vine leaf canopies. It is interesting to note that in aerial imaging studies, microclimatic variation within the region imaged to date has been completely ignored. Thus there is a need to consider installation of several reference surfaces within a vineyard, to ensure that the reference surfaces are in fact in the same environment as the vines of interest in different sections of the vineyard.

Phenotyping

There has recently also been some interest in utilising thermal imaging to better understand different physiological responses in different cultivars. Modern genetic improvement techniques often require phenotypic information on very large numbers of different genotypes. Imaging techniques, including thermal imaging, allow assessment of the physiological performance of large numbers of plants, such as would not be possible with other, more traditional measurements.

An alternative to the use of thermal indices, is to combine leaf temperature with meteorological information in order to estimate stomatal conductance. This approach was described by Leinonen et al. (30), who found good agreement between stomatal conductance estimated from leaf temperature and that measured with a porometer. Comments above regarding microclimatic variation within a vineyard apply to this method, however, as it is unlikely that there can be more than one full meteorological station on the vineyard. It is possible, though, that some sensors measuring the most variable meteorological variables could be dotted around the vineyard. Air temperature sensors, for example, are cheap and robust. To my knowledge, this approach of combining very fine (spatial) resolution leaf temperature data with low resolution data for some meteorological variables, but medium resolution data for others, has not been tested in any crop or ecosystem. A variation on this idea, which has been assessed in the field and greenhouse (21, 30), is to estimate one of the references (usually T_{wet}) from meteorological data, but include reference surfaces to determine the other.

Measurements such as pre-dawn leaf water potential are not influenced by transitory meteorological changes such as brief cloud cover, or the angle of the leaves relative to the sun at the time of measurement. Such measures still therefore are of importance, but in future could be used *in conjunction* with thermography, rather than as the main means of monitoring water status. Thus thermography would provide frequent assessment of large areas of crop, allowing selection of specific time-points and locations that may require other, more labour-intensive or destructive, once-off or infrequent measurements. Alternatively, occasional thermal images could be used to determine vines of interest for continuous measurement, such as installation of sap flow sensors (13). Sap flow sensors are far too expensive to be used on large numbers of vines, but if a small number of vines in strategic locations are selected (making use of the thermal image to define zones with different water status), they can be used for continuous monitoring of vine transpiration.

Despite these issues, grapevine is one of the best studied crops with respect to thermal imaging under field conditions (8), and the potential of thermal imaging for detection of spatial variation in vine water status has been amply proven. With sufficient focusing of effort and collaboration between disciplines, the remaining technical problems should not be insurmountable.

The only application of thermal imaging in determining of variation in performance of different grapevine varieties, to my knowledge, is that of Costa et al. (9). Vine canopy temperature were found to differ between varieties. Additionally, it is interesting that of all the other measurements conducted (leaf area, specific leaf area, leaf stomatal density, chlorophyll content, pre-dawn leaf water potential, net assimilation rate, stomatal conductance, intrinsic water use efficiency, and pre-dawn maximal photochemical efficiency), only stomatal conductance showed significant differences between varieties in *both* years of assessment. This seems to indicate that measuring stomatal conductance (and hence use of thermography) is one of the most sensitive means to detect physiological/growth variation between grapevine varieties.

There is no reason why thermal imaging could not be used for large-scale screening of different grapevine genotypes under particular environmental conditions, as is being undertaken as part of genetic improvement programmes in other crops (29). Phenotypes may need to determined in a wide range of environments, but given the huge current research interest in drought (20), screening responses to drought seems a useful starting point.

Disease detection

Thermal imaging has also been shown to be useful for pre-visualisation detection of pathogen infection. Stoll et al. (37) found that thermal imaging could be used to detect infection of grapevine leaves with the fungus *Plasmopara viticola* at least three days before symptoms were visible to the human eye. Such early detection of fungal attack clearly could be hugely beneficial in vineyard management, allowing spraying prior to further development of the pest. Interestingly, in that study the temperature response to fungal attack differed between well irrigated and drought-exposed vines, but by assessing variation in temperature within a leaf, rather than absolute temperature, it was possible to routinely detect presence of the fungus, independently of water regime. The study was conducted in a greenhouse, and to my knowledge the potential for using thermal imaging in disease detection of field-grown vines has not yet been assessed, but this is an area worthy of future research.

Other applications

Thermal imaging has also been used for monitoring the temperature of developing grapes (an important determinant of final grape, and hence wine, quality) (37). Apart from an assessment of the reductions in stomatal conductance, monitoring leaf or canopy temperature should be useful as a record of the duration for which leaves are at temperatures above optimal for photosynthesis, which can be incorporated into model predictions of productivity. Thermal imaging of soil rather than leaves may be useful in some instances, although detection of water deficit may only be slower in soil than in leaves: for example in a Rioja vineyard soil temperature was only significantly affected by water deficit in September (see Fig. 4C compared to Fig. 4B), whereas leaf canopy temperature was affected as early as July (data not shown). As water resources dwindle and there is increasing pressure for agriculture to use low-quality water (14), assessment of vine response to saline conditions is likely to be of interest. A wide range of stresses lead to partial stomatal closure, so thermal imaging holds potential in monitoring or exploring responses of vines to any such stress.

Diverse uses of thermal imaging in other disciplines, such as ecology, may also be found to be relevant to enhancing modern viticulture. For example, thermal imaging has been used to monitor shifting vegetation temperatures on mountain slopes, as an aid to predicting vegetation distribution under future climatic scenarios (34, 35). A similar study might be relevant to grapevine grown on slopes. From a different perspective, there is no reason why vineyards could not be used as model systems for studying the impact of climate on agriculture, or *vice versa*. Thermal imaging has been applied to modelling regional fluxes of water (2) and, given the close coupling of stomatal conductance and photosynthesis, holds potential for modelling fluxes in carbon dioxide concentration (40). Frequent thermal images of the same vineyard would aid long-term monitoring of the impacts of climate change on crops.

3. FUTURE

In future it is likely that thermography will increasingly be combined with other imaging techniques (near infra-red, chlorophyll fluorescence, multi/hyperspectral, laser-induced) for a more complete understanding of vine, or vineyard, behaviour.

Care, however, needs to be taken in determining *which* type of imaging is most appropriate. For example, in some species maximal photochemical efficiency, measured as the difference between variable and maximal chlorophyll fluorescence of dark-adapted leaves (F_V/F_M), falls drastically when plants are exposed to drought and high light combined. Substantial variation in this decline has been found between populations (16) and cultivars (23), and therefore chlorophyll fluorescence of dark-adapted leaves is being used in screening for alterations in behaviour in the lab in response to manipulated gene expression (e.g. http://biology.nuim.ie/staff/documents/Olga-Grant.shtml), and for screening for stress tolerance. Chlorophyll fluorescence imaging allows visualisation of non-homogenous responses and/or rapid assessment of large numbers of leaves. F_V/F_M, however, has not been seen to fall much below optimal in grapevine in various field studies in Spain and Portugal. F_V/F_M values were around 0.8 in all five grapevine varieties studied by Costa et al. (9) in August 2006, suggesting the absence of photoinhibition. This agrees with earlier work in the Alentejo (10) and more recent work in Rioja (Fig. 5): there is little photoinhibition in grapevine under drought despite high radiation during summer. Moreover it is clear from Figure 5 that stomatal conductance is a far greater determinant of photosynthetic assimilation (which affects growth, yield, and grape composition) than is photochemical efficiency. This suggests that remote sensing methods relating to F_V/F_M would not be very useful for early detection of stress nor for screening for physiological variation. Chlorophyll fluorescence of light-adapted leaves may be more informative, as this can show an impact of stress even where F_V/F_M is not much affected (19); imaging of chlorophyll fluorescence during sunlight is however very complicated (6).

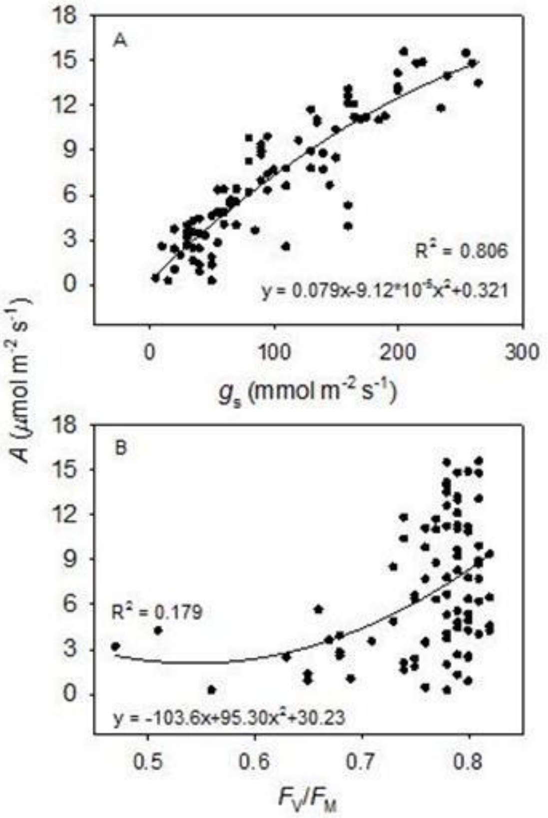

Fig. 5 - The relationship between photosynthetic assimilation rate (A) and stomatal conductance (gs) (A) or maximal photo-chemical efficiency (FV/FM) (B) in leaves of Tempranillo grapevine over the summer of 2010. Equations describe quad-ratic curve fits to the data; both regressions were significant at P < 0.001. These data were collected with H. Ochagavía, M.P. Diago, and J. Baluja.

Hyperspectral imaging is increasingly gaining scientific attention. The Photochemical Reflectance Index based on reflectance at 530 and 570 nm has been considered useful for assessing photochemical function and also water stress (25, 39), and may be worth exploring in grapevine. The clear theoretical basis for using thermal imaging, and the fact that its utility in detecting variation between vines has been proven, however, mean that for the moment where physiological information is required, thermal imaging is unquestionably the most applicable imaging technique for viticulture.

4. CONCLUSIONS

The *potential* of thermography in viticulture has been amply demonstrated in a number of publications over the last ten years. It is now important that viticulturists, engineers, software experts etc. work together to ensure that thermography is applied practically, to improve both the productivity and sustainability of viticulture. While the most explored application of thermography in viticulture is in monitoring vine water status, there are a number of other areas that would benefit from incorporation of thermography into existing or future research programmes.

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