Airborne thermography of vines canopy : effect of the atmosphere and mixed pixel on observed canopy temperature.

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Abstract:

This paper explores the potential of airborne thermal infrared imagery to estimate the temperature of a vine canopy. Experiments were performed at several elevations (from 250 m to 1500 m). The effect of the atmosphere and the occurrence of mixed pixels need to be investigated to know how to correct the measured temperatures from these factors. Two models of corrections based on realistic assumptions were proposed and tested. The atmospheric correction was based on a simple approach which requires the measurement of ground references. It was shown to be effective, providing an estimation of the ground temperature with a RMSE of 0.9 °C. The correction of mixed pixels considers the temperature of the soil and the proportion of the soil and canopy within the pixel. Information on the proportion of canopy at the ground level could be derived from a multispectral image (i.e. NDVI). In the case of a discontinuous canopy like vine, the experiment highlights the significant incidence of mixed pixels on canopy temperature assessment. The correction improved significantly the estimation of the canopy temperature. However, the RMSE remained high (~1.6 °C) showing that our approach doesn't take into account the whole complexity of the phenomenon.

Key words: *Vitis Vinifera*, thermal infrared, remote sensing, canopy temperature, vine water status.

Introduction

Canopy temperature is a good indicator of plant water status (Fuchs, 1990; Idso, 1982; Jackson et al., 1981). With the development of thermal infrared sensors, canopy temperature can be measured without physical contact (Jones et al., 2002; Leinonen & Jones, 2004) and when embedded in airplanes or unmanned aerial vehicles, they could be used to measure temperature over large areas highlighting the variability of the plant water status.

This technology was applied to many crops (wheat, sugar cane, cotton, lemon trees…) and enabled the definition of different indices such as the Stress Degree Day (SDD) (Idso, 1982), the Crop Water Stress Index (CWSI) (Berni et al., 2009; Grant et al., 2007; Jones et al., 2002; Lebourgeois et al., 2008; Leinonen & Jones, 2004; Moller et al., 2007; Stoll & Jones, 2007) and the Water Deficit Index (WDI). To calculate an absolute index of plant water status, these indices require simultaneous reference temperature acquisitions (wet surface, dry surface, air temperature etc.). To simplify the calibration, empirical approaches based on the temperature measurement of a reference vegetation cover (without water stress) were proposed (Clarke, 1997). Although adapted for sparse canopy, these methods require the measurement of a reference corresponding to 100 % plant cover (Clarke, 1997). Because of the rows (~2-3 m large) such reference can hardly be obtained by remote sensing in viticulture for the majority of the training systems.

This is why on vines, to avoid mixed (soil-canopy) pixels, thermography was mainly used close to the plant (Grant et al., 2007; Jones et al., 2002; Moller et al., 2007; Serrano et al., 2010; Stoll & Jones, 2007). However, acquisition information at the plant level is restrictive if the goal is to estimate spatial variability of plant water status at the field or at the whole estate scale. The use of thermography at these scales could bring some advantages like water status zoning based on temperature measurement.
To be realistic, such an application requires an image acquisition (i) at a moderate cost, (ii) at a precise date corresponding to the emergence of a significant water restriction and (iii) with a relevant resolution for mapping spatial variability of each vineyard (minimal spatial resolution of 5 m²). The use of airborne thermal imaging acquired at an altitude above ground level between 1000 m and 2000 m would fit with these specifications. Using such flight altitudes could bring information on a whole vineyard or co-operative scale with a limited number of images, minimizing thereby the cost of acquisition and processing. To our knowledge, image acquisition at these altitudes above ground has never been tested on vines.
However, such an approach raises two questions that need to be investigated: (i) the atmospheric layer between the plant and the camera absorbs a significant proportion of radiation emitted by plants (Cassanet, 1984), (ii) most vineyards are planted in rows and the soil is not totally covered; it is therefore impossible to separate soil from vegetation if the resolution is close to the inter-row distance. In this case, the observed temperature value of a so called *mixed pixel* is a combination of both the temperature of the soil and of the canopy.
The aim of this paper is to present the results of an experiment set up to study the impact of the atmosphere and the presence of mixed pixels (canopy, soil) on the temperature measurement of the vine canopy with airborne thermography images. This paper also proposes two approaches to correct these effects. Quality and relevance of the corrections are discussed.

Material and Methods

Experimental field

Experiments took place in the vineyard of Pech-Rouge (INRA-Gruissan, N 43°08’47’’, E03°07’19’’ WGS84, Languedoc-Roussillon region, France). They were carried out on a 1.2 ha field, planted in 1990 with Shiraz. It is a non-irrigated field with a spacing of 2.5 m within rows and 1.1 m within vines. The vines are trained in vertical shoot positioning system approximately 1.7 m high. Direction of the rows is North-North East. The experimental field is known to exhibit a significant spatial variability of the vine water status (Acevedo-Opazo et al., 2008).

The thermal image acquisition

The images were acquired with an aircraft equipped with a B20 HSV FLIR micro-bolometer thermal infrared camera. The radiance, detected over the 7.5 – 13 µm spectral intervals, is converted to brightness temperature. The system provides a 240x320 pixel images with a radiometric resolution of 0.1°K (www.flirthermography.com). An embedded GPS recorded flight elevation, speed (average speed 40 $m.s^{-1}$) and direction, which was perpendicular to the vine rows.
Several images were taken at different altitudes (see Table 1) in order to study (i) the influence of the atmospheric layer between the ground and the sensor and (ii) the incidence of mixed pixels. One or two images were taken for each altitude. The flight took place the 29th of July 2008. Experiment lasted 37 min. from 11:23 to 11:50, close to solar noon to minimize shadows due to the vines rows.

Table 1. Image acquisitions

Altitude above ground	Number of images	Image footprint	image resolution
248 m	1	part of the field	0.23 m/px
353 m	1	part of the field	0.33 m/px
456 m	2 (duplicates)	part of the field	0.45 m/px
752 m	2 (duplicates)	Whole field	0.78 m/px
1512 m	2 (1511 and 1513 m)	Whole field	1.65 m/px

Ground data

During the flight, the temperatures of several references were monitored. Three references were considered : cold (white sheet), hot (black sheet) and a soil square. They had an area of 20 m² and were therefore visible at each elevation. Radiant temperature of each reference was measured every 5 minutes with a hand-held infrared thermometer (MiniTemp, MT4, Raytek®, Beijing, China). A portion of pine forest was also used as a reference on the images for a continuous vegetation cover (Fig. 1).

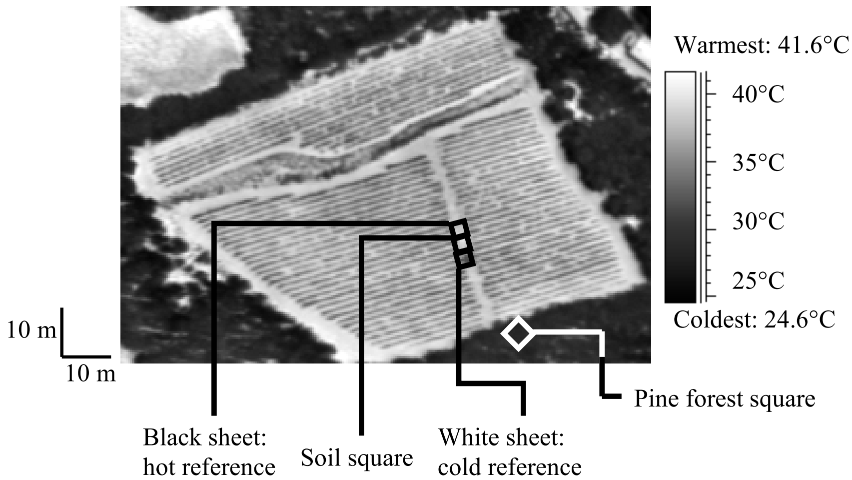

Figure 1. Brightness temperature image of the experimental vineyard and reference targets collected at 750 m altitude above ground.

Empirical correction of brightness temperature

The method hypothesised that whatever the altitude above ground *i*, the fraction $\frac{Tg_i - Tf_i}{Th_i - Tf_i}$ (where Tg_i = observed brightness temperature of an object, Th_i and Tf_i = observed brightness temperature of respectively the hot and cold references) remains constant. Hence, with the ground references temperatures of hot and cold targets Th_0 and Tf_0, it is possible to estimate the brightness temperature of an object at the ground level Tg_0 from brightness temperatures of the object and of hot and cold target references collected at altitude *i*, as shown in equation 1.

$$\hat{T}g_0 = \left[\left(\frac{Tg_i - Tf_i}{Th_i - Tf_i}\right) \times \left(Th_0 - Tf_0\right)\right] + Tf_0 \qquad (1)$$

Effect of mixed pixels (canopy-soil) on observed brightness temperature

To test the incidence of mixed pixels on observed brightness temperature, three assumptions were made: (i) only two kinds of objects can be encountered, the soil and the canopy, (ii) the temperature of a mixed pixel (or set of mixed pixels) *Tm* is a linear combination of *Tc* the temperature of the canopy and *Ts* the temperature of the soil, (iii) the importance of *Tc* or *Ts* in *Tm* is directly determined by the proportion of each element within the mixed pixel. These assumptions lead to modelling the effect of mixed pixels as indicated in Equation 2 where *ac* is the proportion of the area with vine canopy within the pixel (or a set of pixels).

$$Tm = ac \times Tc + (1 - ac) \times Ts \qquad (2)$$

In order to test and validate the proposition (Eq. 2), a database made of 46 squares (named SQ in the rest of the document) was determined. The location of the center of each SQs was randomly defined with the constraint to be within the vine field. Each SQ had an area of 13.6 x 13.6 m. Within each SQ, the proportion of mixed pixels varied depending on the different spatial resolutions (Table 1). For the image collected at 250 m of altitude above ground, it is possible to find a high proportion of pure pixels (soil or canopy), but at 1500 m, all the pixels can be considered as mixed (see Figure 2). The image at 250 m was then used to extract, for each SQ, (i) *ac* the proportion of area occupied by the canopy, (ii) *Tc* the average temperature of the canopy and (iii) *Ts* the average temperature of the soil. *Ts* was assumed constant over the vine field since standard deviation of brightness temperature of soil pixels of all SQs for the 250 m altitude was 0.6 °C. It was then defined as the mean soil temperature over the 46 SQs.

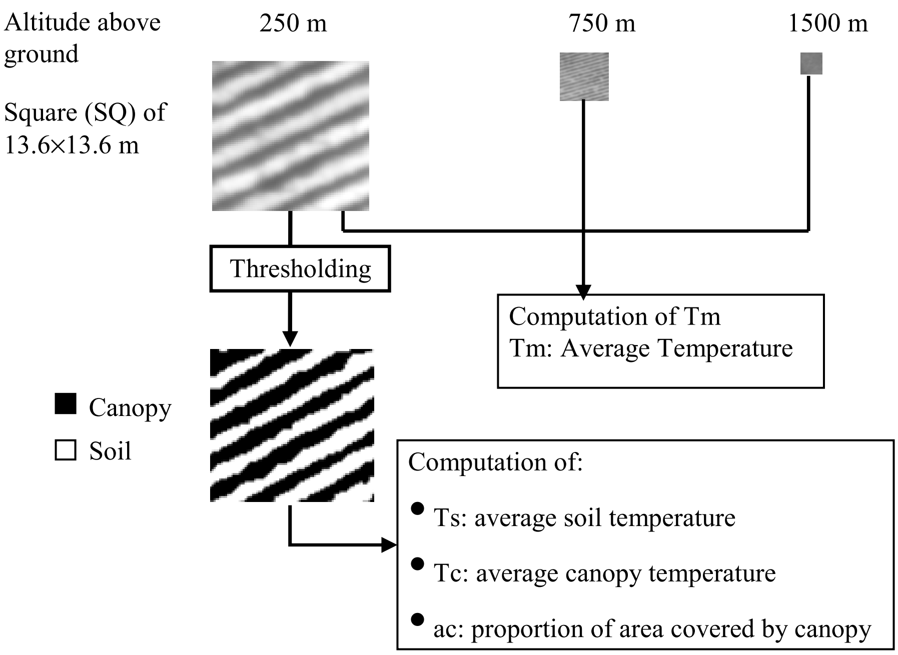

Figure 2. Method used to study the effect of mixed pixels

The segmentation of the soil and the canopy was performed by thresholding temperature values on the image collected at 250 m of altitude above ground. The mean temperature *Tm* of each SQ was then calculated for each altitude and was corrected according to Equation 1. The estimated brightness temperature of the canopy was then calculated using Equation 2. Figure 2 illustrates the method used to extract the information of a SQ from the image.

Tc_i, the brightness temperature of the canopy determined from the image at 250 m of altitude was considered as a reference for each SQ i. Two average deviations were then computed for each altitude (Equation 3); Δs (no correction) the average deviation between Tm the mean brightness temperature of the SQs and Tc. Δc (mixed pixel correction) the average deviation between $\hat{T}c$, the estimated brightness temperature of the canopy from Equ. 2 and Tc.

$$\Delta s = \frac{1}{46}\sum_{1}^{i=46}\left(Tm_i - Tc_i\right) \qquad \Delta c = \frac{1}{46}\sum_{1}^{i=46}\left(\hat{T}c_i - Tc_i\right) \tag{3}$$

Results

Effect of the atmosphere

Figure 3 shows that the observed brightness temperature decreases with elevation for all considered targets. This highlights the effect of radiance attenuation by the atmosphere(Cassanet, 1984). This effect is characterized by (i) a larger decrease of observed brightness temperature for warmer objects, (ii) a magnitude of observed brightness temperatures variation between the hot and the cold target which decreases with the altitude above ground and (iii) as expected, most of the attenuation is due to lower atmosphere. Figure 3 also shows that a correction of brightness temperatures is required if an estimation of the ground temperature is required.

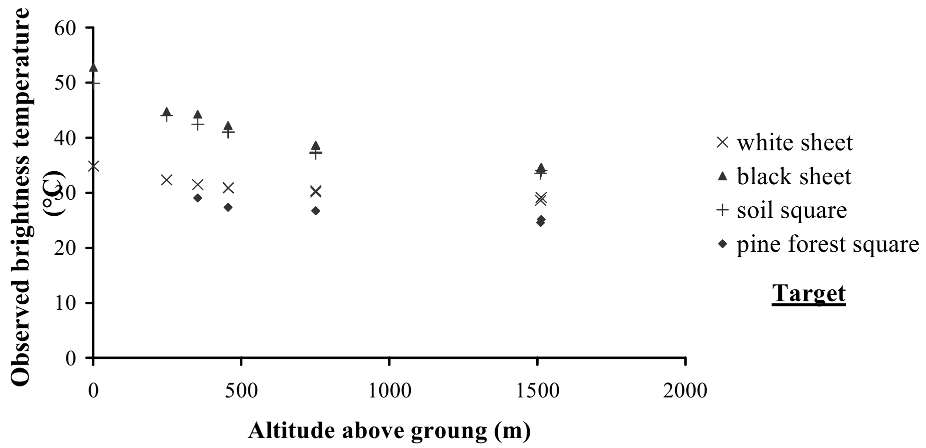

Figure 3. Observed brightness temperatures of the different targets at different altitudes above ground level.

Assessment of the empirical correction of the atmospheric effect

Table 2 summarizes the results of the empirical atmospheric correction performed according to Equation 1. The only temperature known at ground level, beside the ground references temperatures of hot and cold targets used for the correction, was that of the bare soil and therefore was used for evaluating the correction. The reference value of the bare soil temperature reference target was 49.88 °C. It is the mean of all the measurements taken throughout the experiment. Note that a significant variability of the ground temperature was observed during the experiment (σ = 1.4 °C). This variability is mainly due to the random occurrence of a slight breeze which affected the temperature of the soil surface during the experiment.

Table 2. Results of the empirical atmospheric corrections for bare soil brightness temperature

Reference temperature : 49.88 °C (σ = 1.4) (ground temperature of bare soil reference target)

altitude above ground level	Observed brightness temperature (°C)	Δm	Corrected brightness temperature (°C)	Δe
248	44.02	5.86	51.73	1.85
353	42.45	7.43	50.24	0.36
456	41.01	8.87	50.89	1.01
456	41.07	8.81	51.03	1.15
752	37.39	12.49	50.12	0.24
752	37.15	12.73	49.8	0.08
1513	34.07	15.81	50.88	1.00
1511	33.53	16.35	49.93	0.05

Δm: Deviation between observed brightness temperature and measured ground temperature
Δe: Deviation between corrected brightness temperature and measured ground temperature

For each altitude above ground level, table 2 presents the deviation (Δm) between the observed brightness temperature and the ground temperature of the bare soil reference target and the deviation (Δe) between the corrected temperature and the reference temperature. Without correction, the deviation is clearly proportional to the altitude. The largest deviation (Δm ~16°C) was obtained for altitude of 1500 m. The proposed correction significantly reduces the deviation for all the altitudes (RMSE 0.93 °C). Unlike Δm, Δe values are randomly distributed and do not increase with elevation which shows that our method of correction is not dependent on the elevation. Figure 4 shows the scatter plot and regression line of corrected mean brightness temperature collected at 752 m altitude above ground level against that collected at 248 m for the 46 squares (SQs) used for the assessment of the mixed pixel effect. After correction, the brightness temperatures of the SQs of two different images collected at different altitudes are strongly correlated and very similar.
Deviations of corrected brightness temperatures reported in Table 2 from ground measurements may be due to the fact that ground and airborne measurements were not perfectly synchronized, thus allowing changes in weather conditions (wind, even low) to affect the measurements.

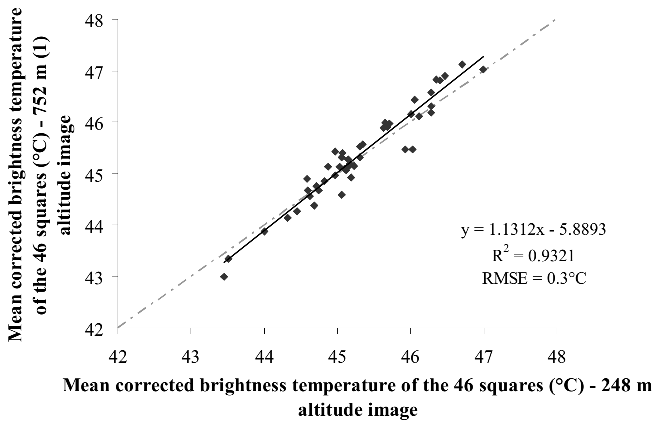

Figure 4.– Comparison of the mean corrected brightness temperature (Tm) for the 46 vineyard squares (SQs) between two images collected at different altitudes above ground level

Effect of mixed pixel

Results of the mixed pixels model (Eq. 2) are presented in Table 3. It presents the average deviation for all the SQs together with (Δc) and without (Δs) correction of the mixed pixel. Before applying the mixed pixel correction, the data were made comparable by the correction for atmospheric attenuation. First, deviations without any correction of the mixed pixels (Δs) are presented; they are around +4°C regardless of the flight altitude. By taking into account the proportion of soil and the temperature of the soil, the deviation decreased significantly to around -0.1°C. The quality of the correction tends to remain constant whatever the considered elevation.

Table 3. Average deviation between mixed pixels brightness temperature and estimated canopy temperature

Altitude AGL	353 m	752 m	752 m	1513 m	1511 m
Δs (deviation without correction)	+ 4.01 (σ =0.53)	+ 3.99 (σ =0.44)	+ 4.02 (σ =0.54)	+ 4.03 (σ =0.63)	+3.99 (σ =0.54)
Δc (deviation with correction)	-0.08 (σ =1.03)	-0.11 (σ =1.10)	-0.08 (σ =1.04)	-0.03 (σ =1.07)	-0.06 (σ =1.18)

Note that the results of image at 450 m were not presented in Table 3. For this particular image, only a small part, centered on the targets, was visible. It was then difficult to define a sufficient number of SQs.

Results presented in Table 3 show that in discontinuous canopy like vines rows in a vineyard, the relative vegetation/soil coverage affects significantly the measurement of brightness temperature by remote sensing. In the experimental condition (sunny day at solar noon), the soil was hot (~50 °C) compared to the vine canopy (~35 °C). An estimation of the vine canopy based only on the temperature of a mixed pixel led to over-estimate the temperature of the canopy. Using a mixed pixel correction like the one proposed (Eq. 2) removed this effect, improving significantly the accuracy of the canopy brightness temperature estimation. Note however that the mixed pixel correction improved the standard deviation of the deviation (Table 3).

The scatter plot and regression line reported in Figure 4 compare the estimated canopy brightness temperatures resulted from the application of the mixed pixel model to the image collected at 750 m altitude with reference canopy brightness temperatures computed from the 250 m altitude high resolution image. As shown in Fig. 4, significant canopy temperature variability occurred at the within-field level. The lower canopy temperature is 34 ° C while the highest is 37 ° C.

Figure 4 shows an over-estimation of the high canopy brightness temperatures and an under-estimation of the low canopy brightness temperatures for the image collected at 750 m altitude as a consequence of the mixed pixel model application. This result highlights the limitations of the proposed approach to extract canopy brightness temperature from mixed pixels. On this specific vine field, Acevedo Opazo et al. (2008) showed that the higher the water restriction, the lower the canopy area and vice versa. Therefore SQs with low canopy temperatures present high canopy areas (and low water stress). We can also assume that the soil temperature can be locally affected by the volume of biomass (shadow effect). The more is the biomass the colder is the soil temperature and vice versa. This assumption needs to be investigated. However, at this stage of the research, results show that canopy temperature estimation by correction of mixed pixels requires a more complete model than the one proposed.

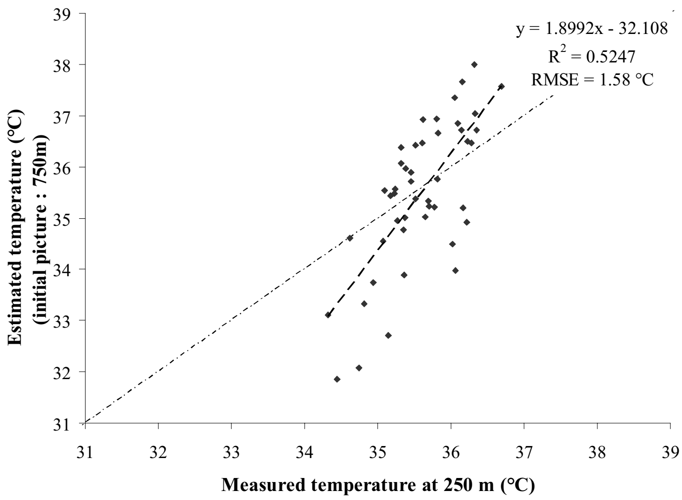

Figure 4. Scatter plot and regression line of estimated (image altitude 750 m) against observed (image altitude 250 m) canopy temperature

Conclusion

This study shows that the use of airborne thermal infrared images to estimate the canopy brightness temperature at an altitude above ground level on a discontinuous vegetation cover like vines rows in a vineyard requires the information to be pre-processed. Results indicate that the effect of the atmosphere attenuation is significant and must be corrected also for low flight altitudes (i.e., 250 m). A simple empirical correction of atmospheric attenuation, based on hot and cold ground reference targets, has proved to be effective. The correction of the effect of mixed pixels seems more problematic. This study showed that in typical conditions existing when water stress is determined (i.e., solar noon, summer) mixed pixels lead to a marked over-estimation of the brightness temperature of vines canopy. A simple model based on the determination of soil temperature and the proportion of area occupied by soil and canopy may be considered. Such an approach has the advantage of being realistic: the proportion of vegetation could be determined from vegetation indices obtained from a multi-spectral image (e.g. NDVI) and soil temperature could be estimated from pure soil pixels (path, field border, etc.) in the thermal image. The results showed that this approach could be effective if the goal is to define major classes of canopy temperature at the whole vineyard scale but it can't provide accurate estimations of the canopy temperature. Assumptions have been made to explain these limitations. They have to be the subject of future investigations.

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