

Article

Towards Site-Specific Management: UAV- and Ground-Based Assessment of Intra-Field Variability in SHD Almond Orchards [†]

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Abstract

Through highly detailed data acquisition, a precision agriculture approach leads to the optimization of inputs, improving, for instance, water and nutrient use efficiency. High-resolution vigor mapping in perennial orchards provides the spatial detail required to achieve such targeted management. This exploratory case study characterizes the spatial variability of vegetative vigor in a young SHD almond orchard in southern Sardinia by integrating high-resolution unmanned aerial vehicle (UAV) imagery and Normalized Difference Vegetation Index (NDVI) mapping with two consecutive seasons of ground measurements; the NDVI raster was subsequently used to delineate three distinct vigor zones. The NDVI was selected as a reference index because of its well-assessed performance in field-variability studies. Field measurements, during the kernel-filling period, included physiological assessments (stem water potential (Ψ_{stem}), SPAD, photosynthetic rates), morphological evaluations, soil properties, yield, and quality analyses. High vigor zones exhibited better physiological conditions ($\Psi_{\text{stem}} = -1.60$ MPa in 2023, SPAD = 38.77 in 2022), and greater photosynthetic rates ($15.31 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in 2023), alongside more favorable soil conditions. Medium vigor zones showed intermediate characteristics, and balanced soil textures, producing a higher number of smaller almonds. Low vigor zones exhibited the poorest performance, including the most negative water status (Ψ_{stem} of -1.94 MPa in 2023), lower SPAD values (30.67 in 2023), and coarse-textured soils, leading to reduced yields. By combining UAV-based NDVI mapping with ground measurements, these results highlight the value of precision agriculture in intra-field variability identification, providing a basis for future studies that will test site-specific management strategies in SHD orchards.

Keywords: *Prunus dulcis*; precision agriculture; Normalized Difference Vegetation Index (NDVI); vigor assessment; Lauranne Avijor; Rootpac20; ecophysiology

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1. Introduction

Over recent years, there has been a significant increase in global demand for almonds, driven by the rising popularity of plant-based diets and the recognized health benefits [1,2]. To meet this growing demand more efficiently, farmers have increasingly adopted super high-density (SHD) almond orchards. This relatively new cultivation system allows for higher yields per hectare and a more efficient use of resources, helping farmers to maximize production and profitability [3]. Managing SHD orchards with high planting densities (~2000 trees/ha) is challenging and requires an understanding of the spatial variability in crop growth responses to implement site-specific management that maximizes resource efficiency within smaller field areas [4]. Factors such as soil characteristics [5], row orientation [6,7], type of rootstock [8], nutrients, light, temperature, and water availability [9–11] contribute to spatial variability, while increasing climate risks also have a significant impact [12,13]. Recent studies highlight that climate change is intensifying drought and heat risks in Mediterranean almond production [14], and that cultivar-specific physiological traits strongly influence resilience and yield stability [15].

Understanding “vigor,” defined as rapid growth and resilience to adverse conditions [16], is crucial for assessing plant health and growth potential, which directly impact yield and quality [17]. High vigor zones typically reflect optimal growing conditions, whereas Low vigor zones may require modifications in irrigation or nutrient management. Excessive plant vigor can be detrimental as it competes with fruit production for resources, induces canopy shading, reduces light interception efficiency, increases soil erosion, restricts machinery access, and reduces the efficiency of pesticide application [18,19]. Controlling plant vigor is vital for orchard productivity and economic success, as monitoring it identifies areas needing targeted management to optimize growth and resources [4,20–22]. This can be quantitatively evaluated through spectroscopic characteristics using remote sensing techniques [23]. Water status is tightly linked to vigor: moderate deficit irrigation during kernel filling can reduce vegetative growth without yield penalties [24], while differences in antioxidant capacity and relative water content explain the contrasting vigor responses among cultivars under drought conditions [25].

Remote sensing techniques, including Unmanned Aerial Vehicles (UAVs), are now essential in modern agriculture, and thanks to high-resolution sensors, monitoring increasingly large and dense agricultural areas is greatly simplified [26]. By combining precision agriculture technology with traditional methods, it is possible to identify varieties, classify land use, monitor health, optimize irrigation, predict yield, and assess climate impact, allowing for a more sustainable and efficient management of agricultural systems, thereby improving yield [27–30]. However, the accuracy of multispectral indices depends on factors like UAV flight altitude, sensor resolution, and environmental conditions, all of which affect data quality [31]. In the literature, only a limited number of studies support remote data with traditional ground-truth agronomic measurements [32]. However, some recent research has successfully improved reliability by combining UAV data with ground observations and detailed plant measurements, such as stem water potential (Ψ_{stem}), canopy structure, and vegetative vigor, to verify and refine multispectral vegetation index maps [33–37]. Comprehensive reviews confirm that the Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index in almond remote sensing ($\approx 46\%$ of studies) and that UAVs are now the second most employed platform after satellites [38]. In parallel, artificial intelligence and machine learning approaches are increasingly applied in agricultural and eco-physiological mapping [39,40]. Recent studies show that models using multispectral and climate data can predict almond yield with high accuracy (R^2 up to 0.80) [38], and that Random Forest can map stem water potential at the orchard scale during critical phenological stages [41]. The

combined use of proximal sensors and UAV data has also improved the accuracy of plant water status monitoring [42]. Despite this progress, no published study has yet examined intra-field NDVI-based vigor zoning in newly established (<7 year) SHD almond orchards under Mediterranean conditions. This clear gap underlines the need for preliminary, hypothesis-generating case studies that can demonstrate methodological feasibility and quantify the magnitude of spatial variability. To date, however, the application of these tools to vigor zoning in young SHD orchards remains unexplored.

Accordingly, the present work is framed as a preliminary case study. Its objective is to explore whether high resolution NDVI maps derived from UAV imagery, when combined with ground data collected over two consecutive seasons during the kernel-filling period, can consistently delineate intra-field vigor patterns (low, medium, and high) in a young SHD almond orchard in southwestern Sardinia.

The study site was selected because (i) it exemplifies the rapidly expanding SHD production model across the Mediterranean basin, (ii) its young age (planted in 2018) offers a rare opportunity to capture the early development of spatial heterogeneity, and (iii) it is managed commercially using standard practices, ensuring that findings are directly transferable to growers. In each vigor zone field, measurements included physiological and morphological assessments, almond yield and quality evaluations, as well as physical and chemical soil analyses. This study aimed to determine whether and how the observed intra-field variability should inform adjustments to current agricultural practices, highlighting the implications for almond growers in terms of targeted management and optimized resource allocation. Figure 1 synthesizes the aims and process steps of the present study.

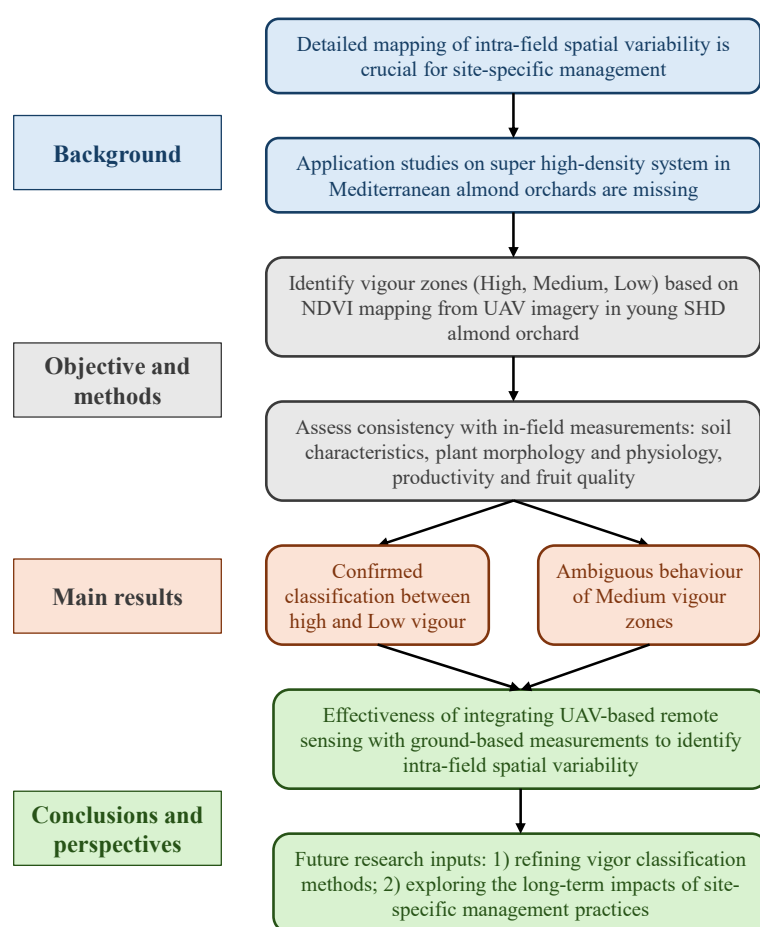


Figure 1. Flow chart synthesizing the work flow of the present study.

2. Materials and Methods

2.1. Study Site

This study was conducted in 2022 and 2023 in a young and productive *Prunus dulcis* (Mill. D.A. Webb) orchard established in 2018 on a commercial farm in southern Sardinia, Italy (39°20'18.1" N, 9°04'46.9" E). The bioclimate of the area is classified as "Mediterranean Pluviseasonal-Oceanic; isobioclimate 6: Upper Thermo Mediterranean, Lower Dry, Euoceanic Weak" [43]. According to the Department of Meteorology and Climatology Environmental Protection Agency of Sardinia (ARPAS), the average data (1991–2010) about the area are as follows: the annual mean rainfall is 453 mm, mainly concentrated in the autumn and winter months; the annual average temperature is 18.1 °C. Summers are hot and dry. The warmest months, July and August, achieve on average levels of maximum temperatures above 33 °C. Whereas winters are mild. The coldest months, January and February, report minimum temperatures on average between 6 and 7 °C. With an average maximum of 22.8 °C and minimum of 13.8 °C.

The orchard features the self-fertile 'Lauranne Avijor' almond cultivar grafted on Rootpac20® dwarfing rootstock (Densipac; *Prunus besseyi* × *Prunus cerasifera*), a vigor and size-controlling rootstock developed by Agromillora (Barcelona, Spain). Trees were planted in a super high-density (SHD) system with a row spacing of 1.2 × 4 m, oriented NW-SE. Following the training phase, the trees adopted a hedgerow formation while maintaining a central leader, reaching a height of 2.70 m, a width of 0.90 m, and a crossing height of 0.5 m. The orchard was irrigated with high frequency localized irrigation, supplying approximately 6000 m³/ha. Rows were kept weed-free through soil tillage, while cover crops were maintained between rows. All cultural practices were applied uniformly across the entire orchard, including irrigation volumes, fertigation schedules, and pruning protocols, thereby ensuring consistent agronomic conditions for all trees and sampling areas.

2.2. UAV Setup

A total of two aerial surveys were conducted using a DJI Phantom 4 Pro UAV (DJI Technology Co., Ltd., Shenzhen, China). The surveys were performed under clear and sunny conditions. The UAV was equipped with an RGB CMOS 1" camera with a resolution of 21 MP (Mapir, San Diego, CA, USA). RGB image acquisition was associated with a 12 MP Red-Green-Near InfraRed (RGN) multispectral camera (Survey 3, Mapir, San Diego, CA, USA). The latter featured a 41° horizontal field of view (HFOV), a 47 mm focal length, an f/3.0 aperture, and a ground sampling distance (GSD) of 2.3 cm/pixel at an altitude of 120 m above ground level (AGL). Such a GSD provides sufficient spatial resolution to capture canopy texture and vigor gradients, while the red, green, and near-infrared bands of the multispectral sensor maximize vegetation contrast within a single-battery flight.

The first preliminary survey was performed at 80 m AGL, with a 2.19 GSD, acquiring the RGB and RGN images at 4.7 m/s, in order to provide initial support for identifying different vigor areas. To ensure complete stereoscopic coverage and radiometric consistency, the UAV survey included 80% forward overlap and 70% side overlap, reaching a total of 169 images. To achieve precise results, an n-RTK GNSS receiver (Emlid Reach+, Emlid Tech Kft., Budapest, Hungary) was utilized to record the geographical coordinates of 12 ground control points (GCPs) distributed across the field. To calibrate the reflectance of the RGN camera, a Spectralon® 18% grey standard panel (Mapir, San Diego, CA, USA) was used both before and after the flight to account for any potential radiometric fluctuations. The raw data were processed using the Mapir camera control software, which created TIFF files applicable for post-processing elaboration software.

The second survey was performed at 45 m AGL, in the mid phases of fruit development (BBCH 75) [44]. This survey was necessary to confirm what was evidenced in the first monitoring period, collecting a total of 565 photos at 1.23 GSD. Out of these images, 98% passed the quality control filters for blur, exposure, and GNSS accuracy.

2.3. Image Processing and Index Calculations

AgisoftMetashape® (Agisoft LLC, St. Petersburg, Russia) structure from motion (SfM) software (Pro version) was employed to process the RGB and RGN images and generate orthomosaics. Metadata about almond canopy height enabled the extraction of tree thickness and height using the Canopy Height Model (CHM) segmentation system [45,46]. The construction of the canopy volume using the CHM was based on two different orthomosaics: the Digital Elevation Model (DEM) and the Digital Terrain Model (DTM). The DEM orthomosaic represents the maximum height of all pixels, while the DTM orthomosaic represents soil reconstruction. The total plant volume is obtained by subtracting the two orthomosaics. Setting a cut-off height of 60 cm from the ground enabled the exclusion of the almond tree trunks and the isolation of the canopy for subsequent multispectral analysis [47].

The Red and Near-InfraRed (NIR) bands from the RGN camera were used to calculate the Normalized Difference Vegetation Index (NDVI). The resulting NDVI raster output and the vectorized CHM layer were clipped in QGIS software (ver. 3.30.0, QGIS Development Team, <https://qgis.org/it/site/>) to identify the vegetation index. From the isolation of the canopy by CHM segmentation, homogeneous areas were created through geostatistical interpolation of the normalized NDVI. This operation involved the creation of regular 6×4 m blocks in the QGIS platform, enclosing five plants in a single row within the polygon. Using the clipping function and subsequent dataset creation, the shapefile was analyzed in ArcGIS (Enterprise 10.7.1 version) using geostatistical interpolation. The data were then processed using the Ordinary Kriging function to obtain the reference map necessary for defining the homogeneous areas for subsequent field analyses [37].

2.4. Aerial Survey Procedure

To assess intra-field variability, a preliminary aerial survey was conducted at the end of the flowering phase (BBCH 69) [44]. Images were acquired between 1:00 and 3:00 p.m. (GMT + 1). The processing of the georeferenced images of individual plants within the selected rows identified three distinct areas within the field, characterized by variations in vigor and vegetative activity. The NDVI and CHM vigor maps (Figures 2a and 2b, respectively) were visually inspected to identify spatial clusters of high, medium, and low canopy vigor. Three variability areas were defined by overlaying the CHM segmentation with the NDVI. The quantile distribution of these two variables placed the experimental areas into three homogeneous field zones, each of which was characterized by a different level of vegetation vigor. This qualitative approach enabled targeted ground-truthing of areas that were representative of the observed spatial variability:

- Low Vigor Area: Exhibited a moderately lower canopy volume and NDVI than the rest of the field.
- Medium Vigor Area: Showed a canopy volume and NDVI consistent with the majority of the field.
- High Vigor Area: Exhibited moderately a higher canopy volume and NDVI than the rest of the field.

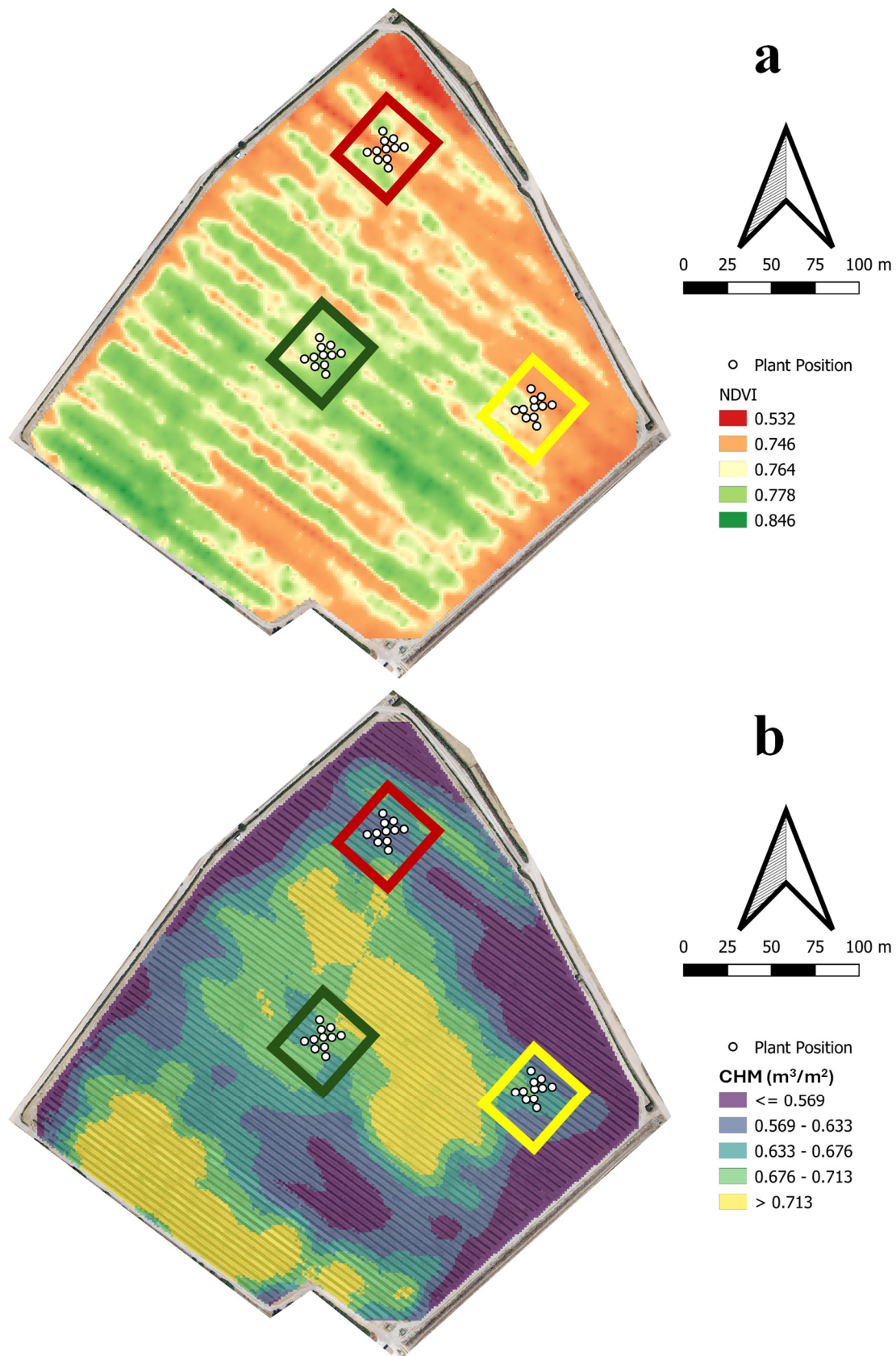


Figure 2. NDVI (a) and CHM (b) maps of the almond orchard obtained from geostatistical analysis. The white points comprised within the red box are the sentinel plants for the Low vigor zone, those within the yellow box are for the Medium vigor zone, and those within the green box are for the High vigor zone.

2.5. Soil Analysis, Plant Based Assessments, and Yield Analysis

The primary physicochemical properties of the soil of each vigor area were analyzed. Soil samples were collected from each vigor class ($n = 4$ per zone), at a standardized depth of 20–40 cm, using a soil auger. For each zone, subsamples from multiple trees were composited to obtain a representative sample prior to analysis. Soil pH and electrical conductivity (EC) were measured using 1:2.5 (w/v) soil-to-water suspensions, following the procedure outlined by the official Italian Gazette [48] (see Table 1). Dissolved organic carbon (DOC) was quantified according to the method described by Manzano et al. [49]. Total C and total N were determined using a Leco CHN628 analyzer (LECO Corporation, St Joseph, MI, USA), with Soil LCRM Leco part number 502–697 serving as the calibration standard. Extractable phosphorus was assessed using the Olsen method [48].

In each area, eleven trees were selected for analysis. This sample size reflects the operational constraints of intensive field measurements and is consistent with previous exploratory studies in perennial crops [34,36]. The goal was not to model population-level effects, but to characterize intra-field variability across multiple agronomic parameters, justifying the use of a compact, balanced design.

In 2022, dimensional measurements (including canopy height, canopy thickness, and trunk diameter) were collected, as the almond orchard had already reached its final structural dimensions, which were expected to remain constant over time. Plant-based surveys, focusing on comprehensive ecophysiological and production assessments, were conducted during the kernel filling periods (BBCH stage 75) in both 2022 and 2023 [44]. Fluorescence was measured on all sentinel plants using a Handy Plant Efficiency Analyzer (PEA; Hansatech Instruments, Pentney, Norfolk, UK), targeting two leaves per plant. Concurrently, leaf chlorophyll content was assessed using a SPAD-502 m (Minolta, Osaka, Japan). Photosynthetically active radiation levels were recorded using an AccuPAR LP-80 linear ceptometer (Decagon Devices, Pullman, WA, USA) at solar noon from a height of 30 cm above the ground. Gas exchange rates were monitored on mature leaves maintained in their natural orientation, utilizing a LICOR 6400 (Li-Cor, Lincoln, NE, USA) photosynthesis unit configured to a $500 \mu\text{mol s}^{-1}$ flow rate and a $400 \mu\text{mol mol}^{-1} \text{CO}_2$ concentration. Stem water potential (Ψ_{stem}) was determined using a pressure chamber (PMS 600, PMS Instrument Company, Albany, OR, USA) on one leaf per plant.

At the end of the fruit maturity phase (BBCH 89) [44] for both years, fruits were harvested from each experimental area of vigor. The weights of the almonds (in-shell, post-hulling) were recorded in grams.

Table 1. Average values ($\pm$ standard error) of chemical and physical soil variables for each vigor class. Different lowercase letters indicate significant differences according to Tukey’s HSD test ($\alpha < 0.05$).

	Low Vigor	Medium Vigor	High Vigor
Sand (%)	43.37	41.41	37.33
Silt (%)	23.60	25.20	28.05
Clay (%)	33.03	33.39	34.62
pH	8.37 ± 0.02^a	8.28 ± 0.03^b	8.20 ± 0.08^c
Total C (%)	4.87 ± 0.02	3.86 ± 1.36	4.72 ± 0.11
Total N (%)	0.035 ± 0.01^a	0.041 ± 0.004^{ab}	0.044 ± 0.004^b
C ing (%)	0.35 ± 0.01	0.37 ± 0.06	0.28 ± 0.07
DOC (mg g^{-1})	0.128 ± 0.002^a	0.125 ± 0.001^b	0.120 ± 0.001^b
Organic Matter (%)	5.22 ± 0.028^a	5.65 ± 0.01^b	5.03 ± 0.013^c
P available (mg kg^{-1})	4.63 ± 0.03^a	5.77 ± 0.09^b	5.64 ± 0.05^c
Cation Exchange Capacity ($\text{cmol}^+ \text{kg}^{-1}$)	24.70 ± 0.05^a	26.39 ± 0.36^b	24.01 ± 0.23^c

2.6. Validation and Statistical Analysis

The agronomic relevance of the NDVI-based vigor classes was assessed by evaluating differences in canopy, soil, physiological, and yield variables among the Low, Medium, and High groups. Data normality and homogeneity of variance were tested using the Shapiro–Wilk and Levene tests, respectively. Each response variable was analyzed through one way ANOVA with vigor class as the fixed factor; when significant effects were found, pairwise comparisons were performed using Tukey’s HSD test. Statistical computations were carried out in R (version 4.3.2) [50] using base linear model functions and the package “Multcomp” with $\alpha = 0.05$ as the significance level.

3. Results

3.1. Meteorological Conditions

Figure 3 shows the meteorological conditions during the two years of study, which differed mainly in precipitation distribution. During the winter–spring season, rainfall in 2022 was 255 mm, while in 2023 the cumulative rainfall reached 358 mm and extended until June (61 mm). Due to this precipitation pattern, the dry season was longer, and temperature values were higher in 2022 than in 2023.

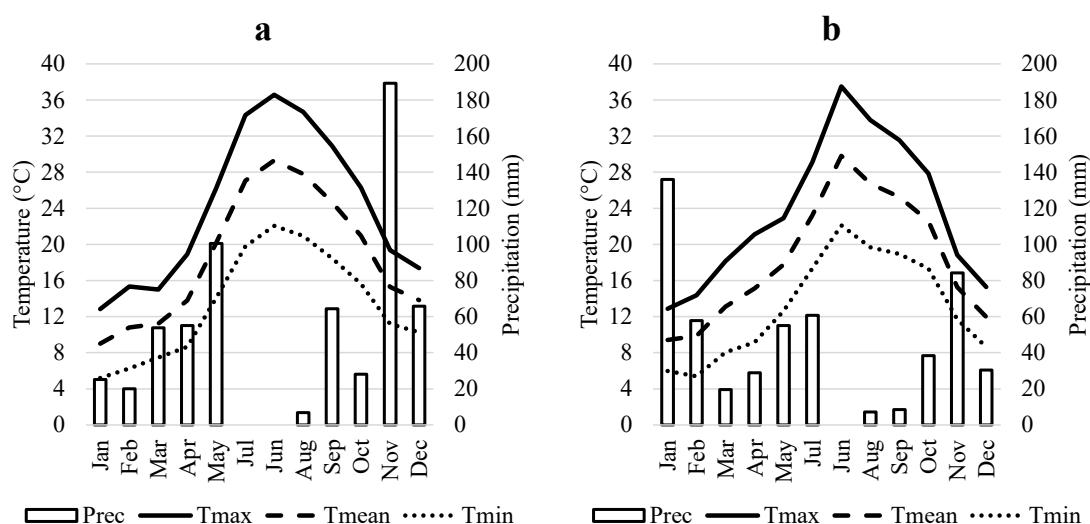


Figure 3. Meteorological conditions of 2022 (a) and 2023 (b). Maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean), and Precipitation (Prec) data were provided by the Environmental Protection Agency of Sardinia (ARPAS).

3.2. NDVI-Based Vigor and Canopy Assessment

A comprehensive image analysis at the SHD almond orchard identified three distinct vigor zones within the field, with NDVI values of 0.78 ± 0.01 , 0.75 ± 0.01 , and 0.74 ± 0.02 for the High, Medium, and Low vigor classes, respectively (Figures 2 and 4). The ANOVA showed significant variability between the High vigor zone and the other two zones based on the NDVI values ($p \leq 0.05$), according to the post hoc comparison. In contrast, the NDVI values for the Low and Medium vigor zones displayed an increasing trend but did not show significant differences (Figure 4A). The field measurements for canopy structure were consistent with the NDVI vigor classes. Significant differences based on the pairwise tests were observed between High and Low vigor in terms of canopy height (229 ± 3.4 cm and 212 ± 1.6 cm, respectively, Figure 4C) and depth (158 ± 2.9 cm and 148 ± 2.2 cm, respectively, Figure 4D). The Medium vigor areas exhibited ambiguous characteristics: their canopy height (Figure 4C) was similar to that of the Low vigor areas, while their canopy depth (Figure 4D) did not differ significantly from either the High or Low vigor

classes. The Medium vigor class demonstrated the lowest PAR attenuation values (Figure 4B), suggesting a sparser canopy density compared to the other two vigor categories. On average, the PAR available at a height of 30 cm under the tree canopy in the intermediate class was $213 \pm 20 \mu\text{mol m}^2 \text{s}^{-1}$. Although the differences were not statistically significant, the High vigor class exhibited a marginally denser canopy (with an average PAR availability of $96 \pm 15 \mu\text{mol photons m}^2 \text{s}^{-1}$) compared to the Low vigor class ($130 \pm 15 \mu\text{mol photons m}^2 \text{s}^{-1}$).

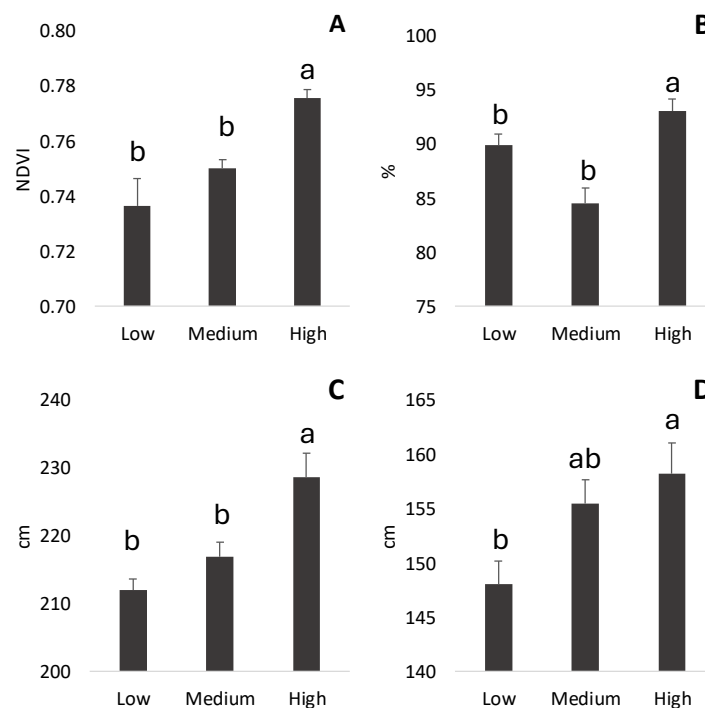


Figure 4. Bar charts of trees' structural parameters: NDVI (A), Photosynthetically Available Radiation (PAR) attenuation (B), Height (C), and Depth (D). Error bars represent standard error. Different lowercase letters indicate significant differences between vigor categories, according to Tukey's HSD test ($\alpha < 0.05$).

3.3. Soil Characteristics

An analysis of the soil properties across areas with varying vegetative vigor revealed distinct differences in texture, chemistry, and fertility, which directly affect plant performance. The results of the soil analyses are reported in Table 1. In the Low vigor areas, higher sand content (43.37%) and lower clay content (33.03%) resulted in coarse-textured soils with large pore spaces. These soils had a higher pH (8.37 ± 0.02), while organic matter ($5.22 \pm 0.028\%$), total nitrogen ($0.035 \pm 0.01\%$), available phosphorus ($4.63 \pm 0.03 \text{ mg kg}^{-1}$), and cation exchange capacity (CEC) ($24.70 \pm 0.05 \text{ cmol}^+ \text{ kg}^{-1}$) were all at their lowest levels compared to the other vigor zones. The Medium vigor areas were characterized by a more balanced soil texture, with moderate sand content (41.41%) and nearly equal proportions of silt (25.20%) and clay (33.39%). Fertility was enhanced in these soils by a slightly lower pH (8.28 ± 0.03), higher total nitrogen ($0.041 \pm 0.004\%$), and the highest organic matter content ($5.65 \pm 0.01\%$). The available phosphorus also peaked in these areas ($5.77 \pm 0.09 \text{ mg kg}^{-1}$). Additionally, these soils exhibited the highest CEC ($26.39 \pm 0.36 \text{ cmol}^+ \text{ kg}^{-1}$). The High vigor soils showed higher clay (34.62%) and reduced sand contents (37.33%). These soils showed the lowest pH (8.20 ± 0.08). The higher total nitrogen content ($0.044 \pm 0.004\%$), elevated total carbon ($4.72 \pm 0.11\%$), and significant levels of organic matter ($5.03 \pm 0.013\%$) reflected active nutrient cycling and enriched

fertility. The available phosphorus remained high ($5.64 \pm 0.05 \text{ mg kg}^{-1}$), and although the CEC ($24.01 \pm 0.23 \text{ cmol}^+ \text{ kg}^{-1}$) was slightly lower than that of the Medium vigor soils, it remained sufficient to sustain robust plant development.

3.4. Physiological Parameters

In 2022, the net photosynthetic rate (P_n) showed a trend across the vigor classes. P_n was highest in the High vigor class, followed by the Low and Medium classes. According to Tukey's HSD test, the High class was significantly different from the Medium class (Table 2). Due to a technical issue with the instrument in 2022, reliable data for stomatal conductance (G_s) could not be recorded and are therefore not reported. In 2023, the P_n rate was lowest in the Low vigor class, consistent with the previous year. In contrast, the Medium class showed a significant increase to $15.94 \pm 0.93 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, reaching values comparable to the High vigor class (Table 2). Stomatal conductance (G_s) in 2023 showed that the High vigor class had a significantly higher value compared to the Medium and Low classes. The observed trend among vigor classes in leaf gas exchange data was in line with the results obtained from canopy structure and plant water status. Indeed, in both 2022 and 2023, stem water potential (Ψ_{stem}) was less negative in the High vigor class, indicating better water status and less water stress. In 2022, both the Low and Medium vigor areas showed moderate water stress conditions, with values of -2.35 and -2.40 MPa , respectively. By contrast, the High vigor area showed significantly greater water availability. In 2023, an overall improvement was observed, with values indicating better overall water status, probably related to seasonal rainfall dynamics characterized by high precipitation in July 2023. The trend among vigor classes was the same during the two years of study, with moderate water stress in the Low and Medium vigor classes, and significantly fewer negative values for the High vigor class ($-1.60 \pm 0.02 \text{ a}$ for High, $-1.78 \pm 0.07 \text{ ab}$ for Medium, and $-1.94 \pm 0.10 \text{ b}$ for Low). In 2022, SPAD measurements of leaf chlorophyll levels indicated that the Medium (39.05 ± 1.68) and High (38.77 ± 1.44) vigor classes had the highest chlorophyll levels, with no significant difference between them, but both were higher than the Low vigor class (36.35 ± 0.53). In 2023, a general decline in SPAD values was observed across all vigor classes, indicating a general reduction in photosynthetic activity (Table 2). The Medium vigor class exhibited a SPAD value of 34.27 ± 1.15 , while the High vigor class presented a significantly lower value (29.67 ± 0.79), similar to the Low vigor class (30.67 ± 0.74). An estimation of the maximum quantum efficiency of Photosystem II (PSII) photochemistry (Fv/Fm) showed no significant differences among vigor classes in either year. In 2022, the Low and Medium classes recorded values of 0.75 ± 0.01 and 0.75 ± 0.02 , respectively, while the High class recorded 0.77 ± 0.01 (Table 2). In 2023, all categories exhibited a significant decline compared to the previous year, with the Low class decreasing to 0.65 ± 0.02 , the Medium class to 0.68 ± 0.02 , and the High class to 0.69 ± 0.02 (Table 2). Despite the overall decline, the High vigor class maintained a comparative advantage.

Table 2. Average values ($\pm$ standard error) of photosynthesis rate (P_n), stomatal conductance (G_s), stem water potential (Ψ_{stem}), SPAD, and photosynthetic efficiency (ϕP_o) measured during two growing seasons according to vigor classification. Different lowercase letters indicate significant differences according to Tukey's HSD test ($\alpha < 0.05$).

	Year	Low	Medium	High
P_n ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	2022	$12.68 \pm 1.62 \text{ ab}$	$9.63 \pm 0.79 \text{ b}$	$18.87 \pm 2.01 \text{ a}$
	2023	11.85 ± 0.93	15.94 ± 0.93	15.31 ± 1.09
G_s ($\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$)	2023	$0.09 \pm 0.01 \text{ b}$	$0.12 \pm 0.02 \text{ b}$	$0.23 \pm 0.01 \text{ a}$
Ψ_{stem} (Mpa)	2022	$-2.35 \pm 0.15 \text{ b}$	$-2.40 \pm 0.05 \text{ b}$	$-1.76 \pm 0.05 \text{ a}$
	2023	$-1.94 \pm 0.10 \text{ b}$	$-1.78 \pm 0.07 \text{ ab}$	$-1.60 \pm 0.02 \text{ a}$

SPAD	2022	36.35 ± 0.53	39.05 ± 1.68	38.77 ± 1.44
	2023	30.67 ± 0.74 ^b	34.27 ± 1.15 ^a	29.67 ± 0.79 ^b
$\phi Po (F_v/F_m)$	2022	0.75 ± 0.01	0.75 ± 0.02	0.77 ± 0.01
	2023	0.65 ± 0.02	0.68 ± 0.02	0.69 ± 0.02

3.5. Yield Performance

In 2022, the Low vigor zones had 33% lower yields per tree compared to the Medium and High vigor zones (Figure 5A). The Medium and High vigor zones exhibited similar yields, but the almonds in High vigor zones were heavier. The Medium vigor zones produced more fruits, but of lower weights (Figure 5B). In 2023, the trends from 2022 were confirmed, with statistically significant differences: the Low vigor zones continued to have lower yields (30%), while the Medium and High vigor zones maintained high yields in terms of g/tree (Figure 5C). Almonds from the High vigor zones remained heavier, and the Medium vigor zones continued to produce more fruits, although of lower weights (Figure 5D).

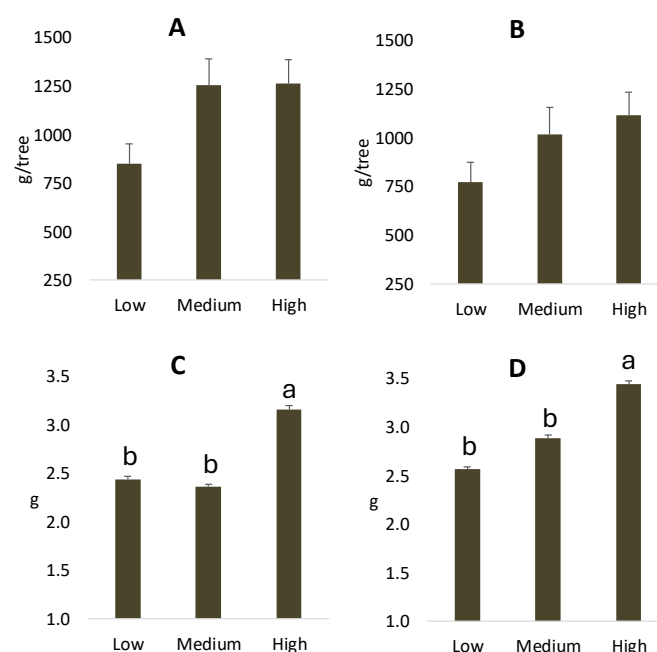


Figure 5. Bar charts of fruit production of 2022 (A) and 2023 (B) growing seasons, and hulled fruit weights of 2022 and 2023 ((C) and (D), respectively) according to vigor class. Different lowercase letters indicate significant differences between vigor categories, according to Tukey's HSD test ($\alpha < 0.05$).

4. Discussion

The NDVI values observed within the field are similar to those found by other authors [51,52]. Statistical analyses confirm the validity of the NDVI and canopy metrics as quantitative surrogates of tree vigor in super high-density almond systems [52]. The pronounced separation between the High and Low vigor zones points to genuine physiological differentiation, plausibly driven by spatial heterogeneity in soil texture and water availability [53]. By contrast, the Medium vigor zone occupies an intermediate niche, indicating a transitional state where uniform management may be inefficient; recent work on zone delineation for precision irrigation supports the need for targeted, site-specific practices in such areas [54]. Comparable results were obtained in SHD almond orchards by Sandonís-Pozo et al. [55], who demonstrated that NDVI-based vigor zones remain consistent across seasons and highlighted that canopy size and tree height

are fundamental parameters for delineating and managing these zones. Similarly, Sapkota et al. [54] reported that a two-cluster classification (high vs. low) often provides the most robust delineation, explaining up to 68% of NDVI spatial variability and showing strong agreement with indices derived from evapotranspiration and crop water status. They also demonstrated that these additional indicators capture the complementary aspects of variability not fully described by the NDVI, highlighting the potential of multi-index approaches for precision management. The tree dimensions measured in this study align with those reported for the hedgerow almond system by Casanova-Gascón et al. [56], validating the data and methods used and confirming their reliability and reproducibility. These observations are consistent with the systematic review of Guimarães et al. [38], which confirmed the NDVI as the most widely adopted vegetation index in almond remote sensing. While the NDVI proved effective and reliable in this case study, future research should assess the potential of integrating additional indices or complementary variables to capture the aspects of variability not fully described by the NDVI.

The ambiguous characteristics of Medium vigor areas have also been reported by recent research [57] and are comparable to the variability observed in vine vigor in relation to vegetative parameters. This indicates the need for further studies to clarify their specific traits and improve the classification of cultivated areas. Our canopy density values are consistent with the previous literature for SHD almond orchards [6,56]. The Medium vigor class demonstrated the lowest PAR attenuation value. One possible explanation for this behavior is that Medium vigor areas represent transitional zones where environmental factors, such as soil fertility, water availability, microclimatic conditions, and crop load interact in complex ways. This interpretation is also consistent with Carella et al. [42], who emphasized that integrating proximal sensors with UAV-derived vegetation indices improves the detection of subtle differences in plant water status across heterogeneous zones, leading to growth patterns that do not always fit neatly into High or Low vigor categories.

The differences in vegetative vigor were supported by the respective soil characteristics. For instance, due to a higher sandy fraction, Low vigor area soils drain rapidly and have a low water holding capacity and limited nutrient retention, conditions that hinder root development and nutrient availability, thus restricting plant growth [58]. Moreover, their reduced fertility, reflected in a higher pH and lower macronutrient and CEC levels, limits the solubility of essential nutrients like phosphorus and micronutrients [59]. Available phosphorus also peaks in Medium and High vigor areas, supporting robust root development and nutrient uptake [60].

The observed trend among vigor classes in the leaves' gas exchange data was consistent with canopy structure and plant water status. These variations underscore how almond trees dynamically respond to environmental factors such as water availability and stressors [24,61,62]. The trend among the vigor classes was the same during the two years of study for both gas exchange parameters and water potential. The better water status of the High vigor class may partly reflect the better water holding capacity of the soils in this zone, due to a higher clay fraction. The overall water status improvement observed in 2023 was likely due to the seasonal pluviometric dynamic characterized by high precipitation during July 2023. Comparable physiological responses were described by Prgomet et al. [24], who showed that moderate deficit irrigation ($\approx 35\%$ ETc) during kernel filling does not compromise yield and keeps plant water statuses stable, and by Vivaldi et al. [63]. The moderate water stress conditions observed, notwithstanding the presence of drip irrigation, particularly in 2022 (-1.76 to -2.40 MPa), are consistent with previous studies [64] on the same rootstock/cultivar combination under drought conditions with temperatures above 35°C .

With regard to the chlorophyll index provided by the SPAD device, although it correlates well with laboratory chlorophyll determinations in almond leaves [65], it is known to saturate at high pigment concentrations ($>50 \mu\text{g cm}^{-2}$) and to be affected by leaf thickness [66]. Consequently, the present study interprets SPAD values in a comparative rather than absolute sense, focusing on the differences among vigor classes. In contrast to the other physiological parameters, better performances were reported in the Medium vigor area, and the trend was confirmed during both years. The observed values (29.67–39.05) fell within the physiological range typically observed in almond orchards (28–40) [65] and should not be interpreted as indicative of nutrient deficiency or chlorosis *per se*. Overall, the obtained SPAD values were largely consistent with previous findings from [56,67,68]. However, according to Ben Yahmed et al. [64], SPAD levels below 35 may indicate chlorosis symptoms. The chlorophyll content in leaves, crucial for photosynthesis, is heavily influenced by nutrient availability [69]. Research shows that nitrogen fertilization boosts leaf chlorophyll content and photosynthetic capacity in almond trees, while nutrient imbalances can cause chlorosis and harm tree health [65,69]. Mestre et al. [70] demonstrated that a rootstock well adapted to growing conditions can lead to satisfactory vigor, higher nitrogen content in the leaves, and increased SPAD values. In genetic screening experiments, Gohari et al. [71] reported higher SPAD values in drought-tolerant genotypes (≈ 49 – 56) and lower values in sensitive ones (≈ 32 – 34). Even though these genotypes differ from those used in our orchard (Lauranne Avijor on Rootpac20), the results confirm that our observations are consistent with the variability expected under water-limited conditions. Similar observations on the benefits of integrating ground-based chlorophyll proxies with remote sensing have been made by Carella et al. [42], who showed that combining temporal SPAD dynamics with UAV indices enhances the detection of water-related stress. These differences suggest that site-specific nutrient dynamics may contribute to vigor variability and merit further investigation, particularly in relation to soil texture and rootstock interactions. In this context, the physiological behavior of the Medium vigor class deserves particular attention. Although it did not exhibit the highest SPAD values, it showed an increase in photosynthetic rate in 2023, possibly supported by the zone's balanced soil texture and moderate nutrient availability. However, the underlying mechanisms require further exploration.

The maximum quantum efficiency (F_v/F_m) showed no significant differences among vigor classes. The lower levels in 2023 indicate increased photosynthetic stress, with all vigor classes showing decreased performance. This trend was corroborated by similar patterns in chlorophyll content and leaf gas exchange parameters, both closely associated with photosynthetic efficiency. The F_v/F_m ratio is a standard indicator of photosynthetic efficiency, with values around 0.83 denoting healthy plants and lower values indicating stress or damage to the plant's photosynthesis system apparatus [56,72]. However, factors such as plant variety, seasonal changes, and the combination of rootstock and variety significantly impact PSII efficiency [65]. In our study, F_v/F_m values ranged from 0.69 to 0.82 for 2022 and from 0.60 to 0.75 for 2023, with most plants falling below the optimal threshold, indicating prolonged thermal stress during the fruit growth period in the monitored orchard. Comparable ranges have also been reported in almonds under water stress: Ranjbar et al. [73] observed F_v/F_m values around 0.79 in tolerant rootstock–scion combinations, while sensitive ones declined to ~ 0.67 ; similarly, Gohari et al. [71] reported F_v/F_m between 0.58 and 0.75 across different genotypes. Although these genetic backgrounds differ from our experimental material, the similarity of ranges supports the interpretation that our values reflect typical stress responses in almonds. These findings also align with Bakhtiari et al. [25], who observed cultivar-specific differences in

antioxidant activity and relative water content under drought conditions, suggesting that physiological stress indicators such as Fv/Fm can be linked to adaptation capacity.

The data from 2022 and 2023 indicate that tree vigor is crucial for almond yield and quality. The Medium and High vigor zones exhibited similar yields (1252 vs. 1261 g tree⁻¹ and 1016 vs. 1111 g tree⁻¹, respectively, in 2022 and 2023), but the almonds in High vigor zones were heavier. Medium vigor zones, while producing a higher number of fruits, face a commercial disadvantage due to the lower weight of the kernels, which is a key quality parameter for the consumption market [74]. The combination of high productivity with small fruits and physiological similarities to the Low vigor zones suggests overproduction relative to growth capacity in the Medium vigor plants. Maldera et al. [75] reported an average almond yield over a three-year period ranging from 1.52 kg to 3.45 kg per tree in an SHD orchard with the same almond variety and planting configuration. Their orchard, approximately 10 years old and operating at full productive capacity, serves as a benchmark for mature SHD almond systems. In contrast, our orchard, while already productive, is relatively young and has likely not yet reached its maximum yield potential.

Recent advances in yield modelling with machine learning approaches confirm that integrating the NDVI with climatic and irrigation data can achieve high predictive accuracy (R^2 up to 0.80) [38], supporting the potential of NDVI-based vigor zoning to contribute not only to physiological assessment but also to practical yield forecasting. Furthermore, Peddinti et al. [41] demonstrated that random forest algorithms can generate orchard-scale maps of stem water potential with an error of about 0.17 MPa, offering a pathway for the future integration of vigor zoning with direct plant water status indicators. The limited number of studies investigating yield and growth parameters in SHD almond systems highlights a significant knowledge gap, particularly concerning the temporal development of yield potential to its maximum capacity. Our findings align with previous research emphasizing the critical importance of growth characteristics and canopy light interception factors [76], which are known to substantially influence yield and fruit quality [57] and are essential for precise yield forecasting, playing a fundamental role in optimizing orchard productivity and maximizing economic returns.

5. Conclusions

This study demonstrates the effectiveness of integrating UAV-based remote sensing with ground-based measurements to identify intra-field spatial variability in SHD almond orchards. The NDVI maps successfully delineated zones of differing vigor, which corresponded with variations in canopy structure, physiological performance, soil properties, and yield. Nevertheless, although the NDVI proved effective, complementary indices are required to capture hidden variability and further enhance site-specific management strategies. The High vigor zones showed a higher NDVI (0.78), taller canopies (229 cm), SPAD values close to 39, Ψ_{stem} around -1.60 MPa, and they produced heavier kernels (≈ 10 – 12% more than Medium zones). These areas were also associated with finer-textured soils and better nutrient availability. In contrast, the Low vigor zones (NDVI 0.74; canopy 212 cm) yielded about 30% less per tree than the Medium and High zones, had lower SPAD values (≈ 31), more negative Ψ_{stem} (-1.94 to -2.35 MPa), and were linked to sandy soils with a lower water-holding capacity and reduced fertility. The Medium vigor zones (NDVI 0.75) produced more fruits but with smaller kernels, confirming a trade-off between yield quantity and quality. Fv/Fm values ranged from 0.60 to 0.82, reflecting higher stress in 2023, particularly in the Low vigor areas.

The results provide quantitative evidence that vigor zoning reflects consistent differences in canopy traits, soils, physiology, and yield, and therefore, can be used operationally to support site-specific irrigation, fertilization, and canopy management. In addition, this preliminary study reinforces the importance of coupling remote sensing

technologies with ground-based measurements, which is useful to better understand the possible ambiguous behavior typical of Medium vigor zones.

Although the results are promising, they should be interpreted with caution due to the limited temporal scope and the site-specific nature of this study. The limited number of ground-sampled trees was intended to provide zone-representative insights rather than continuous spatial modelling, which should be addressed in future studies through denser sampling. Broader validation across different orchards and years will also be essential to confirm general applicability. Future research should focus on refining vigor classification methods and exploring the long-term impacts of site-specific management practices on SHD almond orchards.

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