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DETERMINATION OF LAI AT DIFFERENT GROWTH STAGES OF PEPPER PLANTS GROWN IN FIELD

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Abstract

The leaf area index (LAI) is important for monitoring and assessing crop vigor. It is used in the evaluation of plant condition, as inputs in various models to predict productivity. The main aim of this study was to identify the changes in LAI between major growth stages of pepper. In situ measurements and time series imagery from Copernicus Land Monitoring services were used. In situ data collection was carried out in a production pepper plantation, cv. Slonsko uho is grown under open field conditions in the village of Katunitsa, Plovdiv region, Bulgaria. Measurements were carried out in different stages of the development of plants. The destructive determination of LAI was conducted after collection of plant samples. The leaf area was determined using an electronic plotter Image Analysis Systems "WinDias 3". The leaf area index was calculated as the ratio of plant leaf area covering a unit of land area. The LAI images were downloaded for two years (2022 and 2023), between different stages of the development of pepper. A correlation between satellite data and in situ measurements was established. The dependence of LAI on the time series for the two years was determined.

Key words*: pepper, productivity, vegetation indices.*

INTRODUCTION

Remote sensing and vegetation indices are fast and efficient methods of crop assessment. Satellite and remote sensing images can identify crop classes, predict crop yield, and make inferences about the status of plants and their environmental conditions on an almost real-time basis (Schuler, 2002; Mihailescu & Cimpeanu, 2023). Remote sensing data can be very useful for detecting the phenological variability of a crop (Poenaru et al., 2017). Zhang et al. (2006) applied mathematical models to Moderate Resolution Imaging Spectroradiometer (MODIS) time series to determine vegetation phenology on a global scale. They establish that the spatial distribution of phenological indicators estimated from MODIS data is qualitatively more realistic and shows strong agreement with climatic conditions in agricultural regions. The economic benefits of using remote sensing for crop monitoring include scientific, technological, methodological, and economic efficiency (Badarch, 1990).
According to Liu et al. (2016), leaf area index (LAI) derived from hyperspectral imagery has been successfully used for more than 20 years. The leaf area index is calculated as the ratio of the unilateral (illuminated) leaf area to the soil surface area they can cover (Chen & Black, 1992). Determining LAI for an agricultural crop and tracking its dynamics is very important for a wide range of research as well as for continuous monitoring of the crop and real-time diagnostics (Fang et al., 2011). The ratio of the leaf area covering a land surface unit describes the potential active photosynthetic leaf area, which plays an important role in the basic life processes of the plant organism - photosynthesis, autotrophic respiration, transpiration, stomatal conductance etc. In its wider interpretation, LAI is an index reflecting the physiological and biochemical processes occurring in the plant organism (Viña et al., 2011; Liu et al., 2014). According to Viña et al. (2011), most vegetation indices (including LAI) are species-specific, and need to be determined individually according to the leaf structure and morphological characteristics of the plants and the vegetative growth rate.
In the scientific literature, information on LAI determination in pepper is limited. Li et al. (2017) determined LAI in pepper for stand evaluation using satellite data from Sentinel-2. They recommend the use of remote sensing in

precision agriculture. In their future research, they put the focus on the comparison of LAI and NDVI to build a comprehensive model for remote monitoring of pepper grown in open areas. LAI is not only an important parameter used to describe the geometry of the vegetation canopy but also a key indicator for understanding the ecological processes at the global and regional scale. The growth dynamics and seasonal progression of vegetation can also be timely reflected by the LAI (Qiao et al., 2019). The use of remote sensing and the possibilities of LAI as an active indicator of ongoing plant processes (Soudani et al., 2006; Kobayashi et al., 2007; Wu et al., 2015; He Y. et al., 2016; He L.I. et al., 2016) are the main motivation for this publication.
The main aim of this study was to identify the changes in LAI between major growth stages of pepper.

MATERIALS AND METHODS

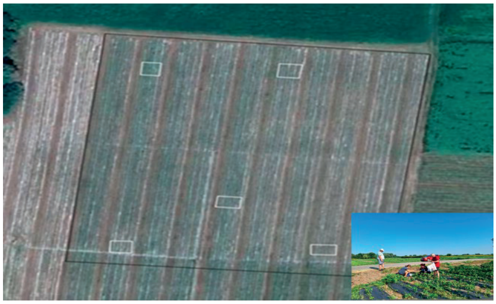
The open field is located in the Sout-Central region of Bulgaria in the village of Katunitsa, municipality Sadovo, Plovdiv district (Figure 1).
Leaf Area Index was obtained from Copernicus Land Monitoring Servies by Sentinel-2 HR multispectral satellite imagery. The LAI images are available at a spatial resolution of 10m x 10m and daily updates of Leaf Area Index are provided at pan-European level and in near real-time (Data Viewer/ Bio-geophysical parameters /Vegetation/LAI,Europe,daily https://land.copernicus.eu/en/map-viewer).
This index is used to forecast crop growth and yield and estimate foliage cover. LAI uses the empirical formula developed by Boegh et al. (2002):

$$LAI = (3.618*EVI - 0.118)$$

where:
- EVI is Enhanced Vegetation Index value.

The images and sample raster values from LAI were processed by QGIS 3.10. Time series images were downloaded for the same period of experimental in situ data collection. The main growth stages are calculated in the days after transplanting the pepper on the open field. The correlations between the studied variables were obtained by regression analysis in Excel Microsoft 365 and were valid within the time range studied.

a) L42°6'49.69"N B24°52'38.77"E
(Goggle Earth 3.07.2022)



b) L42°8'16.77"N B24°52'17.84"E
(Google Earth 29.06.2023)

Figure 1. Location of study areas and target fields

In situ data collection was carried out in the period 2022-2023 on a production pepper plantation. A randomized block design was used. Five target fields were determined. These elementary plots are 50 m^2 with 400 plants in each (Figure 2).
In situ measurements were carried out in four main stages of pepper development - flower buds, flowering, before maturity, and maturity. Destructive determination of LAI was made after the collection of plant samples. The number of leaves per plant was established. Leaf area per plant (cm^2) and total leaf area (m^2/ha) were determined. Leaf area meter, WinDias3 system of the company WinDias Image Analysis System of the company Delta-T Devices, Cambridge, UK was used. The leaf area index was calculated as the ratio of plant leaf area covering a unit of land area (Arnaudova et al., 2022).
The pepper was grown according to conventional technology for middle-early field production in open fields (Cholakov, 2009; Shaban et al., 2014). The scheme used is 90+70/15 with a population of 833.3 plants per hectare and drip irrigation.

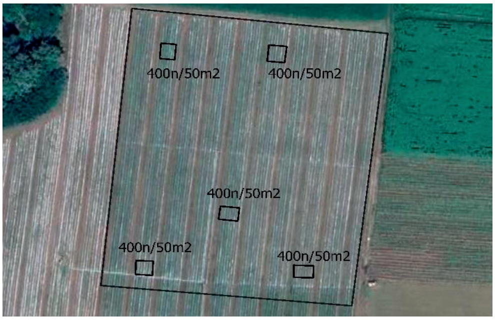


Figure 2. Methodological plan of the experiment

RESULTS AND DISCUSSIONS

The variety 'Elephant ear' belongs to the species Capsicum annumm ssp. macrocarpum ser. var. Leaf formation the intensified setting of reproductive organs and fruit formation is staged and their number increases during all observed phases (Figure 3). This feature was found in both vegetation periods (2022 and 2023).

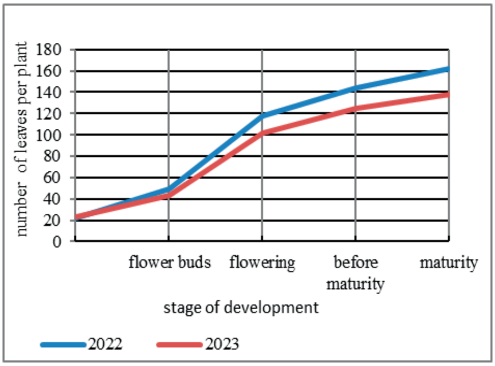


Figure 3. Dynamics of leaf formation during the stage of pepper development

The most intense leaf formation is recorded between the flower buds and flowering phases. In the following stages of development, the rate slows down, which is most likely due to longum var. kapia. It is characterized by large dark green leaves with a broadleaved shape (Panayotov & Jadchak, 2020). As the number of leaves formed on a single plant increases, the leaf area also increases (Figure 4.). In 2022, the change was from 426.86 cm^2 at the bud stage to 2088.36 cm^2 at the botanical maturity stage. In 2023, the change was from 375.64 cm^2 to 1775.11 cm^2.
The results obtained from the in-situ field data for both experimental years highlight a trend of balanced development of pepper plants without any sharp deviations or lag in their development. The formed leaf assimilation surface is a prerequisite for the normal establishment of generative organs and the formation of economic yield (Mihov et al., 2014; Sandhu et al., 2020).

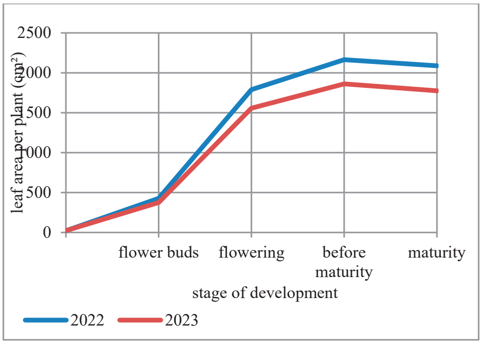
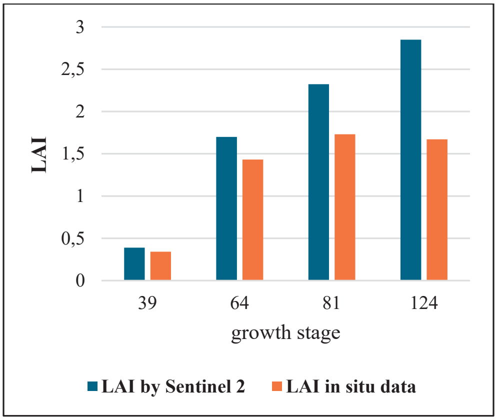
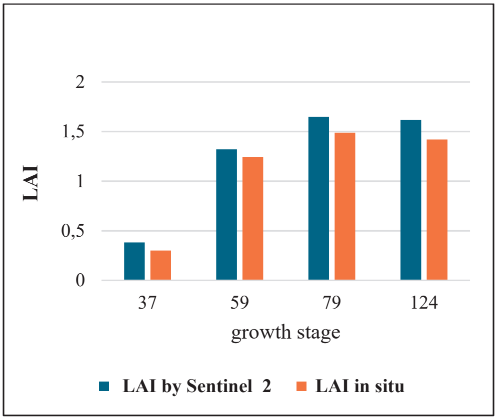


Figure 4. Formation of leaf area per plant during the different stages of grow

In 2022, the LAI calculated by the destructive method increases to the technological maturity phase from 0.34 in the flower buds stage to 1.73, and in the botanical maturity stage decreases to 1.67. This feature is most likely due to physiological senescence and scaling of some of the earliest leaves. The results are similar in 2023 (Figure 5).
The LAI values obtained from the images of the experimental plots compared with the in-situ data increased through all stages of pepper, from 0.39 at the flower bud stage to 2.85 at the botanical maturity stage for 2022. The differences in the constant increase of LAI are due to weeding in the crop.
The values for 2023 increased from 0.38 at the flower bud stage to 1.65 and decreased to 1.61 at the botanical maturity stage due to drought or physiological senescence and leaf scaling of pepper (Figure 5 and Figure 6).
Figure 6 a depicts maps with 10-meter spatial resolution generated by the Copernicus Land Service of the LAI for growth stages in 2022, with the phases occurring at 39, 64, 81, and 124 days after transplanting. The same growth stages are depicted for 2023 in Figure 6 b, occurring at 37, 59, 79, and 124 days after transplanting. The LAI values from the sample points at the five target sites were averaged and compared to the *in situ* data.



a) 2022

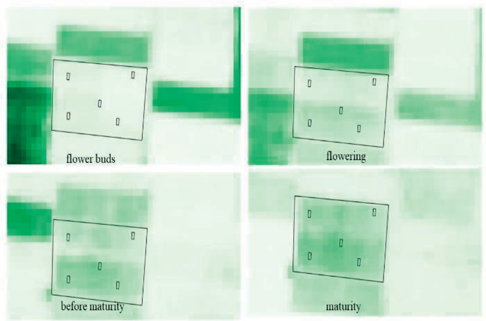


b) 2023

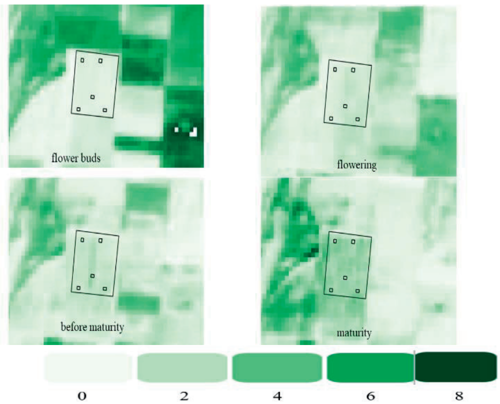
Figure 5. LAI value by satellite and in situ data

To analyze the values thus obtained, a comparative regression analysis was performed between the satellite data and the analytical ones. The coefficient of multiple correlations is very high $R^2 = 0.90$ for 2022 and $R^2 = 0.99$ for 2023 (Figure 7). Two-year dependencies of LAI were identified through investigations, and mathematical models were constructed to describe the difference between LAI values and in situ data by the main pepper stage of development.

The derived equations were used to fit satellite data to the analytically determined indices, allowing for the prediction of expected LAI values. The multiple correlation coefficients were $R^2 = 0.99$ for 2022 and $R^2 = 0.85$ for 2023.



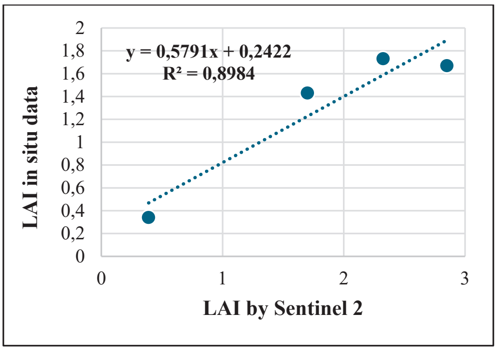
a) 2022



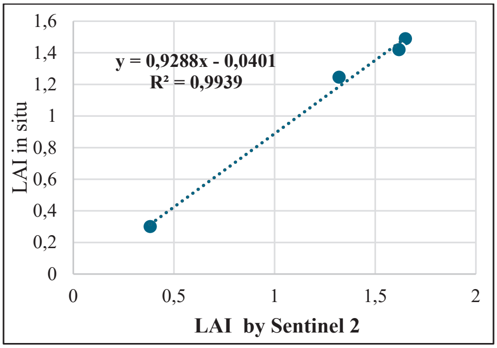
b) 2023

Figure 6. Satellite images of LAI for the main growth stages

The data from both years confirm that using imaging and extracting LAI values from the time series is a reliable method for estimating the stages of pepper development (Figure 8).

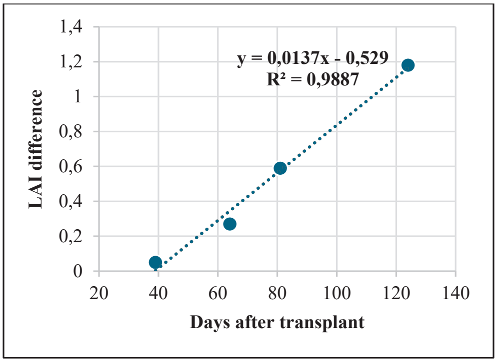


a) 2022

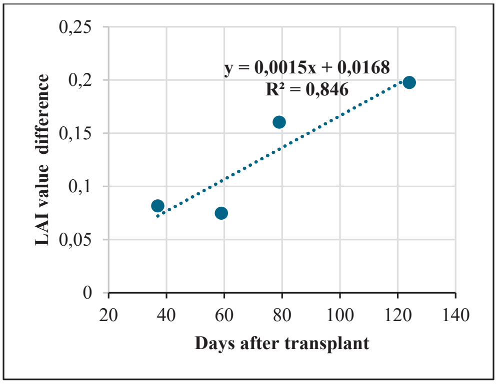


b) 2023

Figure 7. Relationship between LAI value from satellite and in situ data



a) 2022



b) 2023

Figure 8. Mathematical models of the difference between LAI values and *in situ* data by main growth stages

Our results are in line with the research conducted by Li et al. (2017) to use satellite images for determining bio-geophysical parameters and establish the correlation between field data and remote sensing data.

CONCLUSIONS

The investigation results indicate that using 10x10 m spatial resolution time-series imagery for the Sentinel 2 LAI is highly useful.
The robust correlation between the LAI values determined by in-situ and LAI values derived from satellite imagery can be evidenced by the high values of the multiple correlation coefficient R^2 = 0.90 for 2022, and R^2 = 0.99 for 2023.
The mathematical model developed for the discrepancies between LAI estimates obtained from in situ observations and satellite imagery can be utilised to predict the development of pepper plants with high accuracy.
The use of remote sensing data to estimate the LAI is more cost-effective and timesaving compared with other methods and is suitable for large-scale and long-term monitoring of vegetation with minimum effort.
For future pepper plantations remote sensing monitoring research, a relationship between LAI and other vegetation indices for example as NDVI and SAVI can be explored based on the results obtained.

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