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Vegetative mapping of hedgerow olive orchards by NDVI data from satellite images supported by both direct and indirect ground estimation of leaf area index

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Abstract: The normalized difference vegetation index (NDVI) from remote sensing (RS) is applied to mapping homogeneous zones in herbaceous crops or forestry. NDVI has been correlated to total biomass and leaf area index (LAI). Seasonal and long-term monitoring of LAI can provide an understanding of dynamic changes within woody crops. Estimation of the density of the vegetation computed by RS could be implemented by data collected with proximal sensors and this appears most explicitly in discontinuous soil coverage condition such us a olive orchard. Little is known about seasonal variation of NDVI in olive orchards and few information are available about its use in vegetative mapping and LAI estimation. In this paper NDVI calculated during two years were used to identify areas with different plant vigor. LaiPen sensor was applied to measure transmittance correlated to NDVI index and LAI estimated by canopy sampling. This study indicates that NDVI index from RS in hedgerow olive orchard along the growing season varies from 0.28 to 0.81 being largely influenced by the natural variation in green coverage of soil. Mapping of effective differences in olive plant vegetative vigor could be estimated during the summer time. LAI estimated by transmittance 1 m height from the ground explain 80% of variation in LAI estimated by sampling of the canopy and could be used for mapping the orchard vegetative status.

Keywords: Olea europaea; LAI; unmanned ground vehicle; zonation; LaiPen; super intensive; proximal sensor; transmittance

1. 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 it 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 bio-physical parameters mostly derived from red (R) and near-infrared (NIR) reflectance combinations [2, 3, 4, 5, 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, 8, 9]. NDVI has been correlated to total biomass, level of drought and leaf area index (LAI) [10, 11, 12]. This latter is a dimensionless variable defined by Watson [13] as the total one-sided area of leaf tissue per unit ground surface area. LAI is a key variable that bridges remote sensing observations to the quantification of agroecosystem processes [14]. From LAI is possible to compute the rate of photosynthesis, evaporation and transpiration, rainfall interception, carbon flux and primary productivity of crops. Seasonal and long-term monitoring of LAI can provide an understanding of dynamic changes within the crops although the use in olive culture must face several complications compared to herbaceous crops or forestry [15] which both present continuous vegetal coverage of the soil. The NDVI data for precision mapping of vegetation growth in olive orchard must face the well know limitation of this index: lack of sensitivity at high values [1], soil noise [16, 17], and background soil color differences. Differently from annual herbaceous crops or forestry olive crop must also face interferences with the natural vegetative growth by periodical agronomical intervention such us canopies hedging and topping during the spring-summer season or winter pruning [18]. Moreover, modern hedgerow orchards expose important proportion of inter-row space, where no canopy covers the soil surface, to satellite observation. Resolutions obtained from commercial satellite data consist of a mix of canopy and inter-row reflectance and could be affected by both leaf distribution and quantity [19]. Nevertheless, satellite NDVI data could be useful for quick precision mapping of plant vigor of large olive crop areas giving information about the portions of the orchard needing specific differential agronomical intervention [20]. Several companies already provide the agronomist of NDVI maps based on the NDVI index to managing olive groves but in literature there is a general lack of information about absolute and seasonal variation of NDVI index in modern olive orchards trained as hedgerow. Since NDVI ranges from -1 to +1 what do NDVI values represent in terms of plant vigor or vegetative status? The tuning of the information provided by NDVI to actual vegetative growth or ground-LAI is of great importance for precision farming [21]. Since NDVI is calculate from zenithal images the estimation of the density of the vegetation computed by RS could be implemented or integrated by data collected with proximal sensors mounted on Unmanned Ground Vehicle (UGV). UGV are generally considered remote-operated and autonomous and might be the solution for woody crops monitoring and LAI dynamic changes estimation along the season especially after agronomical interventions such as pruning. The individuation of a suitable sensor or device to be mounted on UGV 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 NDVI index by which is possible e.g. to produce also zonation of large areas of cultivated olives. On the market is possible to find several devices that can be mounted on UGV but not all of them have small size, with a quick response and not too expensive. We selected for this task the LaiPen LP 110 (Photon Systems Instruments, PSI, Drásov, Czech Republic). Unlike in other similar instruments the LaiPen LP 110 is accurate in most daylight conditions and does not require cloud cover or specific sun angles for its proper performance although no information was available to our knowledge about its application on olive trees.

With this research we provided the information to extract a reliable vegetative mapping of a twelve-hectare super intensive hedgerow olive orchard in central Italy based on NDVI index. We underlined the most important information to be used for precision agriculture finding correlation between the zonation based on NDVI index and actual LAI estimated both directly by destructive sampling and indirectly by a commercial sensor for light transmittance never applied before on olive trees.

2. Materials and Methods

Olive orchard. 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 ha. 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 area has a typical Mediterranean climate with a mean annual temperature of 16°C and 740 mm of total rainfall. 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 mc of water per hectare year^{-1} starting at the end of June until the middle of 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 along the two seasons of the research. 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. Images from the Sentinel satellites with a spatial resolution of 10 m were selected and downloaded every five days. The images were processed and analyzed performing the atmospheric correction and computing the NDVI values of each pixel. Greenfield, like other commercial companies, uses the data to produce maps, updated after each satellite acquisition, where different colors point out positive or negative variation within the orchard Other than absolute values of NDVI the maps highlight the differential between each date so to indicate the areas with different vegetation behavior as in Figure 1 (b).

(**a**) (**b**)

Figure 1. (**a**) Satellite image of the rectangular olive orchard interested by this study; (**b**) map of the same orchard with area points of different color based on NDVI data from satellite observation. Each color is related to the class of relative NDVI index: red = very low, orange = low, yellow = middle, light green = high, dark green = very high.

For ~~our~~ statistical purposes we used the original NDVI dataset provided as a matrix of values for each geo localized point and each valid date with clear-sky condition. We used the data collected in the years 2020 and 2021 along the seasonal period of vegetative growth of the olive in the area that is from middle of March to middle October. Dates with indexes altered by bad weather conditions were discarded from computing. Production of fruits in year 2021 was reduced almost to zero in the orchard because of the damages caused by cold gusty winds during the blossoming, but the yield did not interfere in any way with canopy shape and vegetative performances.

Indirect LAI estimation. LaiPen LP 100 provides instant readouts of photosynthetic active radiation **(**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 the reference measurement in clear open area to determine what is called ALAI transmittance. To mimic the possible use of the LaiPen LP 110 device mounted on UGV measurement were taken outside the orchard in absence of possible interference and then in proximity of each olive canopy. The olive rows are disposed south-east to north-west (Figure 1a). To achieve a real-time sub-meter-level positioning accuracy (0.05 m), a dual frequency GNSS receiver (S580, Stonex, Italy) was set to receive network RTK differential corrections for each LaiPen reading. The receiver was attached to 3 m pole to make sure that satellite signal was not blocked by trunks and branches.

Three different measurement of LAI irradiance was taken for each plant at 50, 100 and 150 cm from the ground along the shadow side of each row in the morning. The readings were quickly recorded with the LaiPen kept along the zenith direction in a sunny day, 22 august 2021, from 9:43 to 9:55 CET. The PAR during the experiment was equal to 955 μmol m^{2} s^{-1} while the ALAI value was steady at the maximum level of 4049. The decision to record the transmittance, not the PAR, only along one side of the row and during the morning was taken following a preliminary experiment carried out with the purpose to better understand the function of the LaiPen instrument and the robustness of the results. Since these details are supplemental but remain crucial to understanding and reproducing the research, data from preliminary measurements are shown in brief in appendix A. Data were also taken by LaiPen in sixty positions within the orchard characterized by an increasing NDVI value to check the correlation between the vegetational index calculated from satellite image and canopy absorbance manually measured on the ground. One single reading per each plot was taken in August 23 selecting a single representative plant. To check the goodness of this single absorbance measurement and whether this could be representative of the 10 × 10 m plot we also selected three plots within areas with different NDVI value (respectively equal to 0.28, 0.36 and 0.43) and recorded the absorbance in 18 plants to estimate the possible variation present within a single plot.

Direct LAI estimation. Direct LAI estimation was performed by destructive analysis of a selected volume of the canopy. For this purpose, a handmade canopy interceptor was designed and used for the first time. The canopy interceptor (Canceptor©) in Figure 1(a) was made of two woody frames sliding into metal telescopic guides sustained by concrete bases.

(**a**) (**b**)

Figure 2. (**a**) Canopy interceptor with the bases positioned on the two sides of the olive hedgerow. The frame helps to select a 25 × 25 cm area while the long rods delimit the volume of the canopy to be sampled; (**b**) intercepted volume of the canopy. Only the bare shoots are visible after the detachment of all the leaves

Each frame, give support to eight aluminum rods inserted into predisposed holes. By this device is possible to select a 25 × 25 cm area 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 Figure 1 (b). Nine olive plants were selected on the base of their belonging to a different NDVI group and classified in areas with plants characterized by low (L) medium (M) and high (H) vegetation. Two different volumes within each canopy located at 1.00 m and 1.5 m from the ground were selected and the leaves detached. A total of 18 samples of leaves were collected and for each of them fresh (FW) and dry weight (DW) was recorded then 100 g FW leaf sample was taken from each unit of volume, put on a plain surface and photographed. Total area of each 100 g FW sample was determined using ImageJ software [22] then the dry total leaf area (LA) per unit of DW calculated and estimated for each of the 18 collected sample. Total LA of each olive plant was finally calculated taking measures of the canopy in every direction in the space as well as the perpendicular within crown area. Finally, the data of the two destructive sampling were averaged and LAI estimated for each of the twelve plants.

Statistics.

Systat 11 statistical program was used to calculate means and standard deviation. To verify the significance of the data obtained, the t-test (* $p \leq 0.05$, ** $p \leq 0.01$) were carried out to compare the mean values of NDVI index. Linear regression with coefficients calculated by the least squares method were used to compare the LAI estimated directly and indirectly while ANOVA test was applied to verify the action of each independent variables on parameters produced by destructive sampling as well as on PAR and transmittance recorded by LaiPen within the preliminary experiment reported in appendix A.

3. Results

3.1. Seasonal variation of NDVI

The number of passages of the satellite in dates without clouds in year 2021 was the double than in year 2020 (Table 1). The total mean of the NDVI index of the whole olive orchard showed value of 0.4, with a small increase (0.08) between the years. The NDVI index presented a large variation within each season with the lowest value representing only 40-42% of the maximum.

Table 1. NDVI index values calculated for the dates with good weather conditions and main variations during the two vegetative period of the years 2020 and 2021. Means not differing statistically.

Year	Number of observations	Minimum	Maximum	Range	Mean
2020	14	0.28	0.66	0.38	0.40 ± 0.12
2021	29	0.33	0.81	0.48	0.48 ± 0.13

Each of the two years in March the NDVI started from values between 0.65 and 0.80 decreasing progressively and then climbing again at higher values in October. From the curve in Figure 3 is possible to notice that the NDVI presented quite steady values along the summertime in both years.

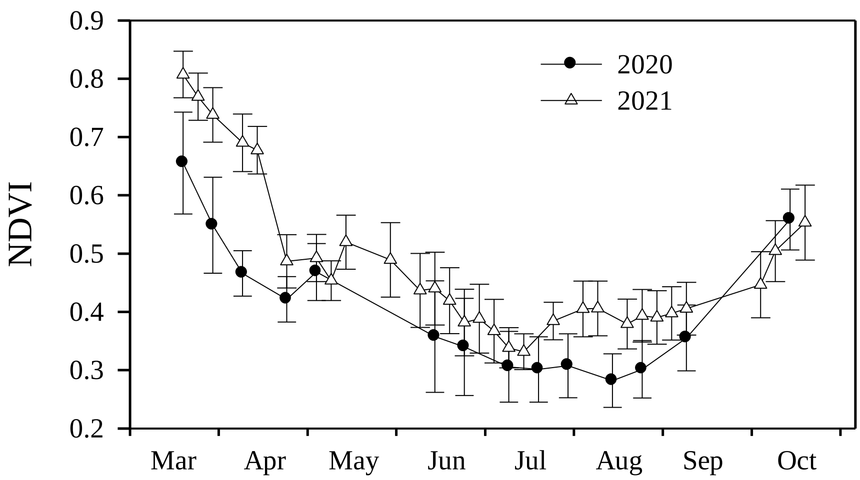


Figure 3. NDVI index calculated in each date with clear sky during the olive vegetative season of both year 2020 and 2021 for the super intensive orchard located in Marina di Grosseto, Italy. Each point represents the averaged index of the 830 total measured areas covering the whole 8 ha orchard. The bar representing ± standard deviation.

Taken into account exclusively the NDVI mean values within the whole orchard during the summer, it was possible to find five and eight dates of useful observations in 2020 and 2021, respectively. The values of the index during this period 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).

Table 2. NDVI index values calculated for the dates with good weather conditions and main variations during the period July 17-September 5 of the years 2020 and 2021. Means differing $p = 0.01$

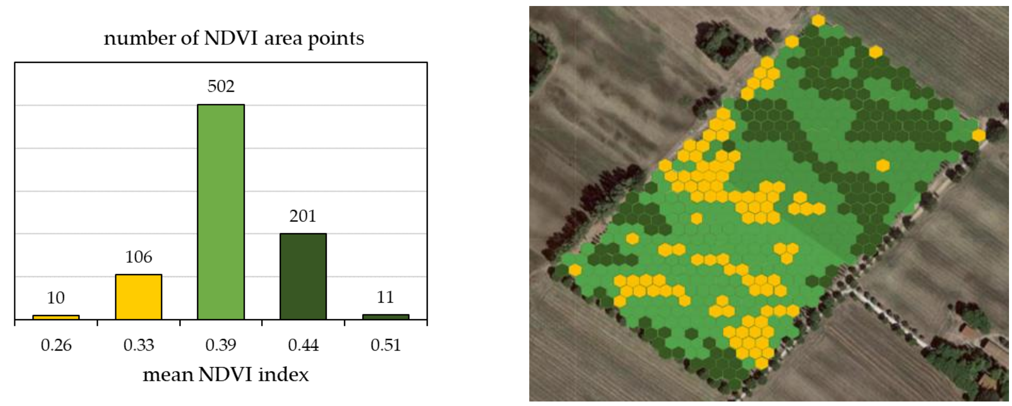
Year	Number of observations	Minimum	Maximum	Range	Mean
2020	5	0.28	0.36	0.08	0.31 ± 0.03
2021	8	0.39	0.41	0.02	0.40 ± 0.01

We use the NDVI data of this steady period to classify the 830 area units covering the orchard in classes based on the range of the index mean (Table 3). The frequency distribution follows a normal shape (Figure 4 a), 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.

Table 3. Subdivision of the 830 area unit covering the whole olive orchard located in Marina di Grosseto in five different classes based on the NDVI index averaged during the steady period July 17-September 5 of the year 2021

Class	Number	Mean NDVI	NDVI Range
1	11	0.506 ± 0.02	0.56 ÷ 0.49
2	201	0.443 ± 0.02	0.48 ÷ 0.42
3	502	0.389 ± 0.02	0.42 ÷ 0.36
4	106	0.334 ± 0.02	0.35 ÷ 0.29
5	10	0.256 ± 0.02	0.28 ÷ 0.22
Total	*830*	*0.39 ± 0.04*	*0.22 ÷ 0.56*

The visualization of the areas colored in relation to the NDVI range simplified as below and above the average is presented in Figure 4 b. This map simply underlines the portions of the orchard with best or worst vegetative condition and was used to select the plants for the destructive sampling.



(a) **(b)**

Figure 4. Distribution of NDVI index of 830 area points covering the whole super intensive hedgerow orchard into 5 classes (a) and visualization on the map of the simplified zonation based on NDVI index below the average (plants with low vegetation - L - yellow) in the average (plants with middle vegetation - M - green) and above the average (plants with high vegetation - H - dark green).

3.2. Direct LAI estimation

Destructive sampling data and measurements of areas and weights of the collected leaves are listed in Table 4. The mean LAI estimated for the three groups of plants scored on the base of the vegetative condition was respectively 1.90, 3.46 and 4.45, for low (L), middle (M) and high (H) vegetation, respectively (Figure 5). ANOVA showed significant differences among the NDVI groups on LAI (p=0.001) with an interaction with the height of the samples (p = 0.027). The L plants presenting less LAI at 1.5 m from the ground respect to 1.0 while M and H presented an increase of LAI passing from 1.0 to 1.5 m height.

Table 4. Anova results (probability level) and the average values for parameters (volume, area of the sampled leaves, total leaf area and LAI) obtained by destructive sampling of canopy portion selected by a 25 × 25 cm metallic frame (interceptor) inserted into nine olive plants. Plants are divided in three groups on the base of their NDVI group: Low, Medium, and High.

		V[1]	Area[2]	Leaf				Total LA	LAI
		(m^3)	(cm^2)	$cm^2 g^{-1}$ DW	Tot DW	Tot m^2	$m^2 m^{-3}$		
Main effect									
NDVI_group (NDVI_g)		ns	ns	ns	**	**	***	***	***
Height_sampling (Hs)		ns	ns	ns	ns	ns	ns	ns	ns
Interaction									
NDVI_g x Hs		ns	ns	ns	ns	ns	*	*	*
Low		0.095	264	59.8	21.4 ^{c}	0.131 ^{c}	1.4	4.6	1.9
Middle		0.106	264	70.1	38.3 ^{b}	0.265 ^{b}	2.5	8.3	3.5
High		0.098	296	71.2	44.7 ^{a}	0.314 ^{a}	3.2	10.7	4.4
H_1m		0.097	272	68.7	31.3	0.214	2.2	7.2	3.0
H_1.5m		0.102	277	65.3	38.4	0.259	2.5	8.5	3.5
Low	H_1m	-	-	-	-	-	0.14 ^{c}	1.54 ^{c}	5.18 ^{c}
	H_1.5m	-	-	-	-	-	0.12 ^{c}	1.17 ^{c}	3.93 ^{d}
Middle	H_1m						0.24 ^{b}	2.36 ^{b}	7.93 ^{b}
	H_1.5m	-	-	-	-	-	0.29 ^{b}	2.58 ^{b}	8.66 ^{b}
High	H_1m	-	-	-	-	-	0.25 ^{b}	2.55 ^{b}	8.57 ^{b}
	H_1.5m						0.38 ^{a}	3.81 ^{a}	12.79 ^{a}

[1] Volume calculated measuring the mean width of the vegetation included in the 25 × 25 cm canopy interceptor

[2] 100 leaves

Probability level (P) as resulting from three-way ANOVA. ns=not significant; *, **, *** significant at P≤0.05, P≤0.01 and P≤0.001, respectively. When F of interaction resulted not significant, main effects are reported.

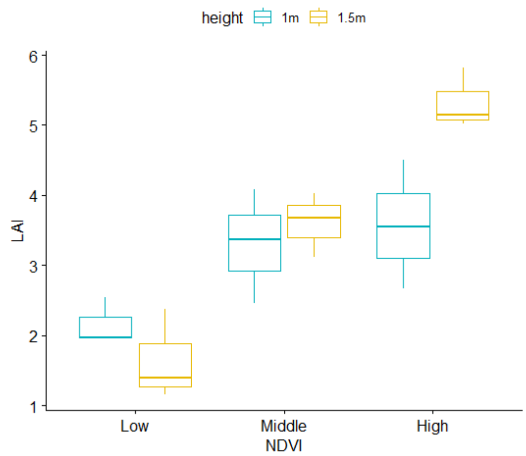


Figure 5 - Box plot of the data grouped by the combinations of the levels of the NDVI groups and the height of sampling.

3.3. Indirect LAI estimation

The measures taken with LaiPen on the same plants before the destructive sampling are exposed in Table 5. The acquisition of the data was very fast to guarantee 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 = 0.040). In particular, when measuring ALAI in olive plants with low vegetation the transmittance at 1.5 m from the ground was deeply affected by gaps in the canopies (Table S2, L1, 1.5 m).

We use the transmittance data obtained by the LaiPen

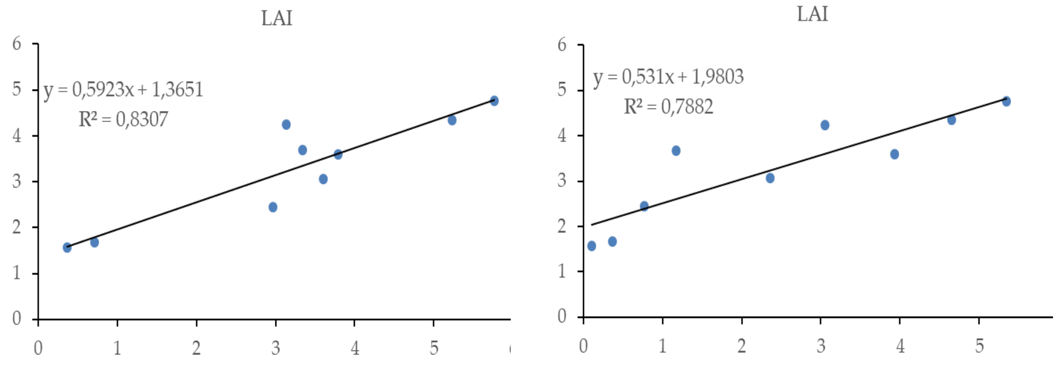
1) to calculate LAI as indicated by the instrument producer:

$$LAI = -\ln(I/I_0)/k$$

where I is the irradiance measured by LaiPen sensor below the plant canopy, I_0 the reference irradiance measured in clear open area, k the radiation extinction coefficient;

2) to determine the covariance between this and the LAI earlier estimated by destructive sampling at 0.5 or 1.0 m from the soil.

As possible to notice in Figure 6 plotting of LAI destructive vs LAI estimated by LaiPen changes in relation to the height to which the measurement was taken. Although R^2 is higher in (a), the original dataset of LAI estimated by LaiPen is poorly distributed with five plants grouped in the central area of the graphics. A better distribution is obtained when considering the data recorded and the LAI calculated at 1.0 m from the soil (Figure 6b). By indirect LAI estimation is possible to explain 80% of the variation in LAI estimated by destructive sampling and the best fit is obtained when applying a k = 0.37 while other figures worsen this fitting.



(a) **(b)**

Figure 6. Plot of the linear regression between LAI estimated by destructive sample and LAI estimated by LaiPen at 0.5 m (**a**) and at 1.0 m (**b**) height from the ground.

The result of the single LaiPen measurement of absorbance in sixty positions of the orchard characterized by increasing value of NDVI is reported in Figure 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 vegetational situation of the plant itself but not of the entire plot to which that plant belongs to.

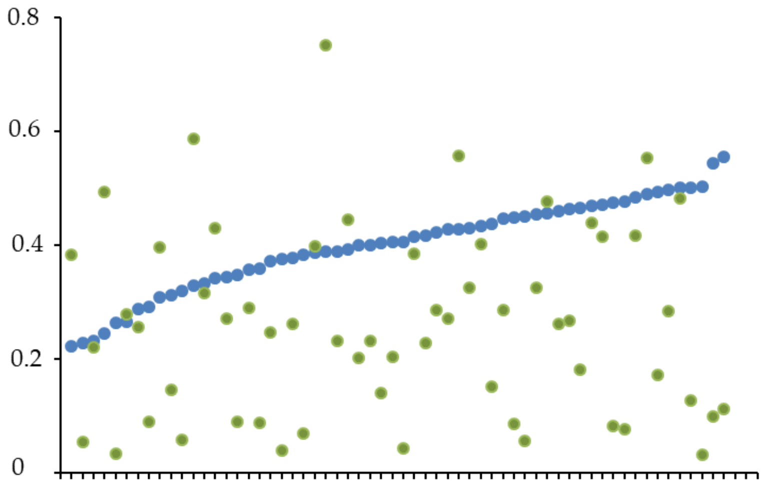
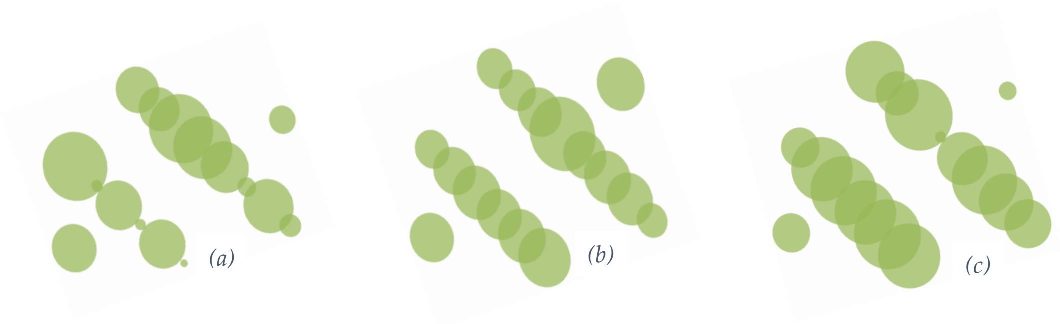


Figure 7. Plot of NDVI data of 60 selected positions (blue dots) within a hedgerow olive grove in Marina di Grosseto compared to LaiPen absorbance data (green dots) recorded as single measurement within each correspondent 10 × 10 m spot.

The result of the measurement taken by LaiPen in two plots with different vegetative status determined by the NDVI index of the area indicated a great difference in the absorbance. The mean absorbance measured on the plants within the two plots with NDVI equal to 0.28 and 0.43 showed respectively value of 0.16±0.12 and 0.60±0.24. The large standard deviation of the data indicates also a large variation among the plants belonging to the same 10 × 10 m plot. Using the transmittance measured for each plant by the application of the formula reported into Figure 6 (b) we estimated the LAI of thirty-six olives and produced the result graphically exposed in Figure 8. Since the circles are proportional



to the estimated LAI the differences among plants within each plot is clearly shown.

Figure 8. The circles represent the LAI estimated from transmittance measured by the LaiPen instrument in thirty-six olive plants. The area of each circle is proportional to the LAI of the plants contained into a 10 × 10 m portion of the grove. The NDVI values of these two selected positions are equal to 0.28 (a), 0.36 (b) and 0.43 (c). The mean estimated LAI are respectively 0.5±0.4 in (a), 1.5±0.6 (b) and 2.9±1.5 in (c).

4. 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 square meters 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 by this experimentation, the mean increase of NDVI index recorded in 2021 (Figure 3) 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 as showed in table 3 this value, although seems low, it is close to the differences calculated among the classes in which the orchard was subdivided (0.06). The results of direct LAI estimation by destructive sampling, essential to validate RS data [23] shows data in the range between 1.6 and 4.8. Cermak et al [24] working with old olive trees in south Italy found values between 1 to 7 with a mean of 3.5 while while Gucci et al [25] measured a LAI equal to 2.8 in ten years old plants located in the same area. Kang et al. [14] reported that LAI, although statistically well related to remotely sensed vegetation indices, is crop-specific and therefore it is the need of ground validation. In modelling study conducted in the area [26] 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 measure by LaiPen showed high correlation with the LAI by destructive samples opening interesting applicative uses. As stated by [27] the extinction coefficient (k) is estimated from shape orientation and position of each element of vegetation canopy and usually close to 0.5 [15] then LAI must be further corrected by proportion of woody elements surface area (WAI). Stenberg et al. [28] 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 (Figure 2b) but we found that the k value to best fit the destructive LAI in this type of plantation was equal to 0.37. Using this parameter in the formula for LAI estimation by LaiPen transmittance measured in the 400 - 500 nm bands was possible to explain 78% of variation in LAI estimated by canopy sampling. This instrument can be further tuned to better investigate olive canopy gaps following pruning or agronomical intervention because seems to better discriminate among plants compared to data produced by RS. While this latter gives good indication of the worst and best condition within the olive hedgerow and can be used to mapping olive orchard the on-ground measurement is more selective within each zone. This proximity instrument can collect data in presence of green coverage of the soil, cloudy condition of the sky and can be applied to better understand small variation in leaf clumping and gaps within the canopy volume not estimable from RS indices calculated from azimuthal position.

5. Conclusions

In this paper a method based on NDVI index is proposed to study the vegetative status of hedgerow olive orchards and to produce maps of vegetative vigor to be used in precision agriculture. 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 canopy vegetative density estimation. This paves the road to the use of this kind of instrument mounted over unmanned ground vehicles in automated determination of LAI for agronomical purposes in hedgerow olive orchard which will be the further goal of our research group.

6. Patents

Patent pending for the new canopy interceptor handmade to carry on this study.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Irradiance measured and transmittance calculated at three different distances from the ground in nine olive plants cultivated as hedgerow in Marina di Grosseto.

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Appendix A

Since any information was available about the use of the LaiPen on olive trees a preliminary experiment was set up to understand the possible use of this instrument for the estimation of light interception by the canopy during the day. Six different olive plants were 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). Five different points were selected for each of the three trees with fair or good vegetative status. The points were identified by inserting 5 canes on the soil at 30 cm from the lateral limit of the vegetation on the opposite side of the insolation. The five canes emerged 100 cm from the soil and were positioned at a regular distance among them along the lateral side of each canopy: in correspondence of the main trunk, 50 and 100 cm from it in opposite directions. In a sunny day of July 23 of the year 2021 the instrument was positioned in each extremity of the canes and the readings taken at 5 timing of the day: 10:00, 11:00, 12:00 am and 2 pm. Each time external PAR and ALAI were taken as reference to compare to PAR and ALAI transmittance measured in each selected point of the canopy. 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 100 cm of distance from the trunk along the row to avoid the presence of large woody branches were the detachment of leaves could have also been easily done.

Table A1. Table of the three-way ANOVA applied to olive canopy transmittance values measured by LaiPen 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.

SOURCE OF VARIATION	T2[1] (I/I0)
Fair	0.671±0.024
Good	0.453±0.024
VEGETATION *p*=	0.000
1 (100 cm left from the trunk))	0.590±0.039
2 (50 cm left from the trunk)	0.520±0.039
3 (in line with the trunk)	0.496±0.039
4 (50 cm right from the trunk)	0.567±0.039
5 (100 cm right from the trunk)	0.637±0.039
POINT *p*=	0.090
10:00	0.553±0.035
11:00	0.542±0.035
12:00	0.525±0.035
14:00	0.629±0.035
TIME *p*=	0.158
VEGETATION x POINT *p*=	0.617
VEGETATION x TIME *p*=	0.911
POINT x TIME *p*=	1.000
VEGETATION x POINT x TIME *p*=	0.983

[1] Light transmittance below the canopy

Table A2. Irradiance measured and transmittance calculated at three different height from the ground in nine olive plants cultivated as hedgerow in Marina di Grosseto. Plants are grouped and indicated with different letters in relation to their position within zone with different vegetative vigor estimated by NDVI. Low (L), medium (M) and high (H).

Plant	**Height**	**Time**	**Reference Irradiance (I_0)**	**ALAI Irradiance (I[1])**	**T[2] (I/I_0)**	**LAI[3]**
L3	0.5	09:43:35	4049	1350	0,3334	2,97
L3	1.0	09:43:43	4049	3040	0,7508	0,77
L3	1.5	09:43:53	4049	3513	0,8676	0,38
L1	0.5	09:46:07	4049	3551	0,8770	0,35
L1	1.0	09:46:18	4049	3889	0,9605	0,11
L1	1.5	09:46:28	4049	4049	1,0000	0,00
L2	0.5	09:46:41	4049	3135	0,7743	0,69
L2	1.0	09:46:47	4049	3538	0,8738	0,36
L2	1.5	09:46:53	4049	3984	0,9839	0,04
M3	0.5	09:51:06	4049	1215	0,3001	3,25
M3	1.0	09:51:16	4049	2620	0,6471	1,18
M3	1.5	09:51:28	4049	2777	0,6858	1,02
M1	0.5	09:53:21	4049	1107	0,2734	3,50
M1	1.0	09:53:27	4049	1692	0,4179	2,36
M1	1.5	09:53:35	4049	2062	0,5093	1,82
M2	0.5	09:55:47	4049	1035	0,2556	3,69
M2	1.0	09:56:00	4049	944	0,2331	3,94
M2	1.5	09:56:08	4049	2400	0,5927	1,41
H1	0.5	09:43:06	4049	509	0,1257	5,60
H1	1.0	09:43:12	4049	560	0,1383	5,35
H1	1.5	09:43:25	4049	1280	0,3161	3,11
H1	0.5	09:44:17	4049	616	0,1521	5,09
H1	1.0	09:44:26	4049	725	0,1791	4,65
H1	1.5	09:44:38	4049	1401	0,3460	2,87
H3	0.5	09:54:54	4049	3096	0,7646	0,73
H3	1.0	09:54:59	4049	1308	0,3230	3,05
H3	1.5	09:55:10	4049	3482	0,8600	0,41

[1] Irradiance measured by LaiPen sensor at 400-500 nm, [2] Light transmittance below the canopy; [3] $LAI=-\ln(I/I_0)/k$ with $k=0.37$

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