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# Estimation of olive grove canopy temperature from MODIS thermal imagery is more accurate than interpolation from meteorological stations

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A method to estimate olive canopy temperature from satellite data was developed. Moderate Resolution Imaging Spectrometer (MODIS) Land Surface Temperature (LST, 1 km) and Normalized Difference Vegetation Index (NDVI, 250 m) products were used. The deviation of LST from the canopy temperature measurements collected with data loggers in different regions and olive orchard environments of the East Mediterranean showed seasonal behavior (i.e. large deviations at summer and small at winter). We built a correction function for the LST, representing the seasonal behavior of the deviation of LST from the in situ canopy temperature. NDVI was used to set the parameters for the correction function. We calculated the average absolute errors of (a) the satellite based estimation of the canopy temperature, (b) LST and (c) air temperature from the nearest meteorological station with respect to the in situ canopy temperature. The satellite-based estimation of canopy temperature was found more accurate than using LST or air temperature from meteorological station, as commonly used in ecological modeling. Therefore, it is expected that the correction function developed in this study will improve the capability to model pest population trends, and other agronomic traits of olive plantations, enhancing orchard management in time and space.

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## 1. Introduction

Modeling ecological phenomenon requires good estimates of the phenomena's driving factors. For most organisms, environmental temperature is a key factor in their biological performance and behavior. The canopy and foliage of vegetation has a strong impact upon the perceived environment of organisms interacting with them. Canopy temperature in olive trees (*Olea europaea* L.), as an example, is one of the main variables known to drive the developmental rate of the olive fruit fly (*Bactrocera oleae*) immature stages and adult flies. Gutierrez et al. (2009) and Gutierrez and Ponti (2011), for instance, used air temperature from the nearest meteorological station as input to a weather-driven physiologically based demographic model of olive fly and developed regional risk maps and global warming scenarios for this and other insect pests.

Meteorological stations, the accepted source of temperature information, are typically deployed at large geographic distances (>10 km), therefore, missing topographic, and other fine scale spatial effects that may be of relevance when trying to model ecological phenomena. Land Surface Temperature (LST) satellite measurements are provided at higher spatial resolution, and therefore can potentially increase precision in forecasting and applying management strategies. Lensky and Dayan (2011) used one km resolution satellite data to reveal the large spatial variability of LST. They showed that fine scale climatic conditions that are driven by local topography (topoclimate) may be responsible for a three weeks delay in the eclosion of adult *Heliothis* spp. moths (a major worldwide agricultural pest attacking a large range of food and fiber crops) from its pupal stage in fields separated by only few kilometers. LST however, provides information on the surface skin (ground) temperature and does not necessarily represent the canopy temperature, which is the temperature perceived by developing insects and diseases within canopies and vegetation, or by regulating systems such as the plant stomata. In order to improve our estimation and modeling, the differential between LST and canopy temperature must be corrected and understood.

Canopy temperature is a statistical mean of the leaf temperature distribution (Fuchs, 1990). The canopy's inside air movement, momentum transport, heat conductivity and radiation, controls diurnal canopy temperature and seasonal behavior (Sinoquet and Le Roux, 2000). Canopy temperature is also a useful indicator for

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**Table 1**
Names of the five sites and their location; minimum NDVI; and daytime mean ($\overline{\Delta T}$), amplitude ($A$) and phase ($\varphi$) for the correction function (Eq. (3)).

| | Site | Lat | Lon | NDVI | $A$ | $\varphi$ | $\overline{\Delta T}$ |
|---|---|---|---|---|---|---|---|
| A | Lahav | 31.360 | 34.856 | 0.23 | 4.26 | 3.49 | 5.58 |
| B | Shaar Hagai | 31.815 | 35.022 | 0.30 | 2.67 | 3.63 | 2.42 |
| C | Makura | 32.636 | 35.002 | 0.47 | 2.54 | 3.07 | 2.09 |
| D | Nablus | 32.263 | 35.268 | 0.23 | 5.23 | 2.94 | 7.08 |
| E | Tull-karem | 32.348 | 35.062 | 0.25 | 3.12 | 3.22 | 4.54 |

plant physiology. Changes in leaf area, stomatal conductance and hydraulic property control water status in the plant (Jones, 1999, 2004; Gonzalez-Dugo et al., 2012); therefore canopy temperature is used to evaluate water deficit and schedule irrigation. Crop Water Stress Index (CWSI) is the basic measure used for this purpose (Idso et al., 1981; Jackson et al., 1981; Ben-Gal et al., 2009). Sepulcre-Cantó et al. (2006) and Berni et al. (2009) estimated olive orchards canopy temperature, CWSI and canopy conductance using airborne LST thermal imagery and in situ canopy temperature. Sepulcre-Cantó et al. (2007) used radiance from ASTER to calculate canopy-air temperature difference in peach and olive trees, and later Sepulcre-Cantó et al. (2009) added Normalized Difference Vegetation Index (NDVI) to distinguish between irrigated and non-irrigated olive orchards. These high resolution airborne and space born (ASTER) data enable assessment of water stress and other environmental variables for individual trees. But these data are relatively expensive and rare, therefore cannot be used for continuous monitoring of the canopy temperature over large areas. The aim of the present study was to use space born daily LST data and NDVI to estimate olive tree canopy temperature. We contrasted LST measurements with in situ canopy temperature in several regions and olive orchard environments, and derived a correction function that provides an approximation to the olive canopy temperature in different geographic and environmental situations. This improved estimation of canopy temperature in olives is expected to provide the basis for future applications in demographic modeling and forecasting, such as the modeling of olive fly population and damage, and for management purposes.

## 2. Data and methods

Moderate Resolution Imaging Spectrometer (MODIS) is a key instrument on board Terra polar orbiting sun-synchronous (10:30 AM/PM local time) NASA satellite. We constructed time series of the 1 km LST daily product (MOD11A1) and the 250 m 16 days averaged NDVI product (MOD13Q1) for the time interval when in situ canopy temperature was available.

In situ data were collected every hour in five locations in Israel and the Palestinian Authority (see Table 1) using U23 pro v2 temperature/relative humidity HOBO data logger (Onset Computer Corporation, MA, USA) from February 2010 to December 2011. HOBO data logger devices were placed within the canopy structure, 1 m above ground. We constructed time series of LST ($T^{Sat}_{surface}$), canopy temperature from the 11:00 AM/PM local time HOBO measurements ($T^{HOBO}_{canopy}$), and the difference between these two ($\Delta T$) for each site:

$$\Delta T = T^{Sat}_{surface} - T^{HOBO}_{canopy} \tag{1}$$

We removed missing data, e.g. due to cloudiness, or mismatch due to cloud contaminated $T^{Sat}_{surface}$, such that $T^{Sat}_{surface}$ was lower by more than 20 °C with respect to $T^{HOBO}_{canopy}$. The remaining data was sorted into a 365-day array according to the Julian date. Finally, to calculate the satellite estimate of the canopy temperature ($T^{Sat}_{canopy}$):

$$T^{Sat}_{canopy}(t) = T^{Sat}_{surface}(t) - \langle \Delta T \rangle \tag{2}$$

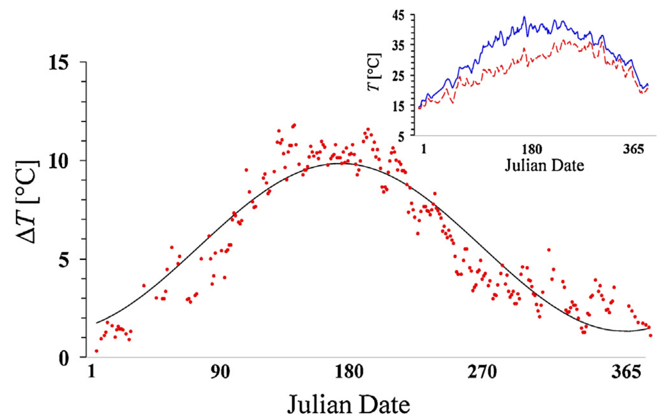


**Fig. 1.** Differences ($\Delta T$, red dots) between daytime (11:00 AM LT) satellite LST and in situ canopy temperature and its Fourier smoothing ($\langle \Delta T \rangle$, —) throughout the year for Lahav sampling location (see Table 1). Inset shows the satellite LST, $T^{Sat}_{surface}$ (—), and the in situ canopy temperature, $T^{HOBO}_{canopy}$ (- -). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we used the $\Delta T$ time series to build a correction function ($\langle \Delta T \rangle$). Since $\Delta T$ is a periodic signal (seasonal), Fourier series were used to model the correction function, consisting of the mean of the $\Delta T$ time series ($\overline{\Delta T}$) and one harmonic, representing seasonal phenomena with annual cycle (Chatfield, 1978; Scharlemann et al., 2008):

$$\langle \Delta T \rangle = \overline{\Delta T} + A \cdot \cos(\omega \cdot t + \varphi) \tag{3}$$

where $A$ and $\varphi$ are the amplitude and phase of the annual cycle of $\Delta T$. The amplitude is a measure of the change along the seasonal cycle, and the phase determines the timing of maximal correction. $\omega = 2\pi/365$ is the angular frequency of the annual cycle, and $t$ is the date (Julian day).

## 3. Results and discussion

We demonstrate the methodology on one of the locations ("Lahav") from Table 1. Fig. 1 describes actual daytime (11:00 AM local time) $\Delta T$ (red dots) and correction function $\langle \Delta T \rangle$ (black line), together with $T^{Sat}_{surface}$ and $T^{HOBO}_{canopy}$ in the inset. Note that $T^{Sat}_{surface}$ is higher than $T^{HOBO}_{canopy}$ (inset) causing $\Delta T$ and $\langle \Delta T \rangle$ to be positive through almost the entire year, with a seasonal cycle featuring low $\Delta T$ during winter and higher through spring and summer. Fig. 2 shows that at nighttime $T^{HOBO}_{canopy}$ is slightly higher than $T^{Sat}_{surface}$ due to night radiative-cooling that affects the ground more than the air in

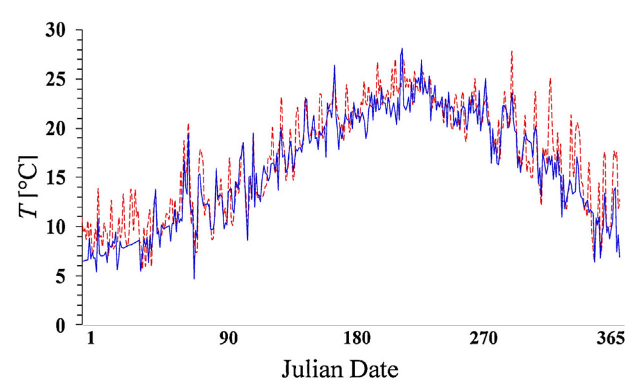


**Fig. 2.** At night time (11:00 PM LT) the difference between satellite LST ($T^{Sat}_{surface}$, —), and in situ canopy temperature of the olive tree ($T^{HOBO}_{canopy}$, - -) are much smaller than in daytime. Data is from the same location as in Fig. 1.

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