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REMOTE SENSING MONITORING OF WATERMELON UNDER DIFFERENT WATER REGIMES: METHODOLOGY AND PRELIMINARY RESULTS

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Abstract: *This study explores the use of unmanned aerial vehicle (UAV) remote sensing to monitor watermelon growth under different irrigation regimes. Field experiments were carried out at the Maritsa Vegetable Crops Research Institute (Bulgaria) across three campaigns during the growing season. The test field included two water regimes (optimal and reduced) applied to three watermelon cultivars. A total of 21 plots were monitored (12 under optimal irrigation and 9 under reduced irrigation). UAV flights were conducted with a DJI Phantom at 30 m altitude, providing very high spatial resolution imagery. Ground data were collected for leaf area index (LAI), fraction of intercepted photosynthetically active radiation (fIPAR), fractional vegetation cover (fCover), and chlorophyll content index (CCI). Preliminary analysis indicates that UAV-based observations can detect differences between irrigation treatments. These results demonstrate the potential of remote sensing for crop monitoring and precision irrigation management in vegetable production.*

ДИСТАНЦИОННО НАБЛЮДЕНИЕ НА ДИНЯ ПРИ РАЗЛИЧНИ РЕЖИМИ НА НАПОЯВАНЕ: МЕТОДОЛОГИЯ И ПРЕДВАРИТЕЛНИ РЕЗУЛТАТИ

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Ключови думи: *Дистанционни изследвания, БЛС, мониторинг на диня, наземни данни*

Резюме: *Настоящото изследване представя използването на дистанционно наблюдение с безпилотна летателна система (БЛС) за мониторинг на развитието на диня при различни режими на напояване. Полевите експерименти са проведени в Института по зеленчукови култури „Марица“ (България) в рамките на три кампании през вегетационния сезон. Изпитването включва два водни режима – оптимален и редуциран, приложени върху три сорта диня в общо 21 площадки. Полетите с дрон DJI Phantom на височина 30 m осигуряват изображения с много висока пространствена резолюция. Събраните данни включват индекс на листна площ (LAI), дял на задържаната фотосинтетично активна радиация (fIPAR), проективно площно покритие (fCover) и индекс на съдържание на хлорофил (CCI). Предварителните резултати показват, че БЛС-наблюденията успешно разграничават ефектите от различните водни режими и потвърждават потенциала на дистанционното наблюдение за прецизно управление на напояването в зеленчуковото производство.*

Introduction

Precision agriculture has transformed crop management by integrating advanced sensing technologies to optimize inputs and improve productivity. Among these, unmanned aerial vehicles (UAVs) equipped with remote sensing capabilities have become indispensable tools for monitoring crop health, growth dynamics, and water stress. Their ability to capture high-resolution spatial and temporal data makes them particularly valuable for site-specific management in diverse agricultural systems (Li et al., 2015). Modern UAV platforms, such as the DJI Phantom 4 Multispectral, incorporate multispectral sensors that capture reflectance data across visible, red-edge, and near-infrared bands. These sensors enable the calculation of vegetation indices like NDVI and EVI, which are strongly correlated with crop biophysical parameters such as biomass, chlorophyll content, and canopy structure (Cubero-Castan et al., 2018).

The integration of these indices into monitoring workflows allows for timely detection of crop stress and supports precision interventions. Accurate estimation of biophysical parameters particularly Leaf Area Index (LAI), fraction of intercepted Photosynthetically Active Radiation (fIPAR), and fractional vegetation cover (fCover) is essential for assessing crop development and photosynthetic efficiency. Ground-based instruments like the AccuPAR LP-80 ceptometer offer non-destructive LAI measurements by quantifying PAR transmission through plant canopies (Decagon Devices, 2013). These measurements are validated through canopy radiation transfer models and have shown strong agreement with destructive sampling methods under controlled conditions (Campbell and Norman, 1998).

Water stress detection is a critical application of UAV remote sensing, especially in regions facing water scarcity. Thermal and multispectral imaging systems mounted on UAVs can detect early signs of water stress before visible symptoms emerge, enabling proactive irrigation scheduling. When combined with vegetation indices, thermal data enhances the understanding of plant water status and supports efficient water resource management (Li et al., 2015).

This study investigates the potential of UAV-based multispectral remote sensing for monitoring watermelon growth under varying irrigation regimes. By integrating high-resolution imagery with ground-based biophysical measurements, the research aims to establish robust relationships between vegetation indices and crop parameters. The ultimate goal is to support precision irrigation strategies tailored to horticultural crop production. The present report focuses on describing the methodology for field data collection and UAV image acquisition, as well as presenting preliminary results from the initial monitoring campaigns.

Materials and methods

Study area

The field experiment was conducted during one agricultural year, within the spring–summer growing season of 2025. The field experiment was carried out at a test field managed by "Maritsa Vegetable Crops Research Institute" (Plovdiv, Bulgaria). The field is located at 42.1772° N, 24.1771° E (Fig. 1). The objective of the experiment was to monitor crop parameters of watermelon under two irrigation regimes—optimal and drought-stressed conditions: 100% optimum and 50% reduced irrigation, where the reduced treatment received half the amount of water supplied to the control plots. Irrigation was performed based on soil moisture data measured by ONDO Smart Farming sensors. The studied crop was watermelon (*Citrullus lanatus*), comprising three cultivars: Youlie, NUN 21613, and NUN 22227. For each cultivar, four replications (rows) were planted under the optimal irrigation regime, and one replication (row) under the reduced irrigation regime (Table 1). Each row contained approximately 32 plants.

For the purposes of this study, field sampling was carried out during three field campaigns, conducted on June 6, July 7, and August 8, 2025. These dates correspond to key phenological stages of watermelon development: flower bud formation, fruit development, and fruit ripening (Fig 2). Sampling was performed on test plots (Fig. 1). The selection of sampling points was based on a randomized design. Under the optimal irrigation regime, where three cultivars were planted in four replications (12 rows in total), one sampling point per row was randomly selected using software-based randomization. Under the reduced irrigation regime, three sampling points per replication (row) were randomly chosen, totaling 9 points. Thus, during each field campaign, data were collected from 21 sampling locations. The sampling points were marked with a wooden stick; the coordinates were measured with RTK GNSS.

Field data

fIPAR, LAI, and fCover measurements

The AccuPAR LP-80 ceptometer (METER Group, Inc., Pullman, WA, USA; formerly Decagon Devices, Inc., Pullman, WA, USA) was used to measure the Leaf Area Index (LAI), the fraction of Intercepted Photosynthetically Active Radiation (fIPAR), and the Vegetation cover fraction (fCover). The AccuPAR LP-80 is designed to measure the Photosynthetically Active Radiation (PAR; 400-–700 nm waveband) under plant canopies and has an 86.5 cm-long probe containing 80 independent sensors, spaced 1 cm apart (Decagon Devices, 2013). The instrument is used to take above and below canopy PAR readings from which it calculates Tau, τ, the ratio of below canopy PAR measurements to the above canopy PAR. In each sampling plot (point) one above canopy reading and ten below canopy readings were taken and averaged. The below canopy readings were taken by placing the probe perpendicular to the row direction, with the middle of the probe coinciding with the middle of the row width. Five measurements were taken to the left and right of the wooden stick spaced 10 cm apart resulting in a sampled area of approximately 100 cm by 80 cm.

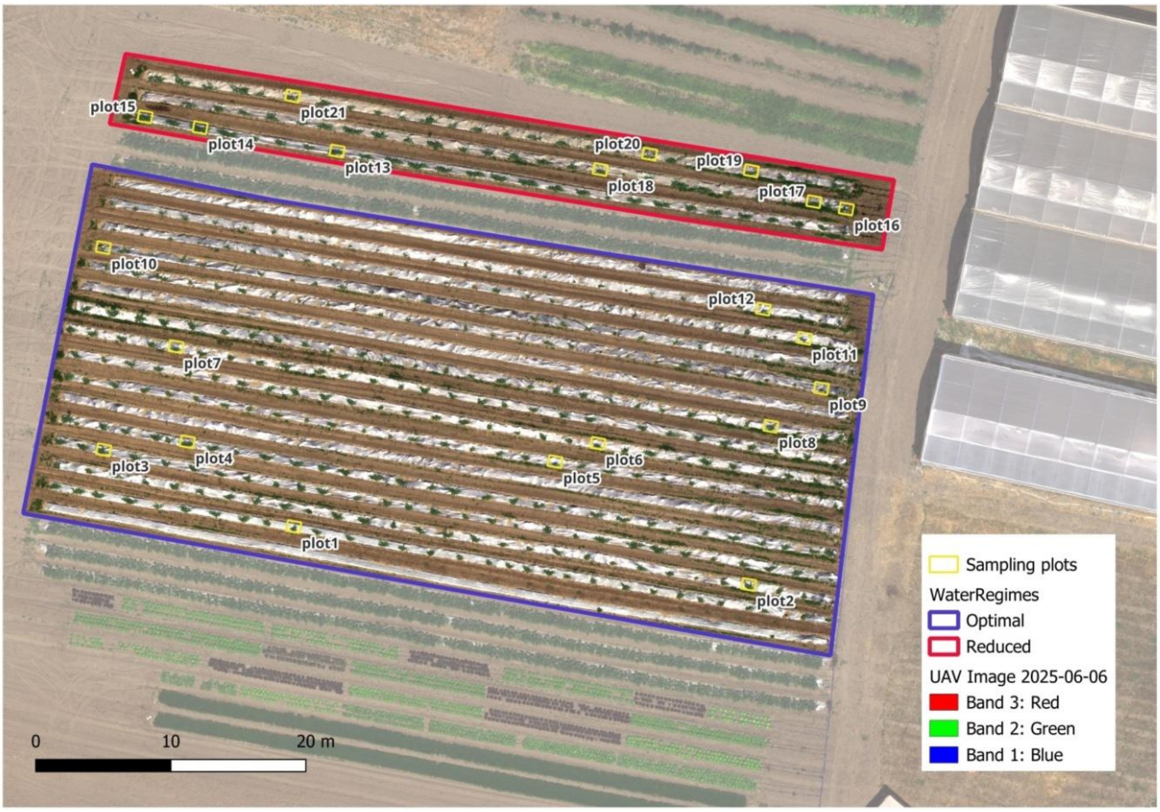

Fig. 1. Study area

Table 1. Field experimental design with irrigation regimes and varieties

Optimal regime																			Reduced regime:				
Other crops	Other crops	Other crops		1| Watermelon - Youlie	2| Watermelon - Youlie	3| Watermelon - Youlie	4| Watermelon - Youlie		5| Watermelon - NUN21613	6| Watermelon - NUN21613	7| Watermelon - NUN21613	8| Watermelon - NUN21613		9| Watermelon - NUN22227	10| Watermelon - NUN22227	11| Watermelon - NUN22227	12| Watermelon - NUN22227		Other crops	Other crops	13| Watermelon - Youlie	14| Watermelon - NUN21613	15| Watermelon - NUN22227

Field campaign June 06/06/2025

Field campaign July 07/07/2025

Field campaign August 08/08/2025

Fig. 2. Photos of field test plots with Watermelon, variety Youlie

The fIPAR was calculated as one minus τ. The LAI is calculated by AccuPAR LP-80 by inversion of a model of radiation transmission and scattering within the canopy (Decagon Devices, 2013). It uses τ, the leaf angle distribution parameter Chi, χ, and parameters related to the sun illumination conditions (e.g. zenith angle, θ) to make internally these calculations (Decagon Devices, 2013). The user is required to set Chi, χ, in this case it was set to 3.00, a value suggested for a crop with a strongly horizontal leaf distribution (Decagon Devices, 2013; Campbell and Norman, 1998) as exact values for watermelon were not available in the known literature. The fCover is defined as the vertical projection area of aboveground vegetation elements per unit horizontal ground surface area (Li et al., 2023). It was calculated in a spreadsheet using the Tau readings and equations suggested in the AccuPAR LP-80 operator's manual (Decagon Devices, 2013):

$$fCover = 1 - \tau(\theta_0) \qquad \tau(\theta_0) = \tau(\theta_m)^p \qquad p = \left(\frac{\chi^2}{\chi^2 + (tan\theta_m)^2}\right)^{\frac{1}{2}}$$

where θ_m is the actual sun zenith angle (in radians) during the measurement, $\tau(\theta_m)$ is the measured Tau, $\tau(\theta_0)$ is the predicted Tau for a sun zenith angle of zero, i.e. nadir (θ_0), and χ was defined above.

Chlorophyll content

The Chlorophyll Content Index (CCI) was measured using a CCM-200 chlorophyll meter (Opti-Sciences, USA). The device estimates relative chlorophyll content non-destructively by measuring leaf transmittance at two wavelengths: 653 nm (red) and 931 nm (near-infrared). The ratio of these signals provides a unitless CCI value, where higher readings indicate greater chlorophyll content. This method allows rapid, in-field assessment of leaf greenness and photosynthetic potential without the need for chemical extraction or sample destruction. On each sampling plot are sampled 5 positions and the data is averaged for further analysis

UAV Data

The test field was imaged with a Phantom 4 Multispectral quadcopter (hereinafter "P4") (SZ DJI Technology Co., Ltd., Shenzhen, PR China). It has a multispectral camera with five bands: Near-Infrared (NIR, 840 nm ± 26 nm), Red Edge (RE, 730 nm ± 16 nm), Red (R, 650 nm ± 16 nm), Green (G, 560 nm ± 16 nm), and Blue (B, 450 nm ± 16 nm), as well as an integrated spectral sunlight sensor on top of the drone, which measured the sky down-welling irradiance in the same wavelengths (https://ag.dji.com/p4-multispectral, assessed 2025-10-03). The data recorded by the sunlight sensor during the flight and stored in the header of each *.TIFF image was used to retrieve the reflectance factors during post-processing. Therefore, a work flow without reference radiometric targets was used (Cubero-Castan et al. 2018). Automated missions were planned and executed using the DJI's GS PRO mobile application with the following parameters: 30 m height, 1.6 cm resolution, 80% front overlap, and 60% side overlap. The missions were executed under clear sky conditions between 11:47 and 12:47 local time. Four targets were fixed on the soil surface in the four corners of the experimental field to serve as Ground Control Points (GCPs). They were made of 30 cm by 30 cm white PVC panels on the surface of which a 2x2 checkerboard pattern was created using black self-adhesive foil. The GCPs coordinates were measured with GNSS equipment Leica GS08 in RTK mode achieving an accuracy of 2–3 cm. The images were processed using the photogrammetric software Pix4Dmapper (https://pix4d.com, assessed 2025-10-03) to generate a georeferenced radiometrically calibrated orthophoto mosaic.

Results and discussion

The field data reveal seasonal trends in canopy development (Tab. 2). LAI, FIPAR, and fCover all increased sharply from early June to early July, indicating crop growth and maximum canopy density during mid-summer. By August, values of these variables slightly declined, reflecting the senescence or reduced productivity. Chlorophyll content (CCI) followed an opposite pattern, peaking in early June and gradually decreasing, consistent with pigment degradation later in the season. The data show distinct differences in distribution across the field campaigns. Early-season measurements display low mean values and small variability, indicating a relatively uniform canopy. In contrast, July exhibits the highest averages and distributions for LAI, FIPAR, and fCover, reflecting heterogeneous canopy across plots. By August, the mean values decline, while variability remains moderate, suggesting uneven senescence. Chlorophyll content shows a wider spread in later campaigns, indicating differing pigment rates. Overall, the data distributions suggest progressive development followed by partial decline. The dataset as a whole shows bimodal distributions across the variables.

Table 2. Field data statistics

LAI				
	Max	Min	Standart deviation	Average
06-06-25	0.55	0.04	0.136	0.281
07-07-25	2.98	1.49	0.47	2.34
08-08-25	2.49	0	0.44	1.71
All	2.98	0	0.91	1.42
CCI				
06-06-25	64.8	48	6.1	56.6
07-07-25	52.8	27.9	7.4	41.1
08-08-25	39.2	0	12.2	23.7
All	64.8	0	14.3	34.7
FIPAR				
06-06-25	0.24	0.03	0.055	0.143
07-07-25	0.88	0.59	0.09	0.77
08-08-25	0.83	0	0.1	0.68
All	0.88	0	0.34	0.46
fCover				
06-06-25	0.23	0.03	0.054	0.14
07-07-25	0.87	0.57	0.09	0.75
08-08-25	0.81	0	0.1	0.66
All	0.87	0	0.334	0.47

On Figure 3 are depicted the relationships between NDVI and the investigated canopy biophysical variables (LAI, Chlorophyll, FIPAR, FCover). The NDVI–LAI relationship follows a strong exponential trend, where LAI increases rapidly with NDVI during canopy development and then saturates at higher NDVI values. This behavior is typical of dense vegetation, as NDVI becomes less sensitive once the canopy closes. In contrast, the NDVI–CCI (chlorophyll content index) relationship is weaker and more scattered. Both FIPAR and fCover show tight positive relationships with NDVI, suggesting that NDVI is a reliable indicator of canopy structural properties.

The plots in Figure 4 show the effect of the irrigation regime on LAI and NDVI. They review a complex pattern that depends on the development of the crop. During the initial stages of development, in June, plants under reduced irrigation regime show higher LAI and NDVI than those under optimal irrigation. This contradicts the general expectation that optimal irrigation will provide stronger growth and more biomass. It is clear that this is not necessary in the early season, probably because reduced irrigation is compensated by spring rainfall. During the middle of the growing season, in July, plants under optimal regime overtake those under reduced regime and have higher LAI and NDVI. After the onset of senescence, in August, the reduced irrigation regime shows a stronger scatter in the data; while the optimal regime has an LAI around 1.5 to 2.0, the LAI under reduced regime varies mostly between 0 and 2.0. This indicates that senescence has started earlier under reduced irrigation.

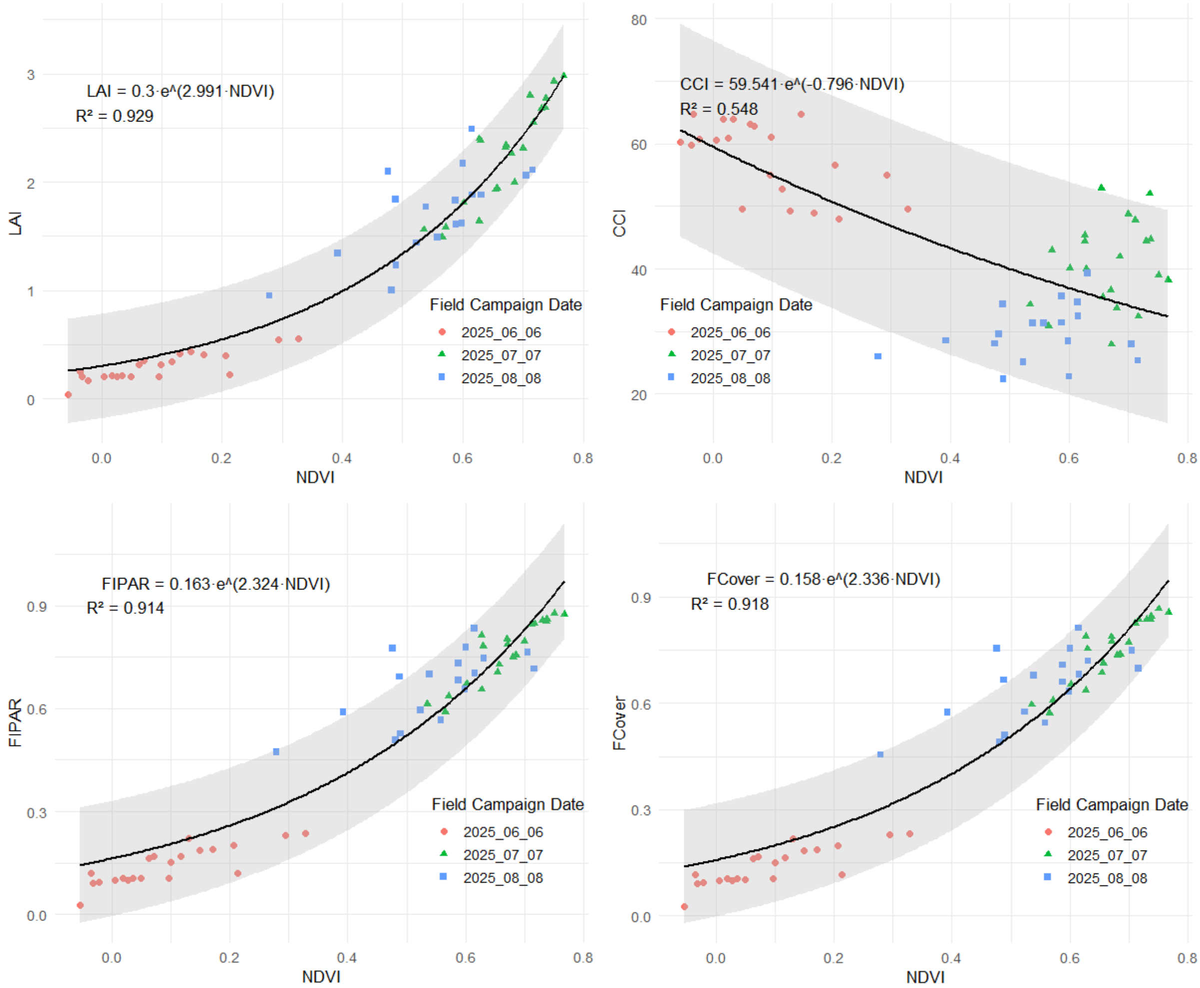

Fig. 3. Relationships between NDVI and canopy biophysical variables (LAI, CCI, FIPAR, FCover)

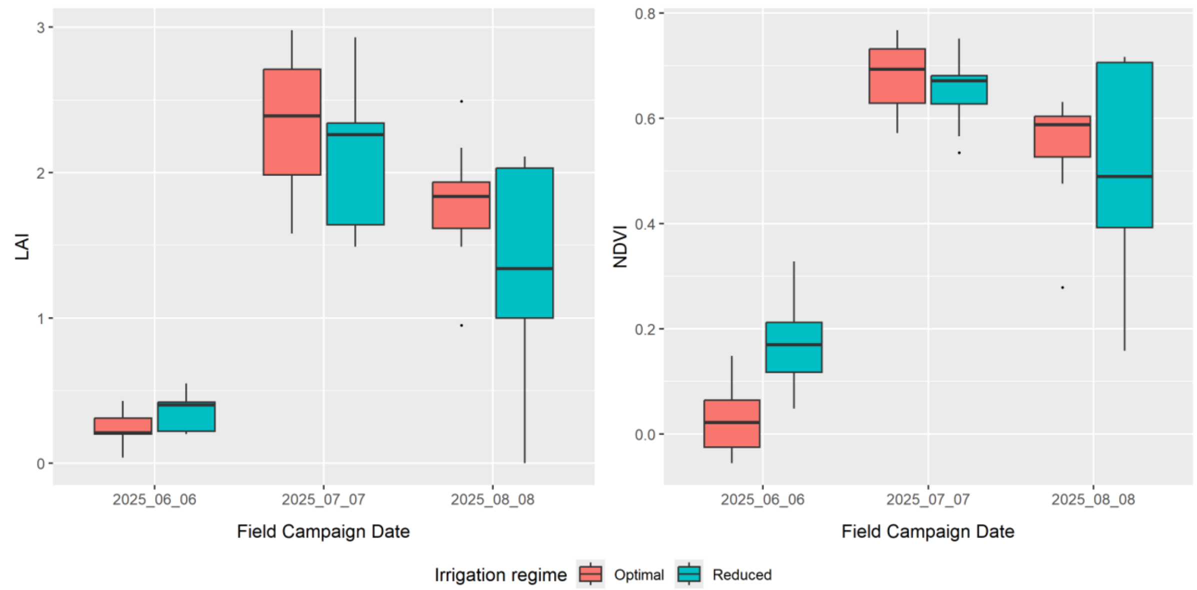

Fig. 4. Distribution of LAI and NDVI, depending on irrigation regime

Conclusions

This paper describes methods used to collect field and drone data on a watermelon experimental field to build models of various crop parameters. In this regard, two aspects were important: 1) precise geolocation of drone images and field sampling locations and 2) a sampling protocol suitable for row crops. Accuracy of up to 2-3 cm was achieved thanks to RTK GNSS. The sampling protocol defines a plot as a rectangle measuring 80 cm x 100 cm, covering a section of a row. The approach allowed the extraction of spectral data from the image from exactly the same area where field measurements were made. Preliminary results show that NDVI responds to LAI, fIPAR, fCover, and CCI of watermelon, with a strong exponential relationship observed for the first three parameters and a weaker, probably linear, relationship for the latter. An effect of the irrigation regime on LAI and NDVI was also observed. In conclusion, the preliminary results review the large potential of UAV-based multispectral observations for monitoring in horticulture. Further studies will model the relationships between the four crop parameters and the spectral data, experimenting with other vegetation indices and different regression methods.

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