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Contribution of High-Resolution Multispectral and Thermal-Infrared Airborne Imagery to Assess the Behavior of Fruit Trees Facing Water Stress: Proof of the Concept and First Results in an Apple Variety Field Trial

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ABSTRACT

A combined airborne thermal and multispectral imagery campaign was performed by UAV in two apple variety trials (flights at 40m elevation) located in South France. Both experimental orchards were dedicated to the assessment of various tree traits, including the response to water deficit. Subplots of each variety were submitted either to normal irrigation (WW), scheduled on the basis of soil hydric potential, or to water restriction (WS) during summer period (July 2015). *In planta* measurements performed in these 'genotype by environment' experiments comprised the monitoring of fruit diameter increase, the assessment of tree water status by stem or predawn leaf hydric potential, while local microclimatic data were also collected. Thanks to remotely-sensed thermal imagery, significantly higher canopy temperatures were found in WS trees compared to WW ones (average of 3 trees), and also significant differences in narrow-range spectral wavebands (multispectral images), and the vegetation indices calculated (NDVI, GNDVI and PRI). Differences were linked to the severity of water deficit reached, assessed by hydric potential, which varied significantly according to the genotype. Two varieties -more water spending- experienced a characteristic water stress while two others -more water saving- were less affected by water deficit, as revealed by image- and tree-based variables. The experiment thus demonstrated the potential of multispectral and thermal high resolution imagery to non-invasive phenotyping of fruit trees cover.

Keywords: Apple, water stress, remote sensing, multispectral sensor, canopy surface temperature, France.

1. INTRODUCTION

In the context of climate change, long drought periods are susceptible to occur more frequently during summer, notably in the Mediterranean region (Giorgi & Lionello, 2008). This will potentially threaten the production of temperate fruit trees, in particular where irrigation is under pressure of limited water resources. Agronomic improvements consist of improved irrigation systems and practices in orchards, aiming at precise management of a scarce resource, and can also be searched through mild restriction during periods of limited yield sensitivity to water

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withholding. Nevertheless, adaptation of fruit trees to water stress appears as a new challenge for fruit breeders (Virlet et al., 2014, 2015). Moreover, new varieties tested prior release to fruit growers could benefit from a double assessment: in conventional but also non-optimal cropping conditions, including water input. This consideration has been determinant for setting-up the Aliage-Fruit program (2014-17) during which the behavior of different new apple varieties facing irrigation limitation was investigated in a field trial.

Remotely-sensed spectral readings in crops are based on the interaction between incoming solar radiation and plant target organs that can be investigated through signature of reflected light. Such signatures are typically used to calculate spectral indices, which are a function of the light absorption properties of the plant at given wavelengths, and can reveal modifications of plant cover structure and/or functions. Moreover, under water deficit, the immediate plant response is stomatal closure, which limits transpiration and the loss of latent heat flux. This causes an increase in canopy surface temperature (T_s), accessible to thermal imagery, and T_s increase is an efficient and precocious indicator of the plant response to drying soil, because stomatal closure occurs before any other change in plant water status (Jones, 2004).

While feasible, proxy-detection of plant responses is usually restricted to a limited number of plants. By contrast, remotely sensed imagery, particularly from unmanned aerial vehicles (UAVs), has received large interest due to low-costs and capacity to meet the requirements of spatial, spectral, and temporal resolutions (Berni et al., 2009). These authors made use of a combination of narrowband multispectral imaging, and thermal infrared imaging. These approaches have been proposed for assessing spatially the plant water status and/or response to water stress detection over whole field crops. This method provides useful instantaneous information over field trials (Meron et al., 2010), and also appears as a promising phenotyping method for detecting differences in stomatal behavior (Jones et al., 2009; Tattaris et al. 2016). As stomatal regulation limits water loss and gas exchange in the same time, it can also affect the plant carbon assimilation capacity and further fruit growth and yield. An important question to address for fruit trees is therefore the ability of varieties to maintain their yield and/or fruit quality under water limitation or dysfunction of the irrigation system.

In this paper, we aimed at assessing (i) the capacity of a conventional fruit variety trial to host different water regimes in order to capture eventually contrasting plant responses, and (ii) the contribution of remotely sensed thermal and multispectral imagery to characterize the behavior of different tree varieties facing water stress at the same time.

2. MATERIAL AND METHODS

2.1 Field set-up

Field experiments were carried out in 2015 in two field apple pre-commercial variety trials respectively located in the South of France, in CTIFL Balandran (N43°76, E04°46, 54m above sea level) and CEHM-SudExpé, Marsillargues (N43°.63, E04°17, 4m a.s.l.). Trees were adult (planted from year 2005 to 2008) and grafted onto type 9 rootstock, with at least 20 trees per

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genotype. The orchard was managed according to the professional practices in force, with trees annually pruning and thinning, integrated fruit production and grassing of the inter-rows. The planting distances were 4m between rows and variable within the row (1.20m to 1.30m in Ctifl, 1.50m in CEHM). Varietal plots (a minimum linear 10m) were divided in two parts: a full irrigation (WW) was scheduled in the half plot, aiming at maintaining satisfactory soil water availability (Watermark® probes, Ctifl) or content (Sentek® capacitive probes, CEHM), while a half irrigation regime (WS) was applied in the other half during one month, either by using half-rate drippers (Ctifl) or simply by stopping irrigation (CEHM). Five apple varieties were planted in common in the two locations (Table 1).

Table 1. Characteristics of the varietal trial located at CEHM-SudExpé

Variety	Rootstock	Plantation (spring)	Water treatment	Row Nr	Planting distance	Tree age in 2015	Observation in 2015
Coop 39	Pajam 1	2004	WW	26	4m x 1m	12y	-
Coop 39	Pajam 2	2005	WS	27	4m x 1m	11y	-
Inored	Pajam 2	2005	WW and WS	30	4m x 1m	11y	-
Coop 43	9 EMLA	2006	WW and WS	32	4m x 1m	10y	-
Inolove	Pajam 2	2007	WS	33	4m x 1m	9y	Few fruits
Inolove	Pajam 2	2007	WW	34	4m x 1m	9y	Few fruits
Gradiyel	Pajam 1	2007	WW and WS	34	4m x 1m	9y	-

In planta measurements made in each trial comprised: (i) a continuous monitoring of branch growth thanks to micro-dendrometers ('Inored' cv., 3 tree replicates per water regime), (ii) a weekly monitoring of equatorial fruit growth 30 fruits on WW trees and 30 fruits on WS trees, equally distributed between the east and west faces), and (iii) assessment of tree water status during the days of remote sensing acquisitions by measuring the predawn leaf water potential (3 leaves per tree * 3 trees, pressure chamber 3000, PMS Instrument) before each flight then the diurnal stem water potential (measured on non-transpiring leaves, after insertion in aluminized waterproof bags during 2hrs) immediately after each flight.

2.2 Remotely sensed imagery

A multi-rotor Unmanned Aerial Vehicle (UAV) was used as vector for performing the flights. This octo-rotor UAV (Mikrokopter®) can carry a payload of 1.5 to 2kg with a flight time of 8 to 10 minutes, which is compatible with remotely-sensed thermal imagery over the field trial on sunny days. Zenithal images were acquired at 40m altitude and flight time was 4-6 minutes approximately, depending on wind conditions. The image along-track overlap was 80% and cross-track overlap was 60%, a series of 15 UAV navigation waypoints being fixed within each flight. The number of images needed to cover the whole field varied according to the sensor used and the orchard site. Over the field plot, a total of 15 ground control points (GCPs) were also placed and geo-referenced using an RTK GPS (Leica Geosystems®) with an accuracy of 1cm.

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The auto-stabilizing UAV gimbal was equipped with different sensors. Thermal IR acquisitions were performed by a low weight Thermoteknix Miricle 307K uncooled camera (640x480 pixels) which acquired in video mode during the whole flight. Multispectral acquisitions were realized either by using two Sigma DP1x digital cameras (2640 x 1760 pixels), one acquiring in RGB bands, the other modified to acquire near-IR images, both programmed to take pictures at each waypoint, or by using an AirPhen 6-channel multispectral camera prototype (Baret, unpublished) conceived to acquire spectral reflectance in blue (450nm), green 1 (532nm), green 2 (568nm), red (675nm), red edge (730nm) and near-infrared (850nm) bands (images in each band being acquired at 1s-interval). With these devices, the combination of the spectral information made it possible to compute different structural and functional vegetation indices, such as NDVI (proxy for crop vegetation fraction and activity, Rouse et al., 1974), Green NDVI (canopy structure and chlorophyll content, Gitelson et al., 1996), and Photochemical Reflectance Index (PRI, proxy for Photosystem II efficiency and radiation use efficiency, Gamon et al. 1992) (Table 2). Tree canopy surface (T_s) minus air temperature (T_a) was used as water stress index (Idso et al. 1981).

Table 2. Three spectral indices calculated from the 6-channel multispectral camera

Indices	Formula	Interest	References
Normalized Difference Vegetation Index NDVI	$(R_{850}-R_{675}) / (R_{850}+R_{675})$	Green area index, proxy for leaf area index, intercepted radiation	Rouse et al., 1974
Green NDVI GNDVI	$(R_{850}-R_{568}) / (R_{850}+R_{568})$	Green area index, more sensitive than NDVI to chlorophyll concentration	Gitelson et al., 1996
Photochemical Reflectance Index PRI	$(R_{568}-R_{532}) / (R_{568}+R_{532})$	Xanthophyll cycle, state of photosystem II, proxy of radiation use efficiency	Gamon et al., 1992

Retrieval of thermal image from video file was carried out according to Gómez-Candón et al. (2016): the procedure used a self-developed software written in Python language developed for automatically performing the process with the avconv command line interface for transcoding multimedia files (Libav Open source video and audio processing tools, www.libav.org). The thermal camera had a system for continuous self-calibration set to occur every 4 seconds, and only the first frame after every self-calibration event was retrieved. After extraction, each raw frame was automatically transformed into the desired format. Geometric correction of thermal images was based on lens correction coefficients provided by camera manufacturer. Brightness temperatures of ground thermal targets were acquired continuously during the UAV flights by IR-120 thermoradiometers. These data were used as references to calculate linear regressions (linking digital numbers to thermal values) for further calibration of thermal images.

2.3 Multispectral and thermal image processing

Preprocessing of UAV image series was optimized according to Gómez-Candón (unpublished, Figure 1). Briefly said, PhotoScan software (Agisoft) was used for digital images processing and

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generating a mosaic image of the entire plot; this involved several steps: automatic or manual detection of georeferenced targets, construction of a 3D structure, projection of the photos on this structure and building of the orthorectified image. Georeferencing relied on the field Lambert 93 GCPs coordinates. Post-processing made use of Erdas Imagine software to extract the desired information from individual apple tree canopy considering a central buffer zone of 0.60 m radius delineated around each tree center (geolocated) and including the individual canopy projection.

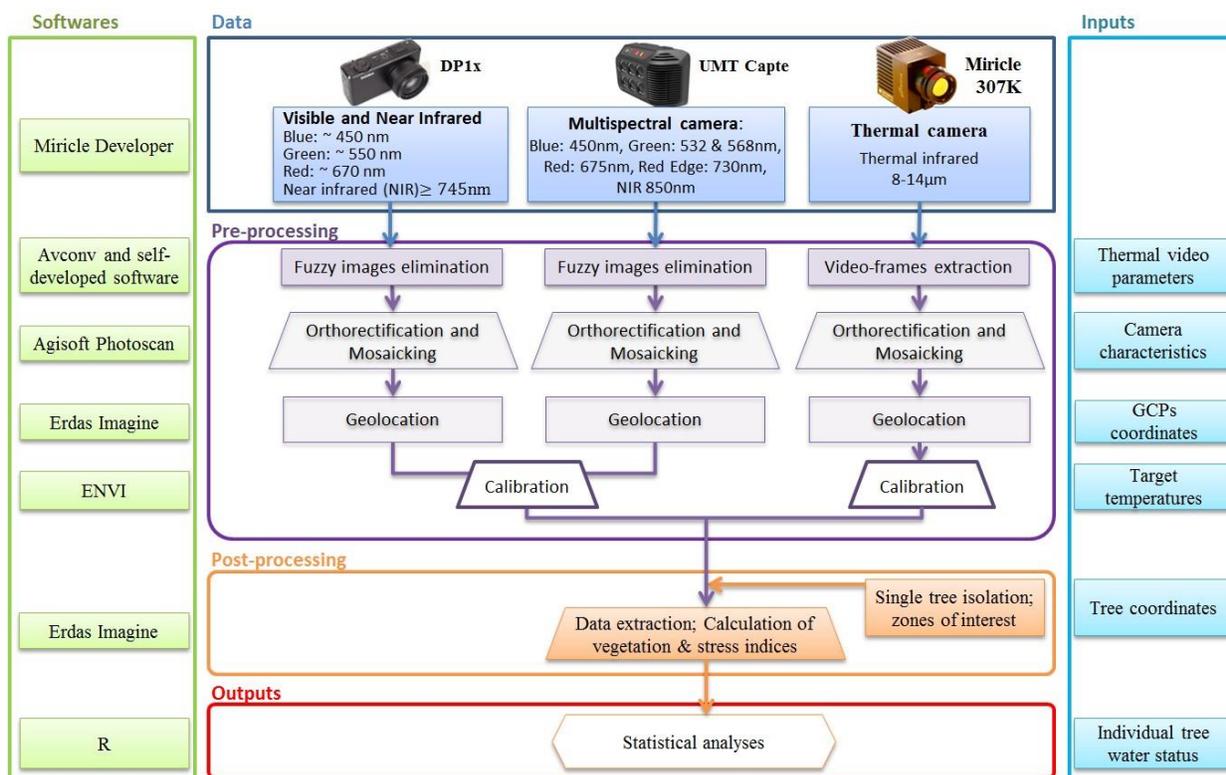


Figure 1. Simplified flowchart for processing high-resolution remotely-sensed images acquired during UAV flights. The diagram presents two possibilities: visible + near infrared acquisition performed by two DP1x digital cameras, giving access to four spectral broad wavebands, and true multispectral acquisition performed by a multispectral camera prototype, giving access to six narrow bands (spectral resolution 10 to 20nm). The softwares used are indicated on left panel, and the inputs required on right panel.

High-resolution images of vegetation scenes were obtained (ca. 2 cm in multispectral and 10 cm in thermal infrared) thanks to the 40m flight elevation. A down- or up-scaling of images to 5-cm pixels was performed by Erdas Imagine® software in order to obtain plant stackable pixels relative to different wavebands. This medium resolution gave access to spectral data which were retrieved at the individual tree scale, in the tree central zone (ca. 300 pixels); this was done four times at a 7-10 day step-time in July, whereas drought stress was progressing for WS trees in the trial. Two to four flights per day were performed, in function of meteorological conditions (wind speed less than 3 m s^{-1} , absence of nebulosity), in order to give access to intra-day dynamics.

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2.4 Statistical analysis

Once pixels related to each tree individual were extracted from image layers, a spreadsheet was established identifying in columns the tree attributes (variety and replicate number), the pixel Lambert coordinates and the reflectance values in the different spectral bands (RGB and NIR, or multispectral and NIR, and thermal IR). Additional columns were created for computation of vegetation and stress indices. Vegetation and water stress indices were submitted to statistical analyses as follows: a first two-way analysis of variance (ANOVA) was performed under the R (version 3.3.2) `Aov` command after Bartlett test for homogeneity of variances. We first considered each apple tree variety separately to assess the respective effects of the water treatment (WW vs WS) and the tree factor (3 individuals). A second ANOVA was then performed considering two factors: the apple variety and the water regime. Results of these analyses were considered in relation with the water status reached by the trees. Finally, a principal component analysis was realized using the `FactoMine` R library, in order to assess the possible relations between the indices.

3. RESULTS AND DISCUSSION

The climatology of July 2015 was very conducive to the trial, due to the absence of rain (except July 31st), on both sites. On a daily base, average air temperatures fluctuated between 22° and 29°C, and atmospheric vapor pressure deficit peaked at midday, reaching a maximum of 2.5 to 3.0 kPa. Focus is put here on the apple variety trial in CEHM-SudExpé site, and more particularly, for imaging results, at the end of water stress period (July 27th & 28th). In CEHM-SudExpé, the monitoring of soil water content (Sentek probes measuring soil moisture at 30, 50 and 70 cm) indicated that field capacity was replenished twice a week on WW trees, while it was rapidly depleted (in nearly 7 days) in the WS treatment. For this reason, on July 17th, a limited irrigation (18mm) was performed on trees of WS treatment to avoid excessive water stress. This may have slightly affected the results for these trees on July 20th.

3.1 *In planta* measurements

The micro-dendrometric monitoring of diameter growth of framework branches (Inored variety) indicated a slow rate of branch growth in WW trees, based on daily maximum, while a clear shrinkage in branch diameter occurred within 3 to 5 days in WS trees (-300 to -500µm), according to the tree individuals (results not shown). Fruit growth was negatively affected by the WS treatment applied over the July 2015 period, which produced a more or less precocious and severe water constraint according to the variety. The growth limitation effect was nil for Gradiyel, limited for Inolove and Coop 43 (-2 to -3mm), intermediate for Coop 39 (-4mm), and more severe for Inored (-7mm). For the last two varieties, fruit diameter growth slowed in WS trees as soon as 3-4 days after irrigation interruption (July 3rd), and this fruit growth deficit occurring in July was maintained until fruit harvest even after normal irrigation resumption (August 4th) whatever the treatment.

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Leaf and stem hydric potential measurements, that are commonly used as water stress indicators (Naor, 2006), showed the same tendencies as those expected (i.e. minimum values during the day, and lowering trend according to tree water status). Figures 2 (A, C, E, G) present the minimum Ψ reached at 12:30 (universal time) throughout July 2015, and Figures 2 (B, D, F, H) show the Ψ diurnal evolution at the end of the period (July 28th) for four of the varieties.

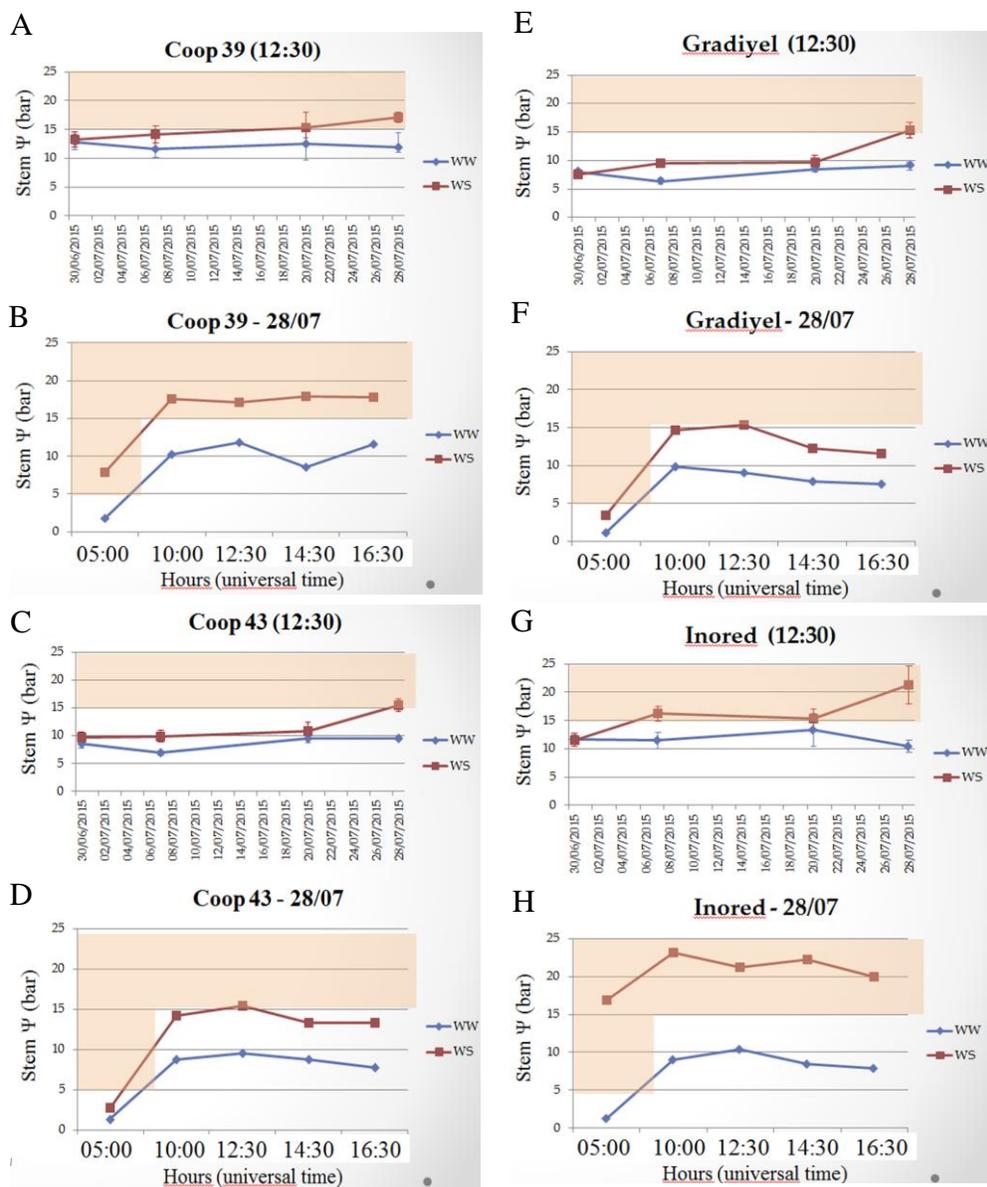


Figure 2: Temporal (A, C, E, G) and diurnal (B, D, F, H) evolutions of hydric potentials (Ψ) in four apple varieties (CEHM-SudExpé site, July 2015). By convention, the Ψ values (bar) have been represented in positive values. Predawn hydric potentials (Ψ measured at 5:00) are considered showing the onset of water stress for values exceeding 5 bars (colored area); Diurnal stem hydric potentials are considered as revealing water stress for values exceeding 15 bars.

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In Inolove variety (not represented), diurnal evolution of Ψ was not relevant; this variety exhibited rapid stomatal closure likely resulting from the very low tree fruit load (biennial bearing, “off” year, cf. Table 1). More interestingly, Coop 39 and Inored apple varieties showed a precocious onset of water stress in WS trees (Fig. 2 A, 2G), with very “low” diurnal stem Ψ values (Fig. 2 B, 2H). Contrastingly, Coop 43 and Gradiyel reached only a slight water constraint on July 28th (Fig. 2C, 2E), which was confirmed by the limited diurnal peak of stem Ψ , which was just at threshold at the middle of the day (Fig. 2D, 2F).

3.2 Stress and vegetation indices issued from thermal and multispectral spectral values

First statistical analysis aimed at assessing the homogeneity of tree responses within the varietal field plots and the response to water regimes, considering the varieties separately. Spectral variables are extracted from the trees (n=3) that have been also tested for water status, through measurements of predawn leaf and stem hydric potential. On that basis, Table 3 shows that canopy surface minus air temperature (Ts-Ta) retrieved from the tree central zones was strongly influenced by the water treatment (highly significant *P*-values, and WS > WW values) but also by the tree replicate, even if significance was lower. Heterogeneity of trees is a feature often found in perennial plant trials, which can traduce differences in tree canopies’ vigor.

Table 3. Thermal response (Ts-Ta) of five apple tree varieties in response to contrasting water regimes (July 28th, 12:30 flight). The five two-way ANOVAs were performed independently on the different varieties. Ts difference not submitted to statistical analysis. Fisher test significance: P: <0.001 :***; <0.01: **; <0.05 :*; ns: not significant.

Variety	Effect tested	<i>P</i> -value	Ts-Ta (°C)		
			WW	WS	(<i>difference</i>)
Coop 39	Tree replicate	8.86E-11			
	Water regime	2.24E-14	2.31	2.75	(0.44)
Inored	Tree replicate	1.05E-02			
	Water regime	<2.2E-16	1.97	4.44	(2.31)
Coop 43	Tree replicate	4.06E-14			
	Water regime	<2.2E-16	2.19	2.87	(0.68)
Inolove	Tree replicate	<2.2E-16			
	Water regime	<2.2E-16	3.52	4.74	(1.22)
Gradiyel	Tree replicate	2.0E-04			
	Water regime	<2.2E-16	3.55	5.28	(1.73)

As the ‘tree’ effect was generally less marked than that of water regime (cf. *P*-values), we assumed that reasonably consistent conclusions can be drawn from the latter. The intensity of thermal response can be assessed either by Ts-Ta values reached in WS trees, and/or by the thermal WS-WW difference. The two-way analysis of variance testing the combined effects of variety and water treatment (Table 4) revealed highly significant effects of both factors.

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Table 4. Analysis of the combined effects of variety and water regime on tree canopy thermal response (Ts-Ta), on July 28th (12:30 flight). Means followed by different letters are significantly different according to Newman & Keuls test.

Ts-Ta (°C)		
	P-value	
Variety	1.14E-06	***
Water regime	5.44E-07	***
Means		
Gradiyel	4.41	a
Inolove	4.13	a
Inored	3.20	b
Coop 39	2.57	c
Coop 43	2.53	c
WS	4.01	a
WW	2.73	b

The effect of water regime (WS-WW difference) was 1.29°C in average, which traduced a general diurnal elevation of foliage temperature due to stress. Gradiyel and Inolove showed the highest Ts-Ta values, contrasting with rather moderate WS-WW temperature differences (Table 3). This apparent discrepancy reveals a rather pronounced stomatal closure in both cases, likely resulting from temporary evaporative demand since Gradiyel was not previously considered to be stressed on hydric potential or fruit growth bases. Inored variety exhibited the most severe response to water stress, from the thermal difference point of view (Table 3), while Ts-Ta values were intermediate (Table 4); the contrasting thermal responses in WW and WS treatments are in accordance with results previously shown for fruit growth and hydric potential in this variety. Finally, Coop 39 and Coop 43 both showed moderately elevated Ts-Ta values and the less elevated WW-WS thermal difference, which matched with results found in fruit growth, even if Coop 39 has been considered water-stressed on the hydric potential basis.

Two distinct similar ANOVAs were realized for the analysis of vegetation indices (NDVI, GNDVI, and PRI) issued from multispectral imaging. For NDVI, a comparison was performed (Table 5 & 6) since this index was computed either from images issued from July 27th flight, using the 6-channels multispectral sensor (narrow bands, 10nm) or from a flight performed on July 28th with DP1x sensors, giving access to broad red wavebands, and NIR considered at $\lambda > 745\text{nm}$. Very similar meteorological conditions were monitoring in both days.

As a whole, the effect of a reduced water regime affected negatively the NDVIs, whatever the spectral data used (Tables 5 & 6). This effect was significant in Coop 43, Coop 39 and Gradiyel, barely significant in Inored variety, while less consistent results were found in Inolove. As quoted for Ts-Ta variable, the tree factor was significant in many cases (Table 5), which reinforces the need to work with inter-tree averages. For varieties where NDVI was the most clearly reduced, notably Gradiyel, the NDVI variation can be attributed to a slight Leaf Area Index decrease, due to leaf margin rolling in response to soil water deficit.

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Table 5. NDVI indices for five apple tree varieties in response to contrasting water regimes (July 27th & 28th, 12:30 flights). NDVI_ms was computed from 6-channels multispectral imaging, and NDVI_dp1 from digital DP1x RGB cameras. The five two-way ANOVAs were performed independently for the different varieties. Fisher test significance: P: <0.001 :***; <0.01: **; <0.05 :*; ns: not significant.

Variety	Effect tested	NDVI-ms				NDVI_dp1			
		P-value	WW	WS	P-value	WW	WS		
Coop 43	Tree replicate	1.50E-05	***			1.30E-01	ns		
	Water regime	9.00E-04	***	0.68	0.65	2.00E-02	*	0.48	0.46
Coop 39	Tree replicate	7.13E-01	ns			2.00E-03	**		
	Water regime	<2.2E-16	***	0.69	0.59	2.20E-14	***	0.53	0.39
Inolove	Tree replicate	6.40E-07	***			8.00E-03	**		
	Water regime	<2.2E-16	***	0.64	0.59	8.35E-01	ns	0.53	0.53
Gradiyel	Tree replicate	8.10E-01	ns			3.50E-01	ns		
	Water regime	4.21E-07	***	0.63	0.59	1.80E-02	*	0.51	0.49
Inored	Tree replicate	<2.2E-16	***			1.60E-02	*		
	Water regime	5.05E-01	ns	0.58	0.58	2.90E-02	*	0.44	0.43

Table 6. Analysis of the combined effects of variety and water regime on tree NDVIs (July 27th & 28th, 12:30 flights). NDVI_ms computed from 6-channels multispectral imaging, and NDVI_dp1 from digital RGB camera. Means followed by different letters are significantly different according to Newman & Keuls test.

Variety	NDVI_ms		NDVI_dp1	
	P-value		P-value	
Variety	3.95E-01	ns	2.50E-03	**
Water regime	2.50E-02	*	1.43E-01	ns
	Means		Means	
Coop 43	0.665	a	0.467	bc
Coop 39	0.641	ab	0.463	bc
Inolove	0.614	ab	0.527	a
Gradiyel	0.608	ab	0.502	ab
Inored	0.579	b	0.436	c
WS	0.642	a	0.497	a
WW	0.600	b	0.461	b

As concerns GNDVI and PRI, analysis of variance revealed non-significant or limited effect of tree replicates, with the notable exception of Inored variety (Table 7). When varieties were considered separately, the effect of water regime on GNDVI was significant but variable. This index decreased significantly in Coop 39, Gradiyel, and Inolove, while it increased significantly in Coop 43 and Inored. Where ANOVA took the combination of varieties and water regime into account (Table 8), effect of water regime considered as a whole was not significant. Similarly, the effect of stress was variable on PRI, with significant increase in Coop 39 and Inored, and

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significant decrease in Coop 43 and Inolove (Table 7). Considered as a whole (two-way ANOVA the effects of variety and water regime were not significant (Table 8).

Table 7. GNDVI and PRI indices for five apple tree varieties in response to contrasting water regimes (July 27th, 12:30 flight). Indices computed from 6-channels multispectral imaging. The five two-way ANOVAs were performed independently for the different varieties. Fisher test significance: P: <0.001 :***; <0.01: **; <0.05 :*; ns: not significant.

Variety	Effect tested	GNDVI_ms				PRI_ms			
		P-value		WW	WS	P-value		WW	WS
Coop 43	Tree replicate	4.90E-01	ns			8.10E-01	ns		
	Water regime	3.22E-05	***	0.52	0.57	6.09E-09	***	0.19	0.10
Coop 39	Tree replicate	5.20E-02	ns			9.00E-03	**		
	Water regime	4.80E-16	***	0.62	0.55	3.34E-13	***	0.00	0.09
Inolove	Tree replicate	9.90E-02	ns			6.05E-01	ns		
	Water regime	1.00E-04	***	0.61	0.58	1.40E-10	***	0.14	0.06
Gradiyel	Tree replicate	2.00E-04	***			1.30E-02	*		
	Water regime	<2.2E-16	***	0.55	0.44	3.60E-01	ns	0.06	0.05
Inored	Tree replicate	<2.2E-16	***			<2.2E-16	***		
	Water regime	1.99E-06	***	0.51	0.55	3.70E-03	**	0.04	0.08

Table 8. Analysis of the combined effects of variety and water regime on tree GNDVI and PRI (July 27th, 12:30 flight). Indices computed from 6-channels multispectral imaging. Means followed by different letters are significantly different according to Newman & Keuls test.

Variety	GNDVI_ms		PRI_ms	
	P-value		P-value	
Variety	1.30E-02	*	1.60E-01	ns
Water regime	1.72E-01	ns	8.21E-01	ns
Variety	Means		Means	
Coop 43	0.545	ab	0.143	a
Coop 39	0.592	a	0.025	a
Inolove	0.593	a	0.101	a
Gradiyel	0.491	b	0.056	a
Inored	0.526	ab	0.058	a
WS	0.563	ns	0.080	ns
WW	0.536	ns	0.073	ns

3.3 Principal component analysis on stress and vegetation indices

Principal Component Analysis (PCA) was performed on the thermal signal (Ts-Ta) and spectral indices respectively issued from thermal and multispectral imaging over the apple variety trial. Focus is put here on these variables for the flights performed on July 27th and 28th 2015. The

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matrix of correlations (not presented) made it possible to observe significant positive correlations between NDVI and GNDVI, on the one hand, and negative correlations between Ts-Ta and NDVI, on the other hand. PRI varied rather independently from these variables.

The graphical representation below (Figure 3 A & B) showed that the first three components of the PCA accounted for 86% of total variability. For component 1, which explained more than 45% of the variation, the highest component loadings were NDVI and GNDVI, indices relative to structure of the crop cover and to chlorophyll content. Component 2 (27% of the variation) was mainly loaded by the PRI, variable accounting for efficiency of the photosynthetic system. Finally, loading of Ts-Ta was noticeable for components 3 and 1.

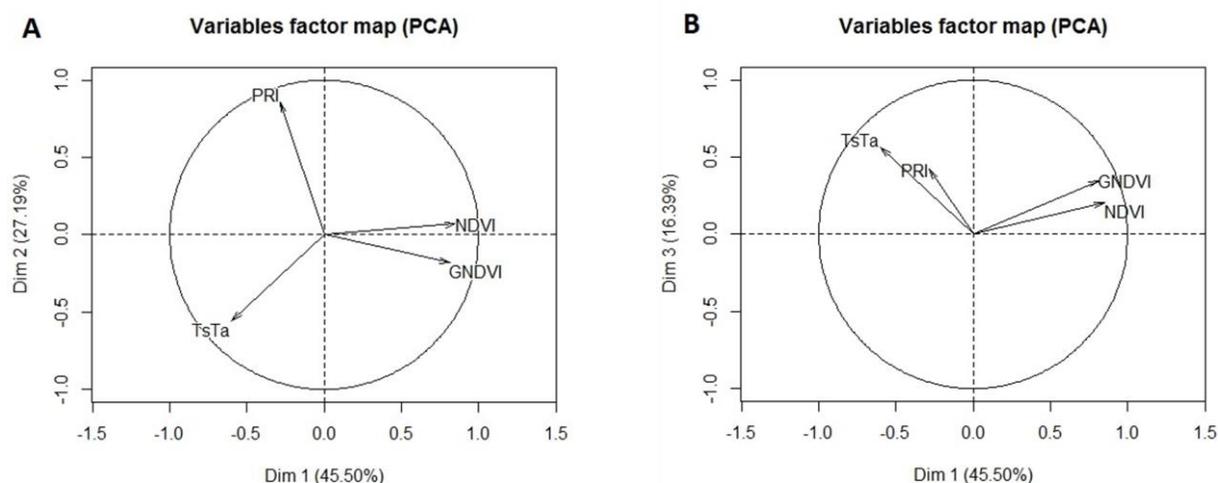


Figure 3 A & B. Graphical mapping of variables considered in Principal Component Analysis (image-based indices for flight performed on July 27th & 28th, CEHM-SudExpé site).

On such bases, and taking into account the ANOVA results previously shown, it appears that the water stress experienced by WS trees negatively affected structural variables, namely NDVI in all cases (more or less severely according to cultivar) and GNDVI in some cases, while the foliage temperature (and Ts-Ta) increased, likely in relation with stomatal closure (functional response). The effects of water stress on the PRI appeared variable according to the variety. As structural and functional variables and foliage temperature evolved rather independently, this is interesting for discriminating the most efficient varieties in terms of carbon assimilation under moderate stress conditions. Further research is ongoing for assessing the effects of water stress for Ctifl site in 2015 and for experimentations carried out in 2016. A more in-depth ecophysiological analysis of contrasting varietal responses to soil water deficit will also be undertaken, with the aim of discriminating the most suitable apple varieties in non-optimal irrigation conditions, looking for a more sustainable fruit production.

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4. CONCLUSIONS

By this work, we established a proof of concept demonstrating the possibility of performing soil water stress in a field trial where pre-commercial apple trees varieties were tested for different agronomic features. Overall, our results showed that it is almost impossible to reach water stress of the same intensity on all the adult trees of a varietal collection, by uniform rationing of the water regime. Nevertheless, differences in water consumption were informative as such. Beyond some differences that occurred in tree size and canopy structure between cultivars in the assay, limited by tree training and pruning practices, implementation of contrasting irrigation regimes within varietal sub-plots made it possible to create progressive hydric constraints and to assess the more or less precocious onset of water stress. It is necessary to apply the contrasting irrigation conditions on a series of trees for producing robust results. Where water rationing did not readily result in water stress, this likely traduced a more economical behavior of transpired water (“water saving”), while other cultivars seem more “water-spending”. Contrary to the time-consuming nature of measurements usually carried out *in planta* (e.g. hydric potential measurements), the contribution of airborne imagery demonstrated its capacity to assess the occurrence of water stress throughout a field varietal trial. The flexibility of UAV as vector, i.e. the possibility of short revisit time, opens an avenue for assessing dynamically different responses to water deficit. The chain of technical operations following the drone flight is now requiring more automation of image processing steps, which will be necessary for the processing of many imaging datasets.

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