Smart Agricultural Technology 5 (2023) 100267

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Direct and indirect ground estimation of leaf area index to support interpretation of NDVI data from satellite images in hedgerow olive orchards

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ARTICLE INFO

Keywords:
Olea europaea
LAI estimation
LAI-Pen
Vegetation index

ABSTRACT

In discontinuous crop soil coverage condition, as for many horticultural crops (e.g. fruit or olive orchard), the low spatial resolution of freely available reflectance data acquired from satellites, affects their agronomic use. Each reflectance pixel value is influenced not only by the reflectance response of the target crop but also by the percentage of pixel covered by the crop, as bare soil and/or spontaneous vegetation strongly affects whole pixel reflectance.

In this context, when the analysis of crop conditions is the main agronomical target, the measurement of Leaf Area Index (LAI), supporting the estimation of the area covered by the discontinuous crop, could represent a crucial step helping the interpretation of remote sensed spectral data including related vegetation indices.

From this perspective, a field experiment has been conducted on an 8.30 ha super intensive hedgerow olive orchard, monitoring (i) variation of NDVI from an 830 pixels' grid of the Sentinel-2 imagery (10×10 m) during two years (2020–2021); (ii) LAI estimated by destructive measurement, and (iii) LAI estimated by light transmittance at soil level under the crop measured by a commercial low cost field instrument (LAI-Pen LP 100) with two light sensors (400 - 700 nm and 400 - 500 nm bands).

Mean NDVI elaborated from Sentinel-2 imagery and referred to the whole orchard, varies from 0.28 to 0.81, along the two years, and was quite stable during the summer months for each year (0.28–0.36 in 2020 and 0.39–0.41 in 2021). LAI estimated by destructive measurements on single plants, ranged between 2.17 and 4.38. LAI estimated by LAI-Pen, was strongly related to LAI estimated by destructive measurements (R^2=0.9473 $n = 9$)

Finally, the average of LAI-Pen measurements referred to all the plants ($n = 16$) included in each pixel of the Sentinel 2 measurements' grid, resulted directly correlated to pixel NDVI values collected in the same date.

Introduction

Precision Agriculture, as stated by the International Society of Precision Agriculture [1] 'is a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines them with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production'.

Satellite gathered data can be widely applied to precision farming and sustained efforts have been directed towards obtaining crop biophysical parameters mostly derived from red (R) and near-infrared (NIR) reflectance combinations [2–6]. The normalized difference vegetation index (NDVI) among the others vegetation indices obtained from remote sensing (RS) is nowadays widely applied to mapping homogeneous zones in herbaceous and tree crops [7–9]. NDVI has been correlated to total biomass, level of drought, crop physiological conditions and leaf area index (LAI) [10–12].

For this reason, satellite NDVI data could be useful for quick mapping of plant vigor giving information about the portions of crop needing specific differential agronomical intervention [13,14], and several companies already provide the agronomist of maps based on the NDVI for crop management.

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https://doi.org/10.1016/j.atech.2023.100267
Received 27 April 2023; Received in revised form 5 June 2023; Accepted 6 June 2023
Available online 12 June 2023

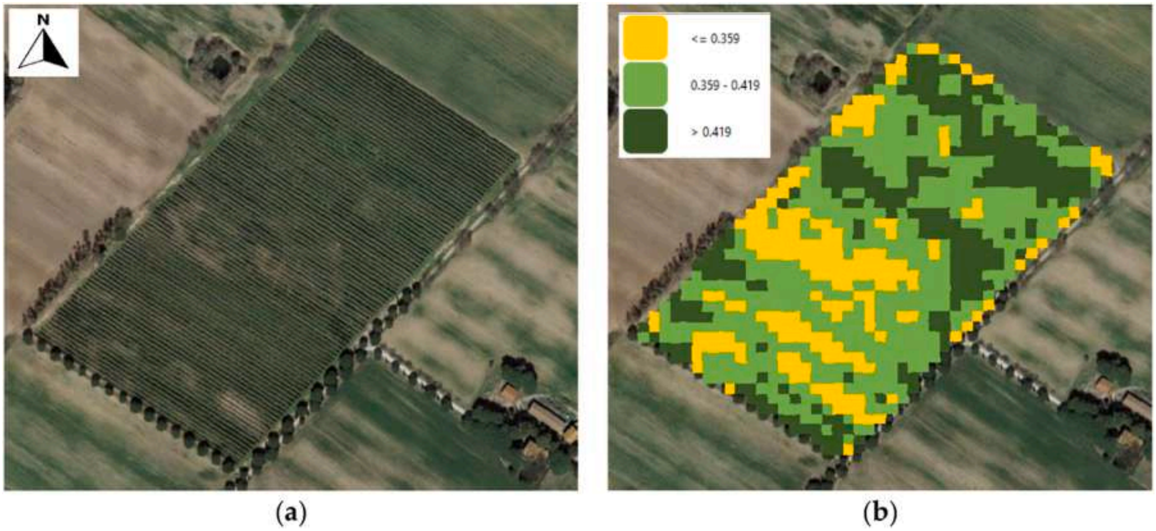


Fig. 1. (a) Satellite image of the olive orchard interested by this study; (b) NDVI computed from the 830 pixel grid (10×10 m) of the Sentinel-2 imagery recorded in a summer day (July 21th, 2021).

However, when utilizing satellite-based NDVI data for precise mapping in discontinuous crops, there are challenges due to the interference of background soil and/or the spontaneous vegetation. These challenges occur both from a qualitative perspective, in terms of variations in the reflectance of the background area, and from a quantitative point of view, due to periodic agronomical management practices such as canopy hedging and topping during the spring-summer season or winter pruning [15]. These interventions have an impact on the extent of the crop area represented by each pixel.

In particular, modern hedgerow olive orchards expose important proportion of inter-row space, where no canopy covers the soil surface, to satellite observation so reporting a mix of reflectance data from inter-row and canopy affected by both leaf distribution and quantity.

Since leaf surfaces are the primary border of energy and mass exchange, LAI is a parameter used to estimate important processes such as evapotranspiration, gross photosynthesis, rainfall interception, carbon flux and primary productivity of crops [16,17], but also to evaluate dynamic changes within the crops by means of long-term monitoring of LAI. Moreover, in particular in remote sensed observations where canopy relations with visible light and near-infrared spectra are regarded, in terms of adsorption, reflectance and transmittance, it can be easily argued the strong relation with the LAI [18].

Nevertheless, LAI measuring or estimation, especially in tree crops, faces several complications compared to herbaceous crops mainly due to plant dimensions, and different methods and instruments have been proposed involving direct or semi-direct measures of leaf area of a sample (e.g. branch, defined volume), by means of leaf area meter, to be inferred to the whole crown [19], or different indirect methods as the measurement of the transmittance of radiation at various angles [20], or the application of digital hemispherical photography [21,22], or digital cover photography [23].

The individuation of suitable methodologies and/or sensors or devices for fast and accurate LAI estimation is of primarily importance and so is the information about the possible correlation between this ground LAI estimation, not affected by the herbaceous cover crop, and low spatial resolution NDVI acquired from satellites.

On the market it is possible to find several devices for LAI estimation, but not all of them have small size, with a quick response and a low cost. For this task, we utilized the LAI-Pen LP 110 (Photon Systems Instruments, PSI, Drásov, Czech Republic). The instrument offers instant measurements of photosynthetically active radiation (PAR) and is recognized for its accuracy in various daylight conditions. However, there is currently no available information regarding its application specifically on olive trees. Based on this knowledge, we planned a field experiment involving an eight-hectare super intensive hedgerow olive orchard in central Italy during two years (2020–2021), (i) to monitor the seasonal variation of NDVI acquired from Sentinel-2, (ii) to estimate LAI by destructive measurement, (iii) to estimate LAI by indirect measurement involving light transmittance at soil level under the crop measured with LAI-Pen LP 110, and (iv) to evaluate the relation between LAI estimated and NDVI on specific pixels (10×10 m) of the grid of the Sentinel-2 imagery measured in the same date.

Materials and methods

Field experiment

The research was conducted in Marina di Grosseto (42.735394 N, 10.986208 E - Grosseto, Italy) in a super intensive olive orchard covering approximately 8.30 ha (Fig. 1a). Olives were planted in the loamy sand soil in year 2009 at a spacing of 4.0 × 1.6 m and trained as hedgerow. The plant rows are disposed southeast to northwest (Fig. 1a). The area experienced a typical Mediterranean climate (Csa, according to the Köppen climate classification system), with a mean annual temperature of 16 °C and 740 mm of total rainfall [24]. The olive orchard is managed with superficial soil tillage performed twice a year and drip irrigation. Watering along the period of the research was done distributing a total of 350 m^3 of water per hectare from the end of June to mid-September. The canopies were topped and hedged in February 2020 before starting the trial, then remained untouched to check the growth of the LAI index from March 2020 to October 2021. The orchard was protected against the main pests so that the color of the vegetation was not affected by any health problem of the canopies.

NDVI data set

Original data set of NDVI was provided by Greenfield (https://greenfield.farm/en/crop-monitoring/) partner of our group in the LIFE Resilience project. The Sentinel-2 satellite images (Level-1C and Level-2A) were downloaded from the European Union Copernicus Platform at https://scihub.copernicus.eu/dhus/#/home. Sentinel-2 Level-1C products required the atmospheric correction and resampling of the images, performed using the Sen2cor atmospheric correction toolbox, whereas Level-2A data allowed further analysis without applying additional atmospheric corrections. To compute NDVI of each pixel, the band 04 (red) and 08 (NIR) with a spatial resolution of 10 m were selected and

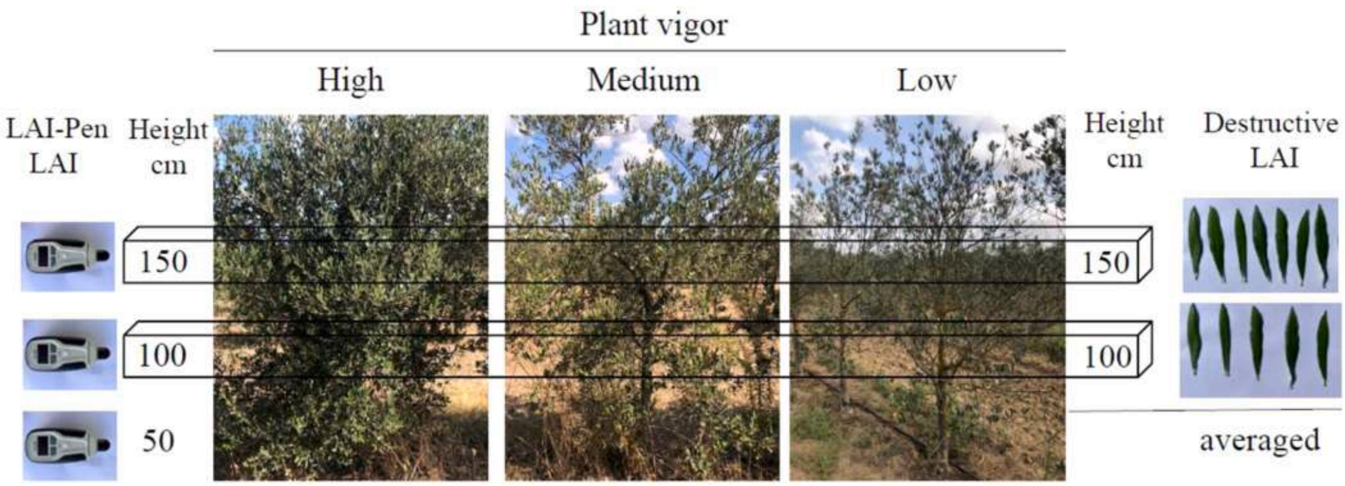


Fig. 2. Schematic representation of indirect non-destructive (left) and direct destructive (right) determination of Leaf Area Index.

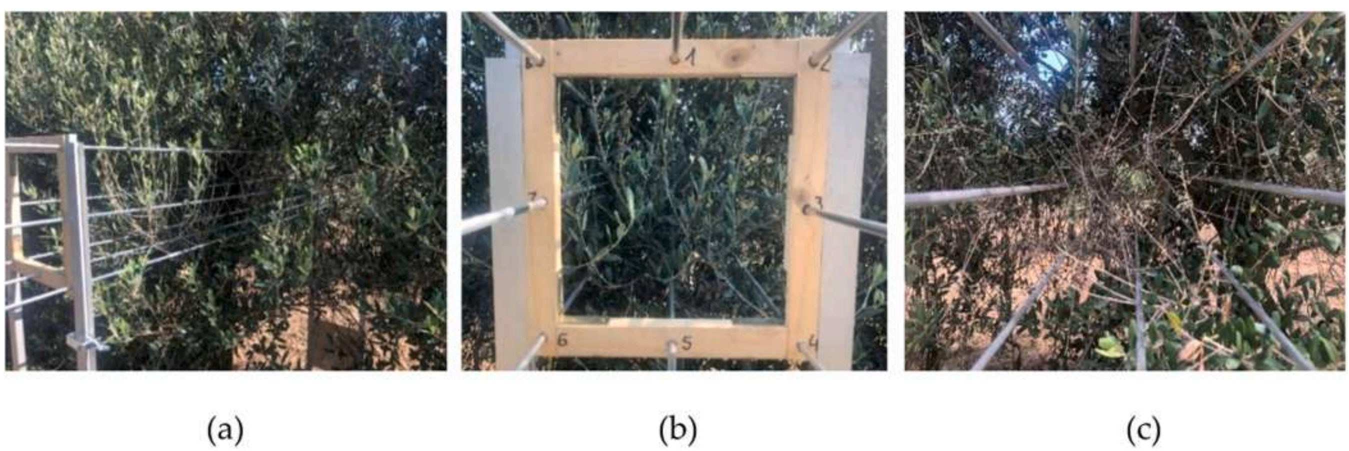


Fig. 3. (a) Canopy interceptor with the bases positioned on the two sides of the olive hedgerow. (b) The frame helps to select a 25 × 25 cm area while the long rods delimit the volume of the canopy to be sampled; (c) intercepted volume of the canopy, only the bare shoots are visible after the detachment of all the leaves.

downloaded every five days in both years (Fig. 1b). Dates hampered by cloud were discarded from computing. NDVI for each available data was calculated for all 830 pixels covering the entire orchard.

For each date with available data, NDVI value of the whole orchard has been calculated as average of the 830 pixels values.

Indirect LAI estimation

LAI-Pen LP 100 provides instant readouts of PAR by a sensor with 400–700 nm band pass filter while a second sensor measures the irradiance at 400–500 nm bands. The measurement of solar irradiance below vegetation canopy is compared to a reference measurement in clear open area to determine what is called ALAI transmittance [25]. Since no information was available about the use of the LAI-Pen on olive trees, a preliminary experiment was conducted to verify the effects on LAI-Pen measurements of time of the day and point of measurement in relation to distance from trunk (Appendix A).

Following the results of the preliminary experiment, LAI estimation has been conducted on nine plants selected on the base of their plant vigor and classified as low (L) medium (M) and high (H) vigor (three plants for each group). For each plant, measures were carried out at mid-distance between trunks (80 cm from each plant) on a line parallel to the row, at 30 cm from the lateral limit of the vegetation and at 50, 100 and 150 cm from the ground on the shadowed side of row (Fig. 2). The heights of the measuring points were chosen in relation to the hedge-shape of the canopies topped at 200 cm from soil.

The readings were quickly recorded with the LAI-Pen kept along the zenith direction in a sunny day, August 25 2021, from 9:43 to 9:55 CET. According to preliminary experiments results, the irradiance at 400 - 500 nm bands (ALAI) was recorded and the data used to calculate LAI as indicated by the instrument producer:

$$\mathrm{LAI} = -\ln(\mathrm{I} / \mathrm{I}_0)/\mathrm{k} \quad (1)$$

where I is the irradiance measured by LAI-Pen sensor below the plant canopy, I_0 the reference irradiance measured in clear open area, k the radiation extinction coefficient.

Direct LAI estimation

Measurements were conducted on the same plants selected for indirect LAI-Pen estimation. Two leaves sampling volumes per plant, at two different heights (lower horizontal surface of the prismatic volumes at 100 and 150 cm from soil, respectively), where disposed perpendicularly to the row at mid-distance between trunks on the row (80 cm from each plant) to avoid the presence of large woody branches (Fig. 2). For this purpose, a handmade canopy interceptor (Canceptor©) was designed to precisely individuate the leaves to be detached for area measurement. The canopy interceptor in Fig. 3 was made of two woody frames (25 × 25 cm area) sliding into metal telescopic guides sustained by concrete bases.

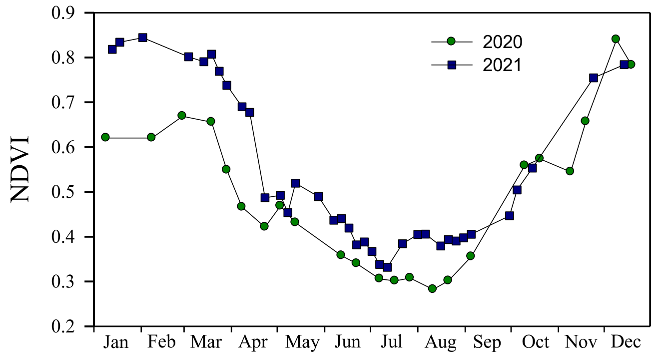


Fig. 4. A two year series of NDVI in 2020 and 2021 for the super intensive orchard located in Marina di Grosseto, Italy. Each point represents the averaged index of the 830 pixel grid (10×10 m) of the Sentinel-2 imagery covering the whole 8 ha orchard.

Table 1
NDVI index values (± standard deviation) calculated for the dates with good weather conditions and main variations during the period July-September of the years 2020 and 2021. Means differing $p = 0.01$.

Year	Number of observations	Minimum	Maximum	Range	Mean
2020	5	0.28	0.36	0.08	0.31 ± 0.03
2021	8	0.39	0.41	0.02	0.40 ± 0.01

Each frame gives support to eight aluminum rods inserted into predisposed holes. By means of this device it was possible to select a volume across the canopy so to identify and detach all the leaves contained in the whole intercepted volume from one side to the other of the tree hedge (Fig. 3c). The two woody extreme frames for each volume were placed aside the most external part of the crown and their relative distance was measured to calculate the sampling volume.

All the leaves contained in the 18 sampling volumes were collected. Total fresh (FW) and dry weight (DW) was recorded. A 100 g FW leaves subsample for each sampling volume, was photographed on a plain surface to determine the leaf area (LA) using ImageJ software [26] then, after drying, the LA per g of DW was calculated and related to the total DW of the leaves collected in each sampling volume, to obtain the actual LA/cm^3 of sampling volume. The whole volume of each crown of sampled plant was estimated measuring the width of the hedge in nine points originated by three different heights in three different areas in the edge. Then relating this crown volume with the LA/cm^3, actual plant leaf area was calculated. Finally, data of the two destructive sampling per plant were averaged and LAI calculated on the base of the area projected by the crown.

Finally, LAI-Pen values were related to LAI-destructively estimated regressing LAI-Pen measures for each measuring height and in the average of the three heights, to the destructively measured LAI for each sampled plant in the average of the two sampling volumes.

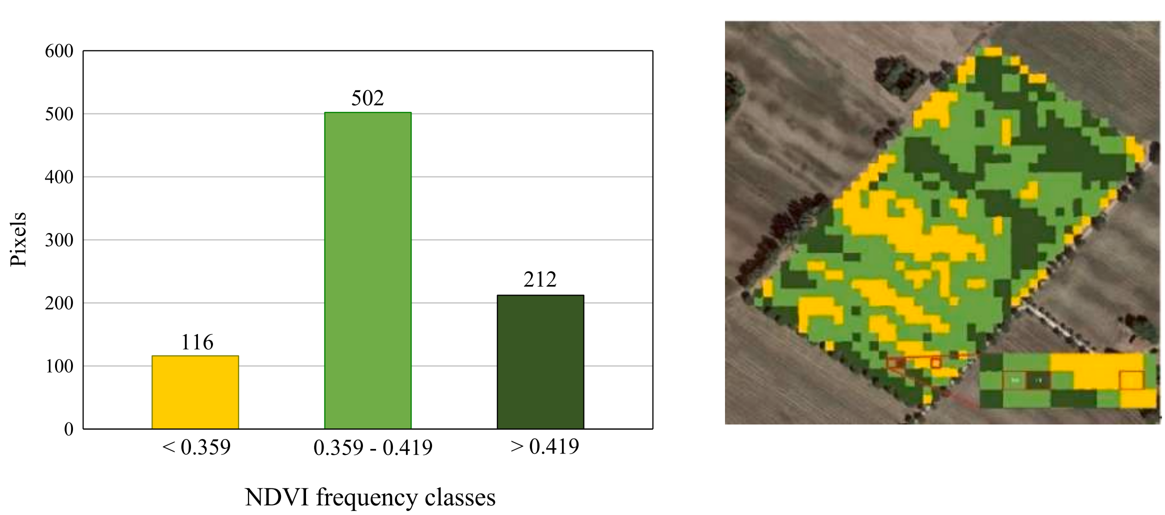
NDVI vs. indirect LAI estimation relation

Georeferenced measures were also conducted with LAI-Pen in the centroids of sixty pixels within the orchard characterized by an increasing NDVI value obtained on the last date available from Sentinel-2 satellite images (21/8/2021) preceding the LAI-Pen measurement to

Table 2
Anova results (probability level) and the average values for studied variables (LAI-Pen estimated and LAI-Destructively estimated) into nine olive plants.

ANOVA results	LAI-Pen estimated	LAI-Destructively estimated
Plant vigor	0.0000 ***	0.0101 *
Measuring height	0.0012 **	0.0913 ns
Plant vigor x Measuring height	0.9262 ns	0.3795 ns
Mean comparison (SNK test)		
Low	0.74 c	2.17 b
Medium	1.99 b	3.36 ab
High	3.17 a	4.38 a
H_50cm	2.49 a	–
H_100cm	2.29 a	2.86
H_150cm	1.13 b	3.75

Probability level (P) as resulting from two-way ANOVA. ns=not significant,.
*,
**,
*** significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. For each main effect, the mean values with different superscript letters, in a column are significantly different (p<0.05).



(a) (b)

Fig. 5. Distribution of NDVI values of 830 pixels (10×10 m) of the Sentinel-2 imagery averaging reflectance measured on 21/8/2021 into 3 classes (a) and visualization on the map of the simplified zonation based on NDVI index (b): plants with low vegetation (L – yellow) with plants with vegetation in the average (middle M – green) and plants with vegetation above the average (high – H – dark green).

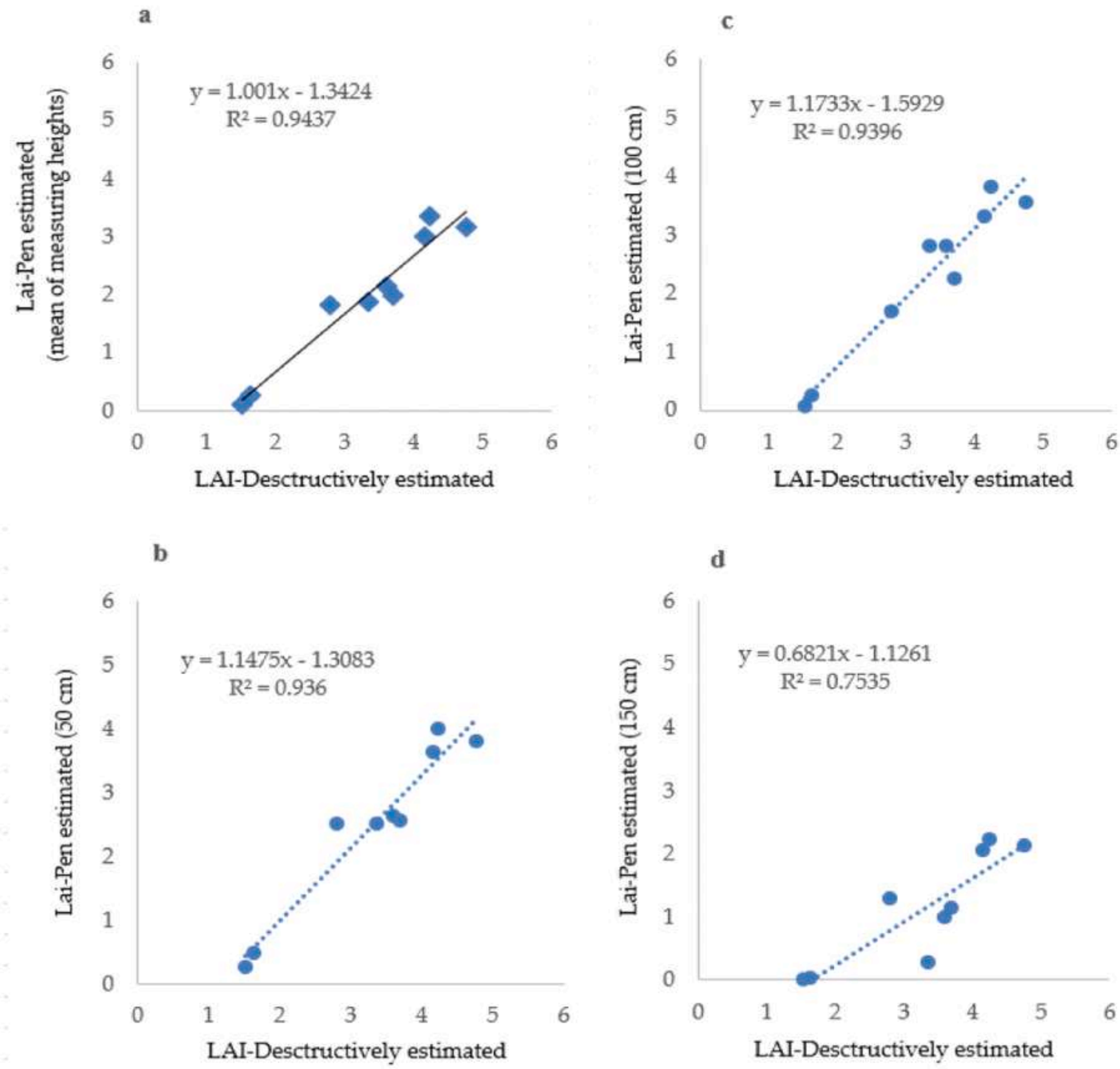
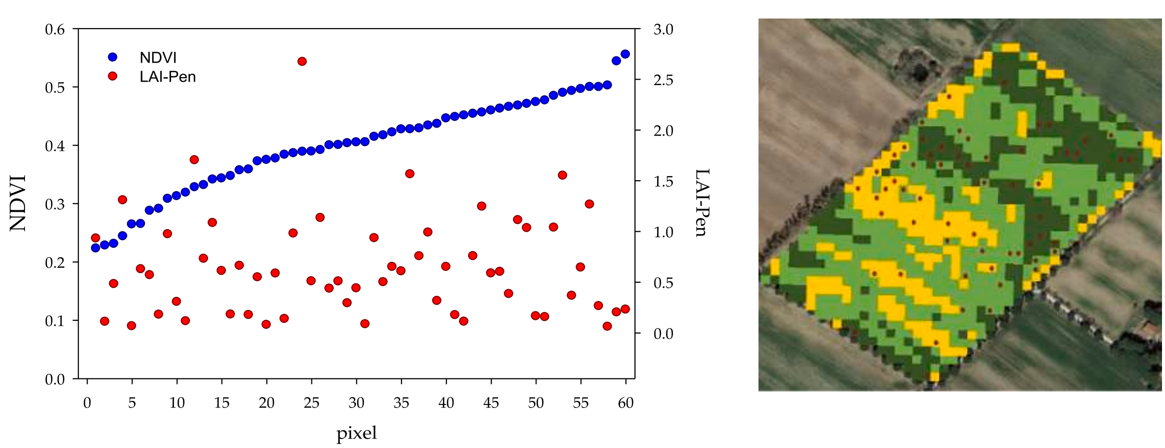


Fig. 6. Plot of the linear regression between LAI estimated by LAI-Pen in the average of the measuring heights (a), at 0.5 m (b), at 1.0 m (c), and at 1.5 m (d) height from the ground and LAI estimated by destructive sample.



(a) (b)

Fig. 7. NDVI (21/08/21 – blue dots) and LAI-Pen (red dots) values (a) estimated in the centroid of 10×10 m pixel of the Sentinel-2 imagery in the sixty selected pixels (b) showed according to an ascending order of NDVI.

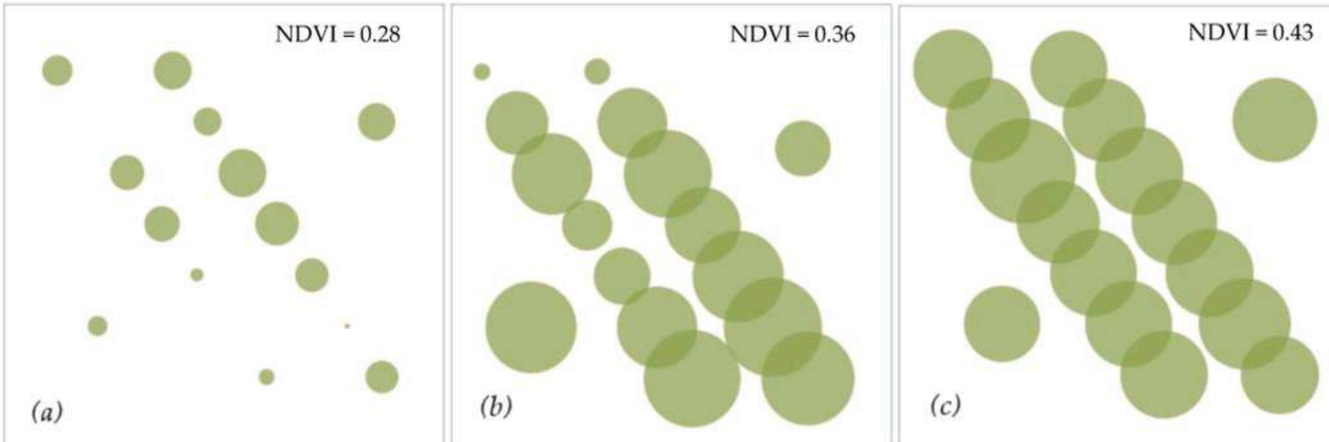


Fig. 8. LAI-Pen measurements registered on 25/8/2021. The area of each bubble is proportional to the LAI measured on each of the 16 georeferenced plants contained in pixels' grid of the Sentinel-2 imagery. Each figure represents a pixel (10×10) of the grid.

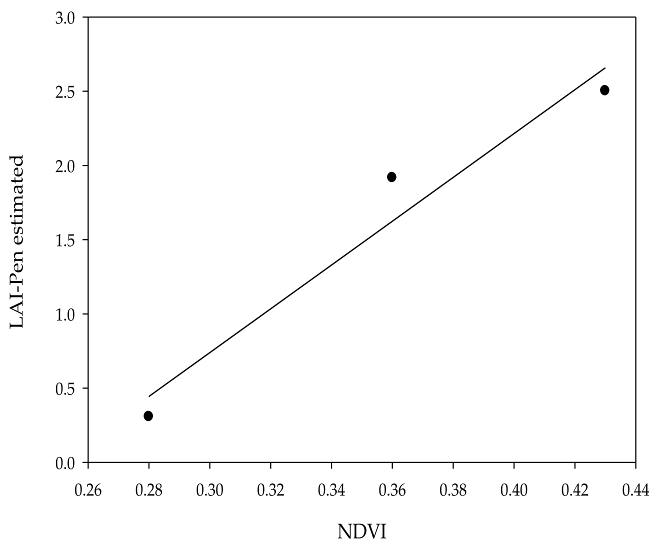


Fig. 9. Relationship between NDVI values in three pixels' grid of the Sentinel-2 imagery and LAI-Pen estimated on the 16 plants of each pixel.

check the correlation between the vegetational index calculated from satellite image and canopy absorbance manually measured on the ground. The single reading per each pixel was taken on August 25th 2021.

Finally, LAI-Pen georeferenced measurements have been carried out for each of the 16 plants included in three pixels selected for their different NDVI values (high, medium and low). For each pixel, LAI-Pen mean value has been calculated and related to NDVI value. To achieve a real-time sub-meter-level positioning accuracy (0.05 m), for each LAI-Pen reading, a dual frequency GNSS receiver (S580, Stonex, Italy) was set to receive network RTK differential corrections. The receiver was attached to 3 m pole to make sure that satellite signal was not blocked by trunks and branches.

Statistical analysis

To drive the selection of pixels where to apply georeferenced LAI-Pen measurements, the analysis of frequency data by means of CoStat 6.45 (CoHort Software) was carried on the NDVI data collected on August the 21th of 2021.

The effects of studied factors (Plant vigor, time and point of LAI-Pen measurement for preliminary experiment - appendix A - and Plant vigor and Measuring height for the two LAI estimation method adopted) have been test by ANOVA and mean comparison have been conducted using SNK Test (CoStat 6.45; CoHort Software).

ANOVA of the regression have been conducted to study the relation between LAI-Pen estimated and LAI-Destructively estimated. The slope of the regression curve has been iteratively adjusted to a unit value tuning the extinction coefficient of the function (1).

Table A1
Table of the three-way ANOVA applied to olive canopy transmittance values measured by LAI-Pen introducing as source of variation the vegetative status of the olives, the location of the instrument along the hedgerow and the time of the day when the measures have been conducted.

ANOVA results	Probability level
Plant vigor (PV)	0.0000 ***
Point for measurements along the row (P)	0.090 ns
Time for measurements (T)	0.158 ns
PVx P	0.617 ns
PVx T	0.911 ns
PVx P x T	1.000 ns
P x T	0.983 ns
Mean comparison (SNK test)	**T2[1] (I/I0)**
Fair	0.671 a
Good	0.453 b
1 (80 cm left from the trunk))	0.590
2 (40 cm left from the trunk)	0.520
3 (in line with the trunk)	0.496
4 (40 cm right from the trunk)	0.567
5 (80 cm right from the trunk)	0.637
09:30	0.553
11:00	0.542
12:30	0.525
14:00	0.629

Probability level (P) as resulting from three-way ANOVA. ns=not significant,. *, **, *** significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. For each main effect, the mean values with different superscript letters, in a column are significantly different ($p<0.05$).

[1] Light transmittance below the canopy.

Results

Seasonal variation of NDVI

The seasonal courses of NDVI (Fig. 4) was characterized by high values (between 0.59 and 0.80, respectively in 2020 and 2021) during the winter (December–March), a steep decrease in spring (April/June), a pronounced minimum (between 0.29 and 0.42, respectively in 2020 and

2021) in summer and early autumn (July–September), and then they start climbing again at higher values from early of October. It is possible to notice that the NDVI presented quite steady values along the summertime, due to absence of natural vegetation ground cover due to dry conditions.

Consequently, to avoid the vegetation ground cover interference, we taken into account exclusively the NDVI mean values from July to September. The values (Table 1) of the index during these periods of time presented a range equal to 0.08 and 0.02 (in 2020 and 2021, respectively) with an increase of the mean index of the orchard equal to 0.09 (from 0.31 to 0.40).

Due to the stable NDVI trend registered since July 2021 and to the forecasted weather conditions, the frequency distribution of NDVI data on August the 21th has been analyzed to select the pixels where to conduct direct and indirect LAI estimation. The distribution follows a normal shape (Fig. 5a), slightly asymmetric toward the higher values of NDVI since 212 areas presented NDVI index above the average while 116 of them had values of the index below the average.

The visualization of the areas colored in relation to the NDVI range is presented in Fig. 5b. This map was used to select the plants for the LAI measurements.

Indirect LAI estimation

The acquisition of the data with LAI-Pen was very fast (from 9:43 to 9:56) to avoid the effects on light measurements from any change in the reference irradiance.

Transmittance below the canopy was affected by both the vegetative grouping of the plants (L, M or H, $p = 0.000^{***}$) and by the height of measurement ($p = 0.0012^{**}$). In particular, when measuring LAI-Pen in olive plants with low vegetation the transmittance at 1.5 m from the ground was deeply affected by gaps in the canopies (Table 2).

Direct LAI estimation

Destructive sampling and measurements have been carried out immediately following the irradiance evaluation on the same plants where LAI-Pen measurements were conducted. The mean LAI estimated for the three groups of plants scored on the base of the vegetative condition was respectively 2.17, 3.36 and 4.38, for low (L), medium (M) and high (H) plant vigor (Table 2). ANOVA showed significant differences among the plant vigor groups on LAI ($p = 0.010^{*}$) but no effects of measuring height has been observed.

LAI-Pen estimated for each measuring height and for their average have been regressed against LAI-destructively estimated Fig. 6). High determination coefficients R^2 have been calculated, with the highest reported for the LAI-Pen estimated averaging all the measuring heights (Fig. 6a). For all the regression curves, negative values of the intercept have been obtained remarking underestimation of the LAI-Pen, when very low LAI-Destructively estimation have been ascertained (LAI lower than 2). In the logarithmic function ((1) applied to obtain indirect LAI estimation from irradiance values, the extinction coefficient (k) has been iteratively tuned up to 0.5191 to obtain a slope equal to 1 and an intercept equal to −1.3424 so quantifying the underestimation affecting LAI-Pen measurements for low values.

NDVI vs. indirect LAI estimation relation

The result of the single LAI-Pen measurements of absorbance, conducted on 25/08/2021 in georeferenced positions of the orchard corresponding to sixty centroids of pixels characterized by increasing value of NDVI (measured on 21/08/2021) is reported in Fig. 7. As is possible to notice there is no correlation between the two sets ($r = -0.006$). This result can be explained by the fact that the instrument must be localized for measurement close to each canopy of the plant and although the care in positioning a single reading made for a single plant can be representative of the vigor of the plant itself but not of the entire pixel to which that plant belongs.

On the same date (25/8/2021), in one pixel of the grid of the Sentinel-2 imagery for each of the NDVI frequency classes described (Fig. 5), georeferenced LAI-Pen measurements have been conducted on the 16 plants belonging to each pixel (Fig. 8).

In the pixel with the lowest NDVI (0.28), the plants appeared very stressed and LAI-Pen mean value was equal to 0.31 with two plants desiccated where 0 LAI has been estimated (Fig. 8a).

On the other hand, in the pixels with medium and high NDVI values (0.36 and 0.43, respectively) no desiccated plants were observed and LAI-Pen was respectively equal to 1.91 (Fig. 8b) and 2.50 (8c).

The LAI-Pen measures have been averaged within each pixel and then related to the corresponding NDVI values (Fig. 9), leading to a closer relation ($R^2 = 0.950$) compared to what observed when single LAI-Pen measurements for each pixel have been conducted (Fig. 7).

Discussion

Vegetative condition within the olive orchard in Marina di Grosseto represents a good picture of the olive plant growth in similar Mediterranean climate and soils. There are several spots with plant presenting the maximum level of vegetative growth other suffering for the extremely poor soil water retention due to high percentage of sand. The wide difference in NDVI index within the orchard represent the agronomical range between poor and favorable vegetative condition of olive plant in hedgerow plantation in Mediterranean areas and can be of general application. The decrease of the NDVI index along the spring season is easily explained by olive orchard management and practice applied in the studied area. Each plant at a spacing of 4 × 1.6 m has theoretically 6.4 m^2s at its disposition for the canopy grow but since this is periodically hedged by machinery the width can reach a maximum occupation of 90–100 cm from the canopy center with an average total width of 1.8 m. When calculating the NDVI index of a 10×10 m pixel by RS only 45–50% of the reflectance is due to the olive canopy while the rest is due to the soil. In traditional olive cultivation in this area the soil within the olives if kept with natural plant coverage in winter and only in late spring the soil is tilled to reduce competition between herbaceous plants and olives. Only during the long and dry summer, the space between each row is completely deprived from weeds/plants and this explains the steadiness of the NDVI index which is mainly due to the olive plants with the growth reduced by high temperatures.

Since the plant were not pruned during the period considered in this experiment, the mean increase of NDVI index recorded in 2021 (Fig. 4) could be associated, in our opinion, to an effective change in the thickness of the hedgerow caused by the annual growth of the lateral shoots. The mean annual increase of the NDVI index within the whole orchard between 2020 and 2021 was equal to 0.09 and, although seems low, it is close to the differences calculated among the classes in which the orchard was subdivided (0.06). The results obtained through destructive sampling, which is crucial for validating remote sensing data [16], indicate LAI values ranging from 1.6 to 4.8. Čermák and coworker [27] conducted a study on old olive trees in south Italy found values between 1 and 7 with a mean of 3.5, while another research [22] measured a LAI equal to 2.8 in ten years old plants located in the same area. Kang and coworker [18] reported that LAI, although statistically well related to remotely sensed vegetation indices, is crop-specific and therefore it is the need of ground validation. modeling studies conducted in the area [28] showed that both olive volume and biomass could be inferred from the diameter of the trunk but the latter did not correlate with LAI. The LAI estimated by LAI-Pen showed high correlation with the LAI estimated by destructive samples opening interesting applicative uses. As stated by Breda [19] the extinction coefficient (k) is estimated from shape orientation and position of each element of vegetation canopy and usually close to 0.5 [17] then LAI must be further corrected by proportion of woody elements surface area (WAI). Stenberg et al.

[29] working with coniferous trees corrected on the base of clumping of needles within shoots. The olive trees trained as hedgerow also present the internal volume of the canopy occupied by a high number of shoots (Fig. 3b) but we found that the k value to best fit the destructive LAI in this type of plantation was equal to 0.5191. Using this parameter in the formula for LAI estimation by LAI-Pen transmittance measured in the 400–500 nm bands was possible to explain 94% of variation in LAI estimated by canopy sampling.

Finally, and as expected, the contribution of LAI measurements for the interpretation of NDVI values resulted ineffective when single measurements per pixel are proposed. On the other hand, more encouraging results followed the measurements of a more representative data for the pixel, obtained averaging LAI calculated for all the georeferenced plants belonging to the pixel.

Conclusions

In this paper two methods for LAI measurements in super intensive hedgerow olive orchard are discussed. For the first time the application of light transmittance data measured in proximity of the plant with a fast reading instrument is proposed as a method for LAI estimation. This paves the road to use this kind of instrument to estimate a strategic variable as LAI for crop modeling.

The restricted number of pixel whit an average LAI for all the plants, due to the manual procedures involved in the experiment, limits the possibility to directly infer interpretation of the low spatial resolution NDVI data for olive orchard. Nevertheless, the results suggest the opportunity to integrate ground level measurement, potentially conducted trough unmanned vehicles, and freely available reflectance data from satellite extending their use also for crops affected by background interferences as olive orchards.

CRediT authorship contribution statement

Claudio Cantini: Conceptualization, Funding acquisition, Methodology, Investigation, Data curation, Writing – original draft. **Pietro Emilio Nepi:** Investigation, Data curation, Writing – original draft. **:** Methodology, Data curation, Writing – original draft. **Ezio Riggi:** Methodology, Data curation, Writing – original draft.

Declaration of Competing Interest

Claudio Cantini reports financial support was provided by LIFE programme.

Funding

This research was partially funded by the European Union in the LIFE Program, LIFE-Resilience project, LIFE17 CCA/ES/000030.

Ethics approval/declarations

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability

The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author on request.

Code availability

Not applicable.

Appendix A

In light of the lack of available information regarding the use of the LAI-Pen on olive trees, an initial experiment was conducted to explore the potential application of this device in estimating the canopy's light interception throughout the day. The measurements were carried out in olive plants selected on the base of their vegetative status determined by visual observation as "fair" (presence of gaps in the vegetation within the hedgerow) or "good" (no gaps visible in the vegetation and presence of leaves within the whole canopy volume). Three plants for each group have been selected. For each plant, five measuring points were fixed along a line parallel to the row, at 30 cm from the lateral limit of the vegetation. The points were positioned at a regular distance among them in correspondence of the main trunk, 40 and 80 cm from it in opposite directions. In a sunny day (July 13 2021,) the instrument was positioned 100 cm above each of the five fixed points and the readings taken at 9:30, 11:00, 12:30 and 14:00. Immediately before and after the five measures per plant, external PAR and ALAI were taken as reference. ANOVA has been conducted using as source of variation the quantity of vegetation, the point of measurement and the time of the day.

The correlation between ALAI transmittance and PAR was relatively low $r = 0.376$ and only 14% of variation in ALAI was explained by a variation in PAR along the day of the experiment confirming a good stability of this parameter. ANOVA analysis of experimental data (Table A1) using as source of variation the quantity of vegetation, the point of measurement and the time of the day showed that the transmittance was not statistically affected by the timing of measurement or the different point within each canopy while a high significant effect was due to the vegetative status. By the results of this preliminary experiment we decided that a fast, reliable way of measuring the transmittance would have been to take a single reading at different height from the soil 30 cm from the lateral dark side of the hedgerow and at 80 cm of distance from the trunk along the row to avoid the presence of large woody branches influencing light transmittance but also the LAI-destructive measure previously described.

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