

Article

Proximal and Remote Sensing Monitoring of the ‘Spinoso sardo’ Artichoke Cultivar on Organic and Conventional Management

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Abstract

The development of new techniques to improve crop management, especially through precision agriculture methods and innovations, is crucial for increasing crop yield and ensuring high-quality production. The horticultural sector is particularly vulnerable to inefficiencies in crop management due to the complex and costly processes required for producing marketable products. Optimal nutritional inputs and effective disease management are crucial for maintaining commercial standards. This two-year study investigated the physiological differences between organic and conventional crop management of the Sardinian ‘Spinoso sardo’ artichoke ecotype (*Cynara cardunculus* var. *scolymus* L.) by integrating a multiplex force-A (MFA) fluorometer and unmanned aerial systems (UASs) equipped with a multispectral camera capable of analysing the NDVI vegetation index. Using both proximal and remote sensing instruments, physiological and nutritional variations in the growth cycle of artichokes were identified, distinguishing between traditional and two organic management practices. The two-year MFA experiment revealed physiological variability and different trends among the three management practices, indicating that MFA proximal sensing is a valuable tool for detecting physiological differences, particularly in chlorophyll activity and nitrogen content. In contrast, the UAS survey was less effective at distinguishing between management types, likely due to its limited use during the second year and the constrained timeframe of the multitemporal analysis. The analysis of the MFA fluorimetric indices suggested significant differences among the plots monitored due to the ANOVA statistical analysis and Tukey test, showing greater adaptability of the conventional system in managing production inputs, unlike the organic systems, which showed higher variability within the plots and across the survey years, indicating aleatory trends due to differences in crop management.

Keywords: precision agriculture; horticulture; fluorometer; UAS; organic management



Academic Editors: Josinaldo Lopes Araújo Rocha, Márcia Michelle Queiroz Ambrosio and Railene Hérica Carlos Rocha Araújo

Received: 18 June 2025

Revised: 30 July 2025

Accepted: 3 August 2025

Published: 14 August 2025

Citation: Deidda, A.; Sassu, A.; Ghiani, L.; Tiloca, M.T.; Ledda, L.; Cossu, M.; Deligios, P.A.; Gambella, F. Proximal and Remote Sensing Monitoring of the ‘Spinoso sardo’ Artichoke Cultivar on Organic and Conventional Management. *Horticulturae* **2025**, *11*, 961. <https://doi.org/10.3390/horticulturae11080961>

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1. Introduction

In recent decades, innovations in agricultural practices have led to significantly higher crop yields per unit area compared to the previous century [1]. This evolution is related

to the gradual rise in the global population [2] and, consequently, increased demand for essential goods, all aimed at maximising production efficiency and ensuring food security [3]. In the agricultural scenario, horticultural crops are crucial, accounting for more than a billion tonnes in 2022 [4]. Traditionally, conventional horticultural crop management involves numerous interventions in soil management, plant nutrition, and disease control [5], with massive treatments to achieve production goals and maintain quality standards [6]. Recently, the emergence of organic management for horticultural crops has led to a significant reduction in production inputs, tillage, and the total elimination of chemical plant protection products [7]. Artichoke cultivation (*Cynara cardunculus* var. *scolymus* L.) represents a typical species of the Mediterranean area in the Asteraceae family, derived from domesticated forms of the wild cardoon (*Cynara cardunculus* var. *sylvestris* Lam.); it occupies a relevant place among vegetable crops [8], counting several varieties and management methods found in the regions where it is cultivated [9]. Artichoke cultivation is considered a high-value agricultural activity, attributable to its substantial yield and economic return per hectare [10], and, depending on the region, it exhibits a wide range of differentiated ecotypes. With regard to its commercial diffusion in Sardinia, one of the principal ecotypes in Sardinia is the “Spinoso sardo”, due to its wide diffusion on the island. Among artichoke ecotypes, the “Spinoso sardo” variety is an autumn–winter re-flowering variety [11]. Traditionally, it is planted with semi-dormant offshoots during the summer and is subject to a forcing technique. This method uses early awakening through irrigation to start the production cycle sooner, allowing the plants to produce first-order flower heads by October or November. Therefore, the forcing technique anticipates the plant’s cycle, allowing for an earlier commercial output. It highlights the significance of cultivation techniques and how different management methods can impact the plant’s physiological development [12].

Conventional artichoke management involves supplementing the soil with mineral fertilisers, weed control, phytotiatric treatments, and, in some cases, the removal of senescent crop residues for potential energy use at the end of the season, despite their low energy yield [13]. This cultivation system is typically based on continuous artichoke monoculture. Traditionally, artichoke cultivation depends on conventional soil management and uniform fertilisation practices throughout the growing season. As a nutrient-absorbing species, artichoke requires substantial inputs of nitrogen and phosphorus–potassium fertilisers, which are typically supplied through mineral fertilisers applied during soil preparation and throughout the growing season [14]. These practices influence both the physiological crop activity and the chemical–structural composition of the soil. In recent years, organic management systems have emerged as a sustainable alternative to conventional cultivation [15]. This approach enhances crop nutrition through intercrops cultivation, which is subsequently incorporated into the soil, promoting natural mineralisation processes and reducing dependency on synthetic fertilisers [16–19]. While the organic system offers more sustainable management and less environmental impact than traditional systems, organic cultivation presents the risk of unpredictable production from both a nutritional and phytosanitary point of view, as the control of production inputs is more limited and potentially less efficient. Nonetheless, traditional cultivation methods, as with many other cropping systems, often lack strategies for the selective application of inputs based on the heterogeneous characteristics within a field. Uniform field management—encompassing tillage and nutrient application—frequently fails to account for spatial variability in soil fertility and crop needs [12,20]. The gradual and site-specific management of agricultural inputs is one of the key innovations introduced by precision agriculture (PA). PA seeks to address intra-field variability by employing advanced technologies and analytical methods for crop monitoring, providing the basis for decision

support systems (DSSs) that guide more efficient and sustainable management strategies. Crop monitoring is a critical component of DSS development [21], enabling real-time data acquisition through dedicated sensors. This data is then processed into actionable information, allowing operators to make informed decisions. A central objective of such monitoring is to generate spatial information that distinguishes local field conditions, thereby facilitating the optimisation of input use. This helps to prevent the over- or under-application of resources in areas where conventional, uniform management might lead to inefficiencies. Proximal sensing systems have emerged as a highly effective tool for localised crop monitoring [22]. By providing high-resolution, site-specific data, these systems capture the physiological variability within the field and enable timely, targeted interventions [23]. The proximal sensing application strategy could integrate and enhance the evaluation of site-specific input applications, such as localised nitrogen fertilisation, water management, and plant protection product (PPP) application [24]. These tools, equipped with the latest technologies, offer rapid analysis and immediate access to critical information, enhancing decision-making processes at the field level. Proximal sensing can provide information ranging from physiological to quantitative variables. Among the various existing instruments, fluorimetric sensors deserve particular mention, as they can rapidly obtain non-destructive information on the crop's physiological variables. This application is applied in numerous cropping systems, from herbaceous to tree crops. Fluorimetry has multiple applications in horticulture as well, enabling the analysis of different physiological characteristics of crops both in the field and in the laboratory [24,25]. In the field of artichoke cultivation, fluorimetry has been used to analyse chlorophyll, chlorosis disease [26], and biomass composition [27,28]. In parallel, remote sensing technologies, using satellite platforms, manned aircraft, and unmanned aerial systems (UASs), have expanded the scale and efficiency of monitoring practices through multiple sensors and vegetational indices [29]. In fact, the application of these techniques has contributed to more rapid crop analysis, reducing the operational costs of acquiring physiological data in the field. Traditionally, analyses conducted for product evaluation involved destructive sampling, which negatively affects production. Over the past decade, these tools have become integral to agricultural surveillance, enabling the collection of data across large areas with increasingly reliable results [30], regardless of variations in ground resolution associated with these different systems [31].

Understanding field variability, achieved through site-specific physiological evaluation of the crop, could enable more efficient management of production resources. This process would allow for a more targeted and potentially localised assessment of individual plants, considering their physiological needs to optimise crop management.

The present study involved non-destructive sampling of 'Spinoso sardo' Sardinian ecotype artichoke leaves during the 2018/2019 and 2019/2020 seasons, covering the vegetative growth and reproductive phases of the plants, monitoring three different cultivation management systems, classified as conventional or organic, using a proximal fluorimetric sensor. The primary purpose is to evaluate the ability and efficiency of fluorimetric indices in detecting any physiological differences in leaves based on the different cultivation techniques adopted. Secondly, due to the high intensity of the work involved in MFA analysis on a wide range of samples, an aerial survey was performed using a UAS to acquire the NDVI vegetation index. The UAS analysis was performed to observe the dynamics of the remote sensing application and compare it with fluorimetric data, evaluating the potential for using a UAS as a substitute instead of MFA.

2. Materials and Methods

2.1. Site and Experimental Design

The experiment took place at the experimental fields of the Agriculture Department, University of Sassari, located in Ottava (SS, Italy, 40°46′31″ N; 8°29′12″ E, WGS84 Coordinate System, 81 m above ground level) during the 2018/2019 and 2019/2020 seasons. These two seasons were characterised by a similar temperature trend, with a 10% reduction in natural water supply from precipitation, settling at around 450 mm.

The monitoring operation was performed in an ongoing experiment plot [16] identified in Figure 1, covering an area of approximately 2500 m². The artichoke plants were distributed in rows oriented in a northwest–southeast direction, with a row spacing of 0.7 m × 1.4 m (along the row and between rows, respectively), resulting in a density of 9524 plants/ha. To minimise the canopy border effect, two rows were planted on the borders, and two additional rows were placed between the crop management sections to prevent contamination. Artichokes were planted in July using semi-dormant offshoots as propagation organs. The adopted experimental design considered three different types of agronomic management for the artichoke, as follows:

- Conventional (CON) management plot;
- Organic plot with annual presence of artichoke (ORG-I);
- Organic plot, alternated annually with cauliflower (ORG-II);

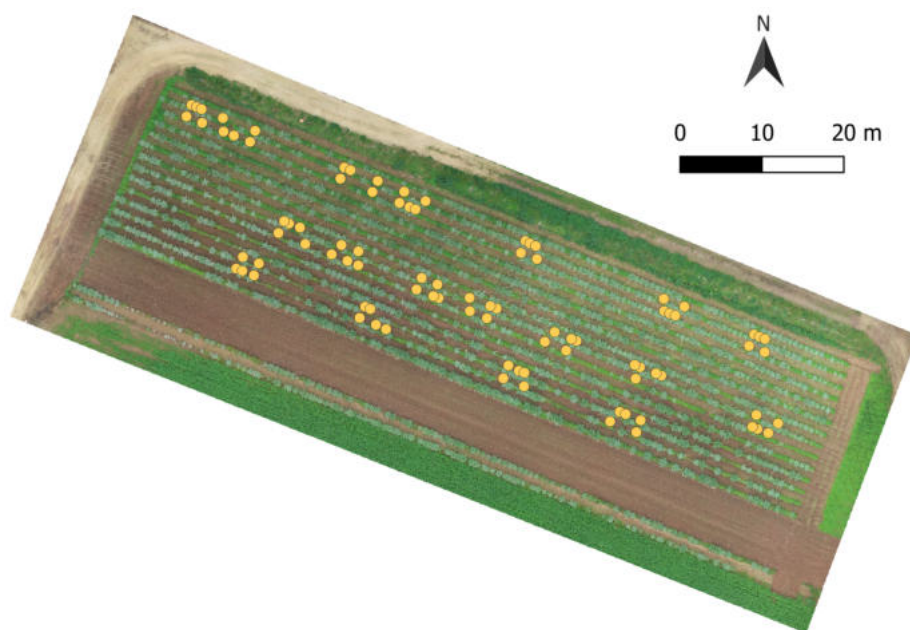


Figure 1. Experimental field under analysis. The plants monitored during the first survey year are marked in yellow. Sampling operations covered specific parts of the field, where the operator visually assessed the location of the measurements around some checking points placed along the field.

The experimental design compares conventional (CON) practices with two alternative organic management types, where artichoke succession occurs annually and biennially in the field (ORG-I and ORG-II, respectively). The management of CON involves monocropping in the same plot, with conventional agricultural practices including mineral fertilisation, weeding, phytoiatric treatments, and the soil incorporation of senescent dried crop residues toward the end of the crop cycle during the spring season.

The artichoke-growing cycle on the annual organic management ORG-I was interrupted early at the end of the marketable harvest period (mid-April), and the fresh residues

were chopped and ploughed into the soil. To restock the soil's nitrogen, a short-cycle legume, French bean (*Phaseolus vulgaris* L. cv. Bronco) (Monsanto Agricoltura Italia SpA, Milano, Italy), was planted in the ORG-I plot. The French bean was interrupted at the reproductive stage, when the plants produced the first pods (end of flowering). The biomass was incorporated in a fresh state to increase the soil's nutrient content. Fresh residues from this bean crop were also incorporated into the soil at the end of June, before the new growing season for artichoke began.

The biennial rotation of artichokes was managed using cauliflower (*Brassica oleracea* L. var. *botrytis* cv. Nautilus). Artichoke and cauliflower species were cultivated alternately in the two plots in the two survey years. *Pisum sativum* L. cv. Attika (Limagrain Verneuil Holding, France), used as a legume cover crop, was sown in the inter-row spaces of artichoke and cauliflower in February. At the end of the primary crop's marketable harvest period, and when the peas were flowering (mid-April), artichoke, cauliflower, and fresh pea residues were incorporated into the soil.

According to organic farming principles, no phytosanitary treatments or chemical fertilisation were applied in the ORG-I and ORG-II management types, and the irrigation criteria followed the ongoing experiment [32,33]. The surveys were conducted during the crop's critical phenological phases, with monitoring operations scheduled according to the weather trend on a three-week basis.

Table 1 reports the details of the survey days during the experiment and their corresponding BBCH (Biologische Bundesanstalt, Bundessortenamt, and CHEMical industry) code identification [34].

Table 1. Experimental survey days with the associated day of year (DOY) and BBCH scale.

Date	DOY	BBCH
21 December 2018	355	59
16 January 2019	16	59
13 February 2019	44	61
7 March 2019	66	67
22 March 2019	81	69
29 November 2019	333	55
27 December 2019	361	59
16 January 2020	16	59
24 February 2020	55	69

Fluorimetric data acquisition involved five representative plants of “Spinoso sardo” positioned around several checkpoints distributed along the field, as some crop failures were found along the rows due to the abortion of the offshoots. As shown in Figure 2a, the monitorable plants have large, well-expanded leaves, apparently not diseased and of normal development. The non-monitorable plants, as observed in Figure 2b, have poor development, with inadequately expanded leaves that cannot be observed with the monitoring instrument.

MFA field measurements were taken on clear days after the morning dew on the plants had evaporated. Figure 3 shows the thesis arrangement in the field; the ORG-II thesis appears on different plots in alternate years with the cauliflower thesis due to their biennial rotation. Figure 3 displays the plots involved in the survey, with experimental rows (Thesis, “T”) spaced by intermediate border rows (“B”) to isolate the different treatments.

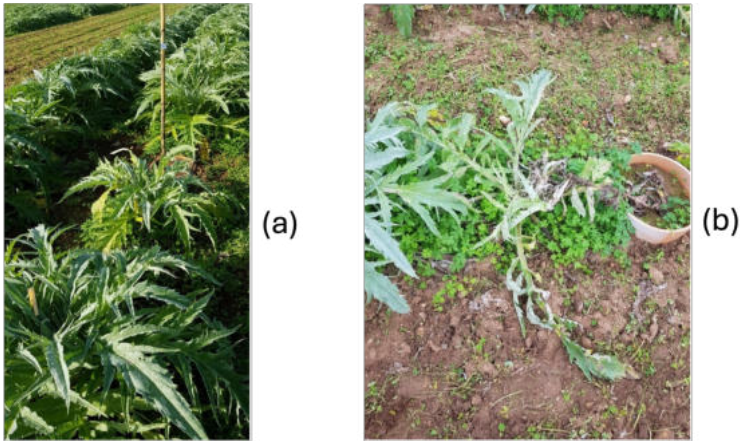


Figure 2. Example of sample selection during the sampling preparation phase. On the right, well-developed plants are adequate for multi-temporal monitoring (a); on the left, plants are unsuitable for monitoring (b). The preliminary identification of the plants permitted their subsequent monitoring along the artichoke production cycle.

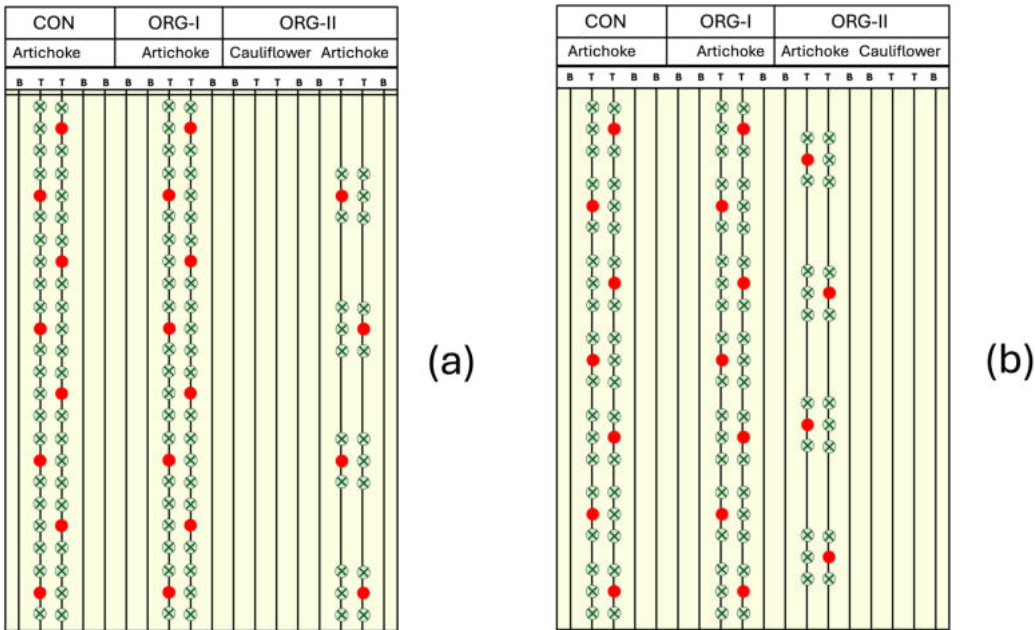


Figure 3. Experimental design adopted for 2018/2019 (a) and for 2019/2020 (b). From left to right, the monitored thesis (T) separated by the border (B) rows are as follows: Conventional (CON) plot; organic plot (ORG-I) in a monocropping and annual rotation with French bean; organic plot (ORG-II) in a biennial rotation with cauliflower, as observable in both designs. Checking points are marked with red circles, and artichoke plants are marked with green crossed-out circles.

2.2. Fluorimetric Analysis

The instrument adopted for the non-destructive monitoring of plants is a hand-held multi-parameter fluorescence device capable of observing the physiological evolution of the crop and extrapolating its main nutritional characteristics [25]. The instrument used was the ForceA Multiplex 3 portable fluorometer (MFA, Orsay, France). The detection system comprises three light-emitting diode (LED) channels that emit pulsed radiation at wavelengths in the visible spectrum (RGB): 470 nm (blue), 516 nm (green), and 635 nm (red), respectively. The instrument features six LEDs that operate at a wavelength of 375 nm in the ultraviolet spectrum [35]. All the detectors are enclosed in a plexiglass structure to protect and isolate input and output radiation. At the centre of the sensor array, there are three sensors responsible for fluorescence detection in three delimited ranges, as follows:

far-red fluorescence (FRF), near-red fluorescence (RF), and blue–green fluorescence (BG-F). The signals processed by MFA provide a total of 24 specific indices, which estimate the main physiological properties of the crop [36]. For this research, the fluorimetric analysis involved the SFR-G, SFR-R, NBI-G, NBI-R, FLAV, and BRR-FRF indices, evaluating chlorophyll, nitrogen, and flavonoid content, over the water stress and other abiotic stress indices. According to the literature, the choice of these indices is based on their ability to investigate the main physiological characteristics of the plant, providing a comprehensive view of the plant’s state [37]. The measurements include the sample fluorescence ratio with excitation channels in the green and red wavelengths (SFR-G and SFR-R) for assessing chlorophyll content and yield [37], and the nitrogen balance index, which utilises excitation channels in red and green (NBI-G and NBI-R) to monitor total nitrogen levels [38]. The flavonoid index (FLAV), defined as the logarithm of the ratio of red to UV excitation of chlorophyll fluorescence in the RF, is widely used in leaf surveys for flavonoid estimation [39]. Furthermore, the blue-to-red emission ratio index (BRR-FRF) is a comprehensive indicator. Depending on the specific crop analysed, it can identify stress, nutritional deficiencies in field crops, the presence of pathogens, or grape ripening [40].

In the experimental design, the MFA instrument was used to monitor the artichoke vegetative architecture, dividing it into three different layers, as follows: pre-senescent adult leaves (first stage), adult leaves (second stage), and newly formed leaves (third stage), respectively. The MFA analysed each leaf at three different points—the apical, central and basal parts—for a total of nine leaves per plant, at a 10 cm distance between the sample and the sensors. The application of a three-layer analysis was necessary to obtain a homogeneous multitemporal analysis; during the growing period, and until its final stages, all the measurements focused on the same kind of leaves, guaranteeing the uniform analysis of the plant.

The indices used in the MFA monitoring are listed below.

$$SFR - R = \frac{FRF_R}{RF_R}, \quad (1)$$

$$SFR - G = \frac{FRF_G}{RF_G}, \quad (2)$$

$$FLAV = \log\left(\frac{FRF_R}{FRF_{UV}}\right), \quad (3)$$

$$BRR - FRF = \frac{YF_{UV}}{FRF_G}, \quad (4)$$

$$NBI - R = \frac{FRF_{UV}}{RF_R}, \quad (5)$$

$$NBI - G = \frac{FRF_{UV}}{RF_G}, \quad (6)$$

2.3. UAS Survey

During the 2019–2020 season, MFA monitoring was combined with a UAS survey to observe the different management types through a vegetation index. To avoid environmental variability in remote and proximal sensing data acquisition, the surveys were conducted on the same day. The aerial system involved in the monitoring operations was a commercial UAS Phantom 4 Pro (DJI, Shenzhen, China) with an RGB CMOS 1-inch 20-megapixel camera, equipped with a multispectral red–green–near-infrared (RGN) Survey 3 (Mapir) sensor mounted on the UAS frame. The Mapir calibration target was positioned on the ground due to reflectance corrections for raw data acquisition. The flights were planned on sunny days, in order to maintain a constant meteorological situation and ensure ho-

homogeneous and adequate image acquisition conditions. All the surveys were performed at 40 m above ground level (AGL), with a ground sampling distance (GSD) of 1.096 cm. To acquire a high-resolution orthomosaic reconstruction, the overlap values were 75% and 85% for frontal and side directions, respectively. The RGB camera was necessary to reconstruct and segment the canopy into three dimensions, allowing for the digitalisation of individual artichoke plants. This operation facilitated plant-specific analysis using the structure-from-motion system Agisoft Metashape (St. Petersburg, Russia). Specifically, the RGB orthomosaic, combined with the height values obtained from the digital terrain model (DTM) and the digital surface model (DSM), enabled the identification of individual plants using the canopy height model (CHM) segmentation technique. The reconstructed plants allowed the analysis of vegetative crops through the normalised difference vegetation index (NDVI) derived from the bands collected by the RGN sensor, enabling the assessment of physiological variability between the three management methods adopted. Below is the equation for the extraction of the NDVI index.

$$NDVI = \frac{NIR_{(850\text{ nm})} - Red_{(550\text{ nm})}}{NIR_{(850\text{ nm})} + Red_{(550\text{ nm})}}, \quad (7)$$

2.4. Data Processing and Software Elaboration

The raw data from MFA and UAS were pre-processed prior to statistical analysis. Regarding the fluorimetric analysis, the three MFA measurements taken from each leaf were averaged. The result was then averaged across the three leaf layers to yield a single value for each plant, representing its overall trend. The CHM technique for the canopy reconstruction involved subtracting the DTM layer from the DSM layer to isolate the heights of the plants effectively [41]. The digital layer segmentation process was performed on QGIS using the following formula:

$$CHM = DSM - DTM \quad (8)$$

The reconstruction and extraction of individual plants through the CHM model enabled the calculation of the NDVI vegetation index for the examined plants, as the multispectral sensor was externally implemented in the UAS frame, and the NIR RAW data did not contain GNSS positioning information, which required the overlaying of the CHM model.

The preliminary dataset construction and processing allowed the association of the fluorimetric measurements with the corresponding vegetation indices for individual plants. The MFA data were processed using the open-access software R for statistical analysis and reconstruction of the relative graphs. After the preliminary statistical analysis check for normality distribution, the analysis of variance (ANOVA) was used to identify significant differences among the studied groups, and subsequently, the Tukey test [42] was performed to assess the subdivision between the CON, ORG-I, and ORG-II groups. The statistical results were integrated by incorporating the respective graphs for each variable, which illustrated the evolution of indices over the monitoring period.

The indices derived from the MFA were categorised into the following four groups: (a) date, (b) management, (c) checking points, and (d) index. The “date” refers to the measurement days, “management” pertains to the type of cultivation practice applied, and “checking points” indicate the relative positions of the plants to the sample points. The “index” represents the value of interest, averaged across different leaf stages and plants at the various checking points. Among these variables, “management” serves as the key discriminating factor, as it represents the primary source of variation in the fluorimetric indices. Additionally, potential interactions between “management” and

“date” (date $\times$ management), as well as between “management” and “checking points” (management $\times$ checking points), were explored to assess whether the survey dates or the spatial arrangement of the checking points in the field could contribute to variability in the fluorimetric indices. The NDVI data from UAS followed the same MFA statistical analysis. They were then compared with the MFA indices using a correlation matrix in R through the ggcorrplot and emmeans libraries to observe any correlations between UAS and MFA data.

3. Results

3.1. Fluorimetric Analysis

The present subsection explores the statistical results of the MFA survey in the 2018/2019 and 2019/2020 research years.

3.1.1. First Survey Year

The ANOVA analysis for the SFR indices displayed in Table 2 observed a highly significant statistical difference, evidencing a different canopy evolution among the management during the survey period. Table 2 also reports the Tukey test analysis to identify any affinities between ORGs and CON based on the chlorophyll detection indices. The comparison between ORG-I and ORG-II did not indicate a significant difference, but a difference emerged when they were compared with CON management.

Table 2. ANOVA and Tukey test results on SFR-G and SFR-R.

Index	SFR-G		SFR-R	
	F-Value	p-Value	F-Value	p-Value
Management	23.609	1.69×10^{-10} ***	22.401	5.09×10^{-10} ***
Date $\times$ Management	5.314	2.12×10^{-6} ***	5.337	1.97×10^{-6} ***
Tukey Test	p-value		p-value	
CON-ORG-I	$<1.0 \times 10^{-16}$ ***		$<1.0 \times 10^{-10}$ ***	
CON-ORG-II	3.0×10^{-4} ***		0.030 **	
ORG-I-ORG-II	0.205 ns		0.080 ns	

The level of significance (p-value) is shown in the table, where ** indicates $p < 0.01$, and *** indicates $p < 0.001$. ns represents no significant difference.

The results from the three management types were plotted in a line graph to observe the seasonal trend across the survey days. The SFR-G and SFR-R graphs in Figure 4 show that, for the CON management, photosynthetic activity was initially slightly lower than in the ORG-I and ORG-II theses, but rose to higher values starting in January 2019. The ORG management types, however, did not provide a statistical discrimination between them, but the graphs in Figure 4 highlight the SFR index decrease for ORG-II management, which is 23% lower than the other plots.

The BRR-FRF index did not provide a statistical discrimination between the treatments during the first survey year, as observed in the ANOVA analysis and Tukey test results. Different from the stress index, the FLAV index showed a significant difference between the ORG-I and ORG-II treatments. The index increased steadily over the days of monitoring, increasing tenfold on the last day. Table 3 shows the results of the ANOVA and the Tukey analysis.

The graphical reconstruction of the stress and flavonol indices during the survey confirms the low level of significance among the management types due to the overlapping of the obtained values. In particular, in the graph in Figure 5a, the trends of the three management types run side by side during all the sampling dates, separating only at the end of the cycle (22 March 2019). In this survey year, the ORG-I and ORG-II treatments show

a much higher stress level than the CON management, especially in the last monitoring survey, despite the FLAV index in Figure 5b, which indicates an increasing and constant trend in all three management types. The ORG-II plot, despite the lack of a significant response, showed higher values than the other management types for most of the time (+11%), a level that the ORG-I management type reached in the last survey.

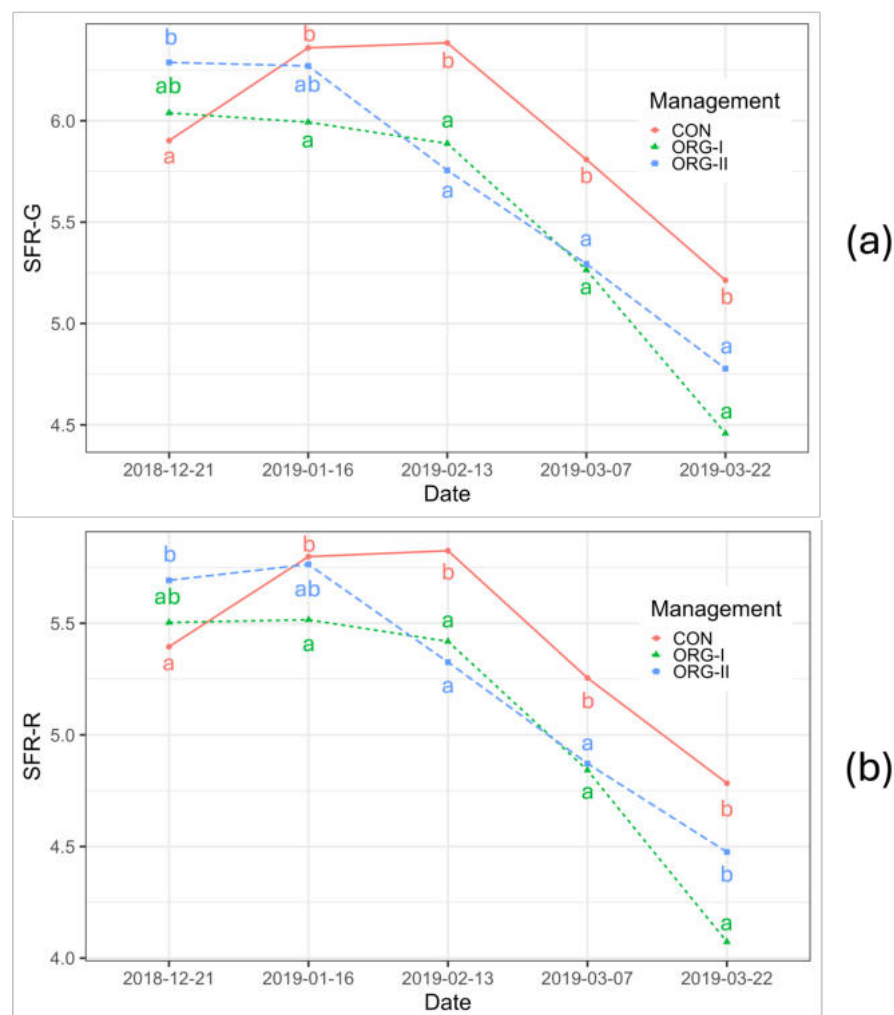


Figure 4. Evolution of SFR indices through the first survey year. On the x-axis are the survey dates, and on the y-axis are the index values. The two graphs show the SFR-G index (a) and the SFR-R (b). The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

Table 3. ANOVA results on BRR-FRF and FLAV.

Index	BRR-FRF		FLAV	
	F-Value	p-Value	F-Value	p-Value
Management	1.165	0.313 ns	2.945	0.054 ns
Date × Management	1.140	0.335 ns	1.546	0.139 ns
Tukey Test	p-value		p-value	
CON-ORG-I	0.449 ns		0.770 ns	
CON-ORG-II	0.371 ns		0.156 ns	
ORG-I-ORG-II	0.937 ns		0.044 *	

The level of significance (p-value) is shown in the table, where * indicates $p < 0.05$. ns represents no significance.

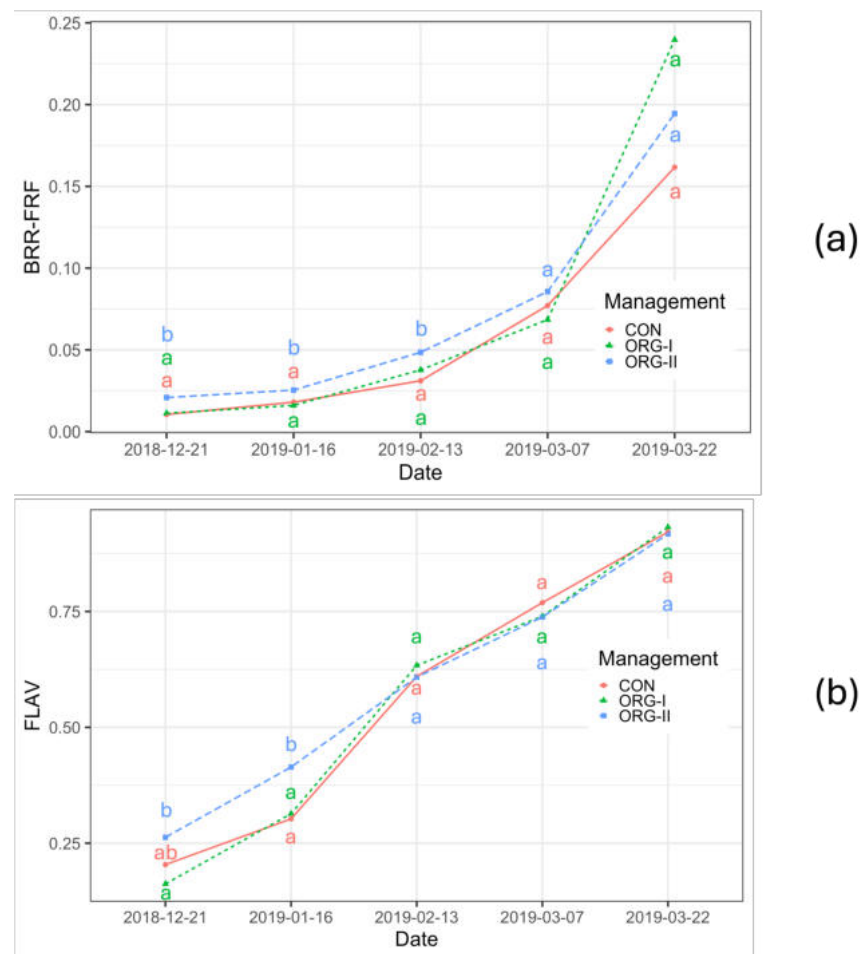


Figure 5. BRR-FRF (a) and FLAV (b) indices, indicating the evolution of stress and flavonol indices during the season. The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

The final aspect considered is the total nitrogen content, observed using the NBI-G and NBI-R indices. The statistical analysis, as with the previous ones, identified fluctuations in the nitrogen fluorimetric indices among the survey dates. Unlike the previous indices, especially those focusing on chlorophyll activity, the Tukey test revealed a significant difference between the ORG-I and ORG-II treatments, while showing no particular differences with the CON thesis. Table 4 shows the ANOVA and Tukey test statistical results.

Table 4. ANOVA results on NBI-G and NBI-R.

Index	NBI-G		NBI-R	
	F-Value	p-Value	F-Value	p-Value
Management	6.468	0.002 **	5.662	0.004 **
Date × Management	3.460	0.001 ***	2.786	0.005 **
Tukey Test	p-value		p-value	
CON-ORG-I	0.132 ns		0.089 ns	
CON-ORG-II	0.118 ns		0.277 ns	
ORG-I-ORG-II	0.001 ***		0.003 **	

The level of significance (*p*-value) is shown in the table, where ** indicates $p < 0.01$, and *** indicates $p < 0.001$. ns represents no significance.

The fluorimetric data in Figure 6 indicate that the nitrogen indices show a constant inflexion throughout the survey dates, with continuous overlapping of values between the three management types, consolidating what was identified by the statistical analyses.

These graphs, despite the low test significance, reflect what is indicated by the SFR, BRR-FRF, and FLAV indices. For each NBI index, the decrease fell to more than 80% during the first monitoring year, according to the other fluorimetric indices observed above.

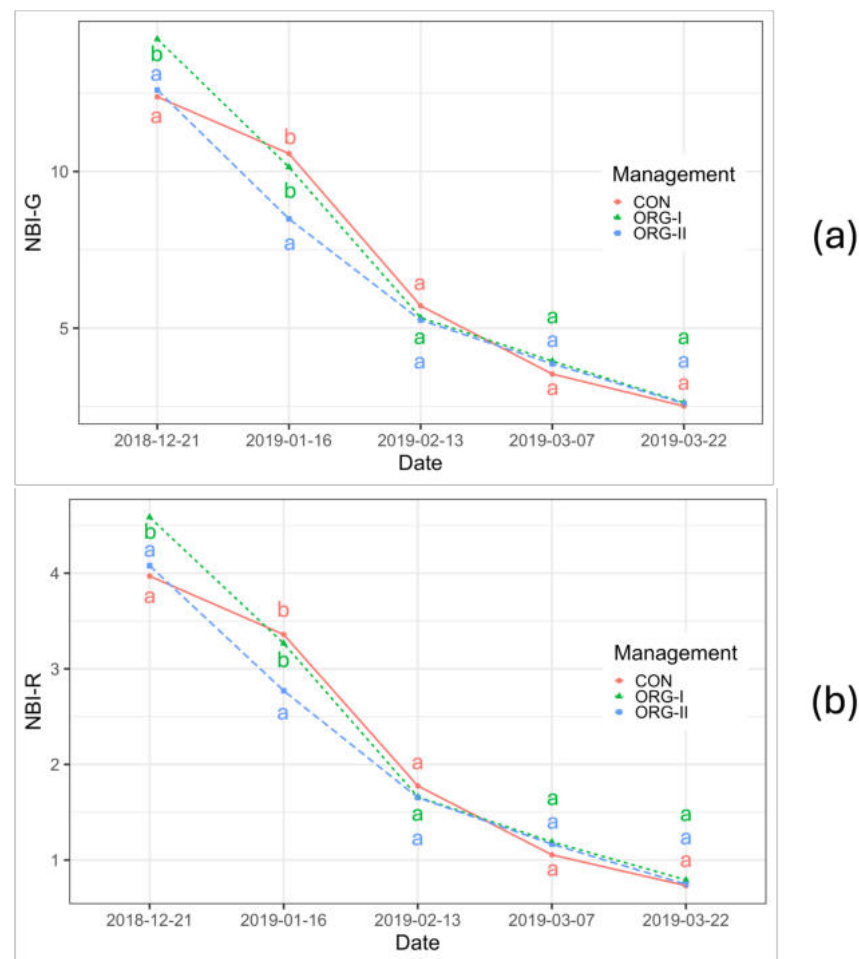


Figure 6. NBI-G (a) and NBI-R (b) on leaves during the first survey year. The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

3.1.2. Second Survey Year

The second monitoring year is characterised by different evolutionary dynamics compared to the previous one. Regarding the chlorophyll indices SFR-G and SFR-R, the ANOVA analysis in Table 5 reports a significant difference among the three management systems, highlighting statistical variability across the survey dates. According to the Tukey test, the primary differences are observed between the CON and ORG-I management systems due to the high significance values and, for the SFR-R index, between the CON and ORG-II management systems. For both fluorimetric indices, no significant differences are reported between ORG-I and ORG-II.

The graph construction of the SFR indices in Figure 7 shows the evolution of the three theses during the multi-temporal analysis. The ORG management types display high chlorophyll values in the early stages of the cycle, peaking in December and then undergoing a slow but continuous decrease until the end of the plant's physiological cycle. The CON thesis, on the other hand, shows the opposite trend to the ORG theses, starting with values consistently lower than those of the ORG types in the early growth stages, then experiencing a rapid escalation (+16.6% and 18.9% for SFR-G and SFR-R, respectively) until it surpasses both organic theses in January (+8.9% and 9.4% for SFR-G and SFR-R), remaining steady until the end of the cycle.

Table 5. ANOVA results on SFR-G and SFR-R.

Index	F-Value	SFR-G <i>p</i> -Value	F-Value	SFR-R <i>p</i> -Value
Management	7.388	<0.001 ***	7.622	<0.001 ***
Date × Management	17.743	<2.000 × 10 ^{−16} ***	17.798	<2.000 × 10 ^{−16} ***
Tukey Test		<i>p</i> -value		<i>p</i> -value
CON-ORG-I		<0.001 ***		<0.001 ***
CON-ORG-II		0.342 ns		0.039 *
ORG-I-ORG-II		0.133 ns		0.677 ns

The level of significance (*p*-value) is shown in the table, where * indicates $p < 0.05$, and *** indicates $p < 0.001$. ns represents no significance.

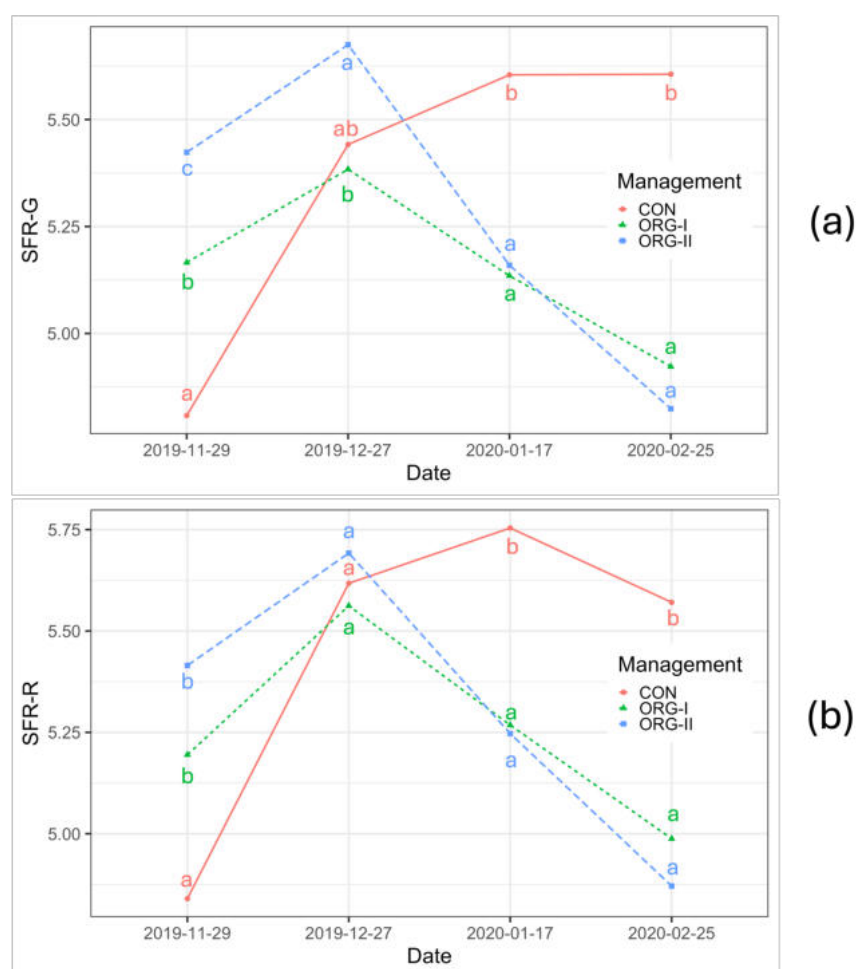


Figure 7. The SFR-G (a) and SFR-R (b) index trends during the 2019–2020 survey. The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

The spatial–temporal variability of the BRR-FRF-2 and FLAV-2 indices is presented in Table 6, revealing significant differences among the management systems, in contrast to the results from the previous year. ANOVA analysis of the management and date variables indicated a significant separation among the management systems, unlike the 2018/2019 season. All pairwise comparisons performed using the Tukey test showed significant differences between the CON and ORG management systems, while no statistical significance was found between ORG-I and ORG-II. Table 6 summarises the analysis of BRR-FRF and FLAV indices.

Table 6. ANOVA results on BRR-FRF and FLAV.

Index	BRR-FRF		FLAV	
	F-Value	p-Value	F-Value	p-Value
Management	15.676	3.12×10^{-7} ***	32.590	1.19×10^{-13}
Date × Management	6.148	$<3.96 \times 10^{-6}$ ***	4.150	4.89×10^{-4} ***
Tukey Test	p-Value		p-Value	
CON-ORG-I	<0.001 ***		<0.001 ***	
CON-ORG-II	0.006 **		<0.001 ***	
ORG-II-ORG-I	0.192 ns		0.207 ns	

The level of significance (*p*-value) is shown in the table, where , ** indicates $p < 0.01$, and *** indicates $p < 0.001$. ns represents no significance.

The graphical results of the BRR-FRF and FLAV indices provide a valuable overview of the temporal evolution of the three management systems. The BRR-FRF index (Figure 8a) shows that the values of the three plots are similar during the early growth stage but begin to diverge from late December until the end of the monitoring period, with the ORG systems displaying significantly higher stress levels compared to the CON management (+49.3%). Similarly, the FLAV index (Figure 8b) exhibits the same trend, indicating that ORGs show higher values than the CON management. Throughout the production cycle, the CON system consistently maintains lower levels of stress and flavonoids than the ORG systems (−28.3%). These findings align with the SFR indices, where the lower stress and flavonol values observed in the CON management complement the higher chlorophyll content.

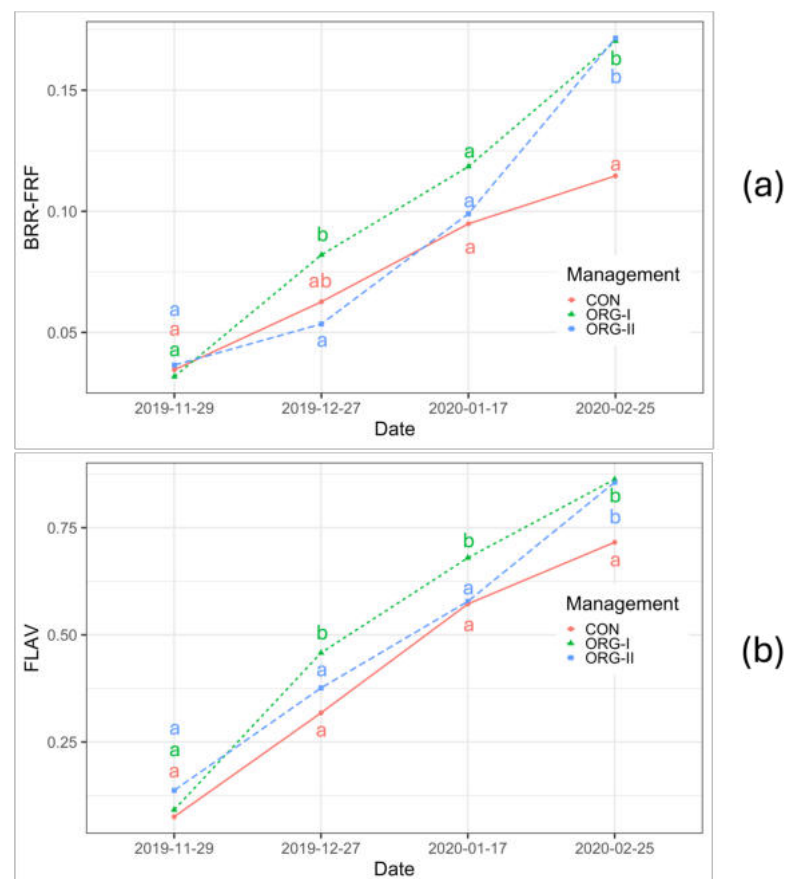


Figure 8. The stress index BRR-FRF (a) and the flavonol index FLAV (b) during the second survey year. The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

According to the previous indices, the statistical analysis of the NBI-G and NBI-R MFA indices demonstrated significant differentiation among the management systems. The ANOVA analysis revealed high variability in both the management and date variables, as indicated by the significance values. The Tukey test confirmed a distinction between the CON and ORG systems, similar to the BRR-FRF and FLAV indices, with the CON system being statistically different from the ORG system. However, no significant differences were observed between ORG-I and ORG-II. The ANOVA and Tukey statistical results are reported in Table 7.

Table 7. ANOVA results on NBI-G and NBI-R.

Index	NBI-G		NBI-R	
	F-Value	p-Value	F-Value	p-Value
Management	15.02	5.69×10^{-7} ***	15.119	5.19×10^{-7} ***
Date × Management	5.42	2.31×10^{-5} ***	5.667	1.27×10^{-5} ***
Tukey Test	p-value		p-value	
CON-ORG-I	<0.001 ***		<0.001 ***	
CON-ORG-II	0.017 *		0.007 **	
ORG-I-ORG-II	0.115 ns		0.214 ns	

The level of significance (*p*-value) is shown in the table, where * indicates $p < 0.05$, ** indicates $p < 0.01$, and *** indicates $p < 0.001$. ns represents no significance.

The NBI-G and NBI-R graphs in Figure 9 show a general decline in nitrogen content, which gradually decreases throughout the growth stages, averaging a 77% reduction across the management systems. As indicated by the Tukey test, although ORG-I and ORG-II exhibit relatively similar MFA values, both differ significantly from the CON system, consistent with previous observations from other indices. Notably, on the first monitoring day, the CON system displays lower NBI values compared to ORG-I but rises to higher values on all subsequent survey dates. Figure 9 resumes the MFA management evolution during the surveys.

This observation reflects what was highlighted in the SFR, BRR-FRF, and FLAV indices, where the CON thesis consistently maintains higher levels during the intermediate and final phases of the artichoke's biological cycle, suggesting a higher nitrogen content than that of the ORG types.



Figure 9. Cont.

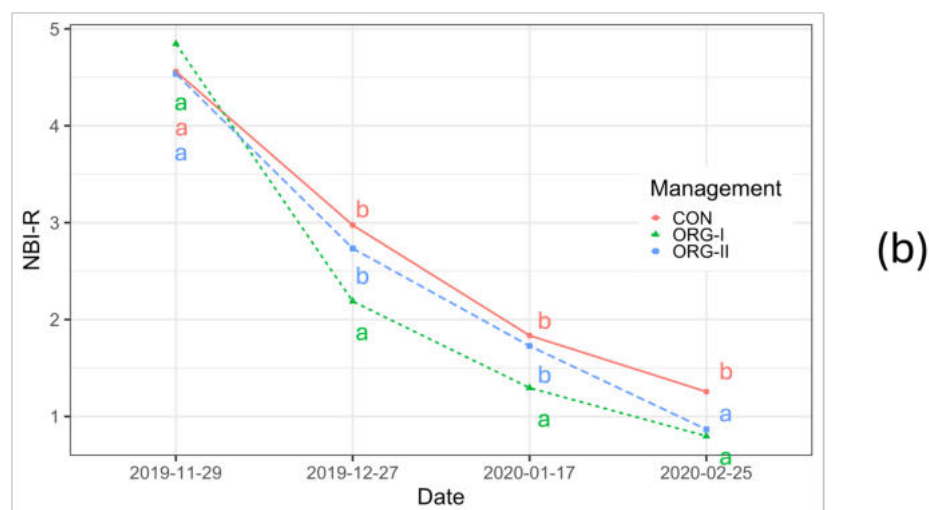


Figure 9. Trends of the NBI-G (a) and NBI-R (b) indices during the second survey year. The letters in the graphs indicate the differences between the various management systems identified in the Tukey test.

3.2. UAS Survey

The remote analysis performed by the UAS allowed the acquisition of vegetative vigour using the NDVI vegetation index. The plant segmentation performed in QGIS with the CHM technique enabled analysis exclusively on the plants, without the soil and the weeds within the field. The multi-temporal survey was conducted on the last three dates of the second year of monitoring, during the period of maximum vegetative–reproductive activity. The ANOVA analysis performed on the three management types did not observe a comparable trend to the fluorometric indices, as it did not discriminate particular differences between the plots. As observable in Table 8, no statistical difference was found between the treatments during the season, while instead, the ANOVA analysis evidenced a variability among the checking points (management×checking points), suggesting an internal heterogeneity on the three plots. Further analysis of singular surveys found that only on the last date (24 February 2020) was there significant variability between plots, with the ORG-II management differentiating itself from the others (+13.5%).

Table 8. ANOVA analysis on the NDVI index, where p -value < 0.05. The high p -value for the management variable suggests that the UAS did not evidence particular differences between the treatments, but rather indicated significant differences within the plots.

ANOVA	F-Value	NDVI	p -Value
Management	5.9524		0.002 **
Date×Management	1.9541		0.116
Tukey Test		p -value	
ORG-II-ORG-I		0.835 ns	
CON-ORG-I		0.676 ns	
CON-ORG-II		0.985 ns	

The level of significance (p -value) is shown in the table, where ** indicates $p < 0.01$, and ns represents no significance.

The NDVI data development is summarised in Figure 10, comparing the three plots during the survey period. The data graph confirms what was observed in statistical analysis, where the CON and ORGs NDVI values follow a uniform development.

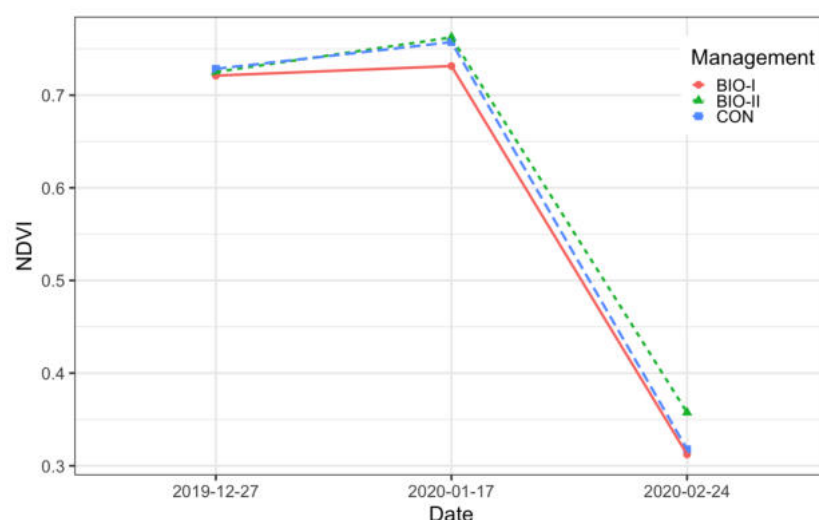


Figure 10. NDVI indices performance from the UAS survey. The field evolution across the three management plots did not identify any differences between treatments, pointing to a uniform tendency.

3.3. Correlation Matrix

Lastly, a correlation matrix was created between the NDVI and the MFA-generated index, as shown in Figure 11. The results show that the NDVI, SFR, and NBI indices perform unidirectionally, indicating a direct proportional correlation among them. As observed in the graphs in Figures 5 and 8, the BRR-FRF stress index and FLAV show an inverse correlation with the other indices. Specifically, high correlation values were observed between the NBI indices and the FLAV and BRR-FRF indices, suggesting that total leaf nitrogen content is closely related to stress and vegetative decay, with this result being associated with the more moderate relationship detected with the SFR data.

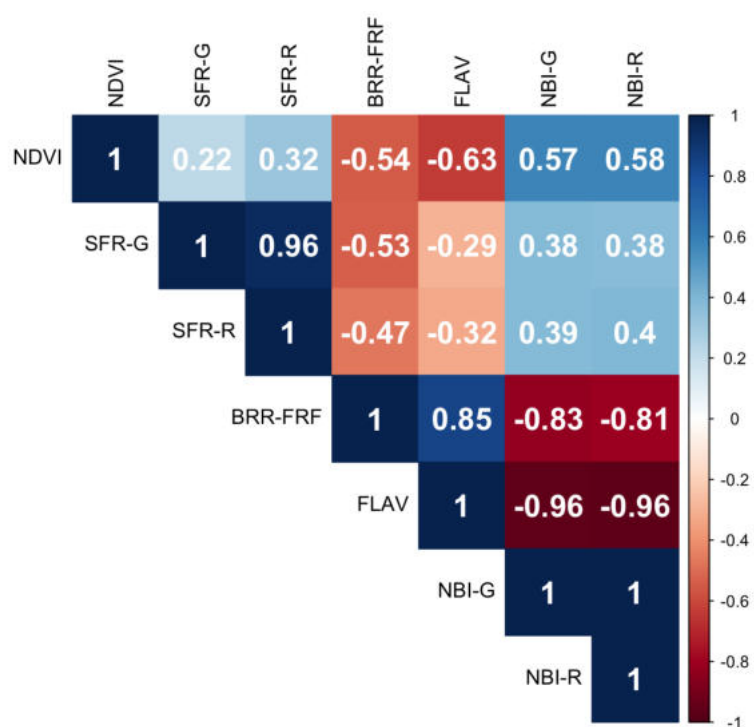


Figure 11. Matrix correlation of all variables considered in the experiment, converging MFA and UAS indices. The palette legend illustrates the proportional correlation (blue) to inverse correlation (red) between the indices. The white numbers in the matrix represent the correlation coefficients.

4. Discussion

The fluorimetric analysis conducted with the MFA in the three management areas provided a similar overview during the two seasons. Statistical analysis of the chlorophyll indices (SFR) showed a different evolution between the ORG and CON theses. The survey performed with the MFA revealed that the traditional CON management starts with lower SFR values. It reverses the trend toward December and maintains a higher level of photosynthetic activity until the senescence phase compared with the ORG management. This phenomenon can be explained by the effect of the agronomic strategy that was applied. The CON field relied on chemical fertilisation multiple times throughout the year, ensuring a continuous nutrient uptake. In contrast, the ORG-I and ORG-II plots only received fresh residues for nutritional supplements, as expected under organic conduction. In line with this assumption, leaf nitrogen analysis using the NBI indices led to similar conclusions, suggesting different developments between organic and conventional management. In fact, during the mid-periods of the two-year study, the nitrogen indices in the CON treatment were continuously higher than in the ORGs. This phenomenon suggests that the effect of fertilisation in the CON treatment extended the phenological phases, showing higher photosynthetic activity and total nitrogen content than in the ORGs. The NBI data did not identify a substantial and stable difference between the theses during the two monitoring years. This result may be explained by the plant's ability to manage nitrogen, as the uniform course of the three theses suggests that crop management did not affect leaf nitrogen uptake and management. It is important to note that the ORG-I and ORG-II management types can be compared with the CON during the first and second years of monitoring, respectively. This similarity is particularly evident during the winter period (December–January), i.e., at the crucial time of harvesting. It could suggest variable nitrogen management in the two ORG theses, depending on soil conditions and the availability of productive soil inputs, particularly due to the drier weather trend in the 2019–2020 season. This result was also observed for stress and flavonoid indices, which continued regularly in the three management types throughout the monitoring period, except peaking at higher values for the two organic management types than the CON one on the last monitoring day in 2020.

The BRR-FRF stress index trend significantly reflected the decline of the artichoke cycle, particularly in the ORG management, showing higher values in the cycle ending, while the chlorophyll and nitrogen indices showed decreasing values. The lower BRR-FRF and FLAV values in the CON thesis over the two seasons suggest that CON plants managed to extend their vegetative cycle, compared to the organic theses.

The MFA sensor and associated indices proved to be efficient tools for monitoring the physiological status of artichoke plants, revealing statistically significant differences among the three crop management systems. The non-destructive methods agree with existing literature, confirming that the assessment of physiological variables in fruits and vegetables is highly correlated with conventional destructive analysis methods [43]. This finding underscores the potential of non-destructive sensors in horticulture, enabling timely and targeted agronomic interventions through spatial and temporal management.

According to Kim et al. (2022) [44], integrating proximal and remote sensing techniques, such as using a fluorometer in combination with a UAS-mounted NIR sensor, can be a valuable approach for crop monitoring and management, provided proper calibration within the experimental design. However, in this experiment, the UAS-based aerial analysis did not reveal significant differences between the plots. This suggests a lower sensitivity of the UAS in detecting variations among the different management types, making its performance less comparable to that of the MFA. A first consideration is that the application of the UAS was conducted only in the second year of monitoring, reducing the possibility of detecting a significant difference between the three management types throughout the

two-year experiment. As shown in Figure 9, NDVI values remained similar between treatments, following the same trend until the end of the analysis. Additionally, remote sensing measurements from UAS captured the entire plant, unlike the MFA survey method, which focused exclusively on leaves. By including all leaves and flower heads, UAS altered the NDVI values of representative leaves in monitored plants [45]. This highlights the broader function of the NDVI index, which serves as a general measure of vegetative vigour and should be considered differently depending on the research conducted. Another consideration for UAS monitoring is based on the multitemporal survey during the artichoke growth cycle, as the NDVI data were collected when the artichoke had already reached the vegetative and reproductive growth peak. Since important differences were observed in the early stages, one or more overflights in the early stages of the cycle would have helped to reinforce the UAS observations, possibly in support of additional vegetation indices to obtain a more complete view of the progress of the three treatments. Furthermore, the UAS was only used for a few months during the two-year experiment, so a more complete trend could not be followed as in the case of the MFA. Over the temporal limitation, another aspect has to be considered. The experiment, therefore, was conducted at a single site, where the pedological and climatic conditions play an important role in physiological development and the respective fluorimetric response.

Overall, the MFA system was able to distinguish the CON thesis from the ORGs during the survey period. However, proximal monitoring does not offer significant advantages in speed and convenience, as it requires the operator to spend several hours performing the monitoring. Additionally, to ensure reliable results, more than a thousand singular measurements with the MFA are provided to achieve a sufficient sample size. Furthermore, the MFA's interaction window should always be occupied by the sample to avoid interference from external elements, such as impurities, weeds, etc., which could lead to inaccurate readings of the physiological parameters. Due to these operational requirements, the MFA analysis can be employed as a high-performance sensor for conducting site-specific field investigations, following an initial crop assessment using an alternative wide-range system analysis.

5. Conclusions

The MFA showed a significant characterisation of plant physiology between the three crop management types analysed. The parameters of chlorophyll, stress, flavonoids, and, to a limited extent, nitrogen were adequate to observe the progression of the various theses throughout the entire crop season. The statistical analysis showed that the fluorimetric indices systematically correlated with the chlorophyll content over the two years between the ORG-I and ORG-II theses, suggesting a homogeneous trend, as indicated by the low significance value of the Tukey test. The different performance of the NDVI compared to the fluorimetric indices suggests that two high-performance instruments, such as the UAS and the MFA, do not always provide comparable results, as has been observed in other research contexts [46], as they perceive the vegetative characteristics of the crop differently. Consequently, the UAS cannot replace proximal sensing monitoring techniques for evaluating physiological differences in artichoke management. Future research activities will focus on characterising the fluorimetric indices provided by the MFA with the quantitative values of chlorophyll, nitrogen, and flavonoids to construct the respective agronomic calibration curves by correlating the indices obtained from the MFA with their equivalent quantitative values. This correlation, associated with crop control and the management of production inputs, could provide a valuable monitoring and decision-support tool for field operators to better control the main physiological characteristics of the artichoke, ultimately enhancing precision in cultivation management and input optimisation. The integration of advanced technologies, such as multi-sensor systems combining thermal imaging, hyperspectral data,

and LiDAR, can capture a more comprehensive physiological and structural profile of the crop. These approaches could contribute to the development of more precise, repeatable, and immediate decision-support tools for the sustainable management of artichoke cultivation. Future research activities on artichoke management will also consider different fields and agroclimatic conditions to test and validate proximal and remote sensing applications through a longer multitemporal analysis, examining the responses from the two approaches during all the artichoke stages.

Author Contributions: Conceptualisation, F.G. and L.L.; methodology, A.D., M.T.T., F.G. and A.S.; software, A.D.; validation, A.D., A.S. and L.G.; formal analysis, A.D.; investigation, A.D. and A.S.; resources, F.G.; data curation, A.D. and A.S.; writing—original draft preparation, A.D.; writing—review and editing, A.S., F.G., P.A.D. and M.C.; visualization, A.D., A.S. and F.G.; supervision, F.G. and L.L.; project administration, F.G. and L.L.; funding acquisition, F.G. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Advanced Technologies for LANDs management and Tools for Innovative Development of an EcoSustainable agriculture, ATLANTIDE (CUP J88D20000070002). This project has received funding from the “Regione Autonoma della Sardegna” (RAS) by “Progetti di Ricerca e Sviluppo (R&S)”, and this work is part of the activities of the project “ATLANTIDE”, topic of Work Package 7. This research is also supported by Project RESTART FSC 2014-2020 (CUP D66C18000260002), and Project PEROLACRU PSR 16.1 (CUP H82E20000070006) funded by the Autonomous Region of Sardinia.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGL	above ground level
ANOVA	analysis of variance
BBCH	Biologische Bundesanstalt, Bundessortenamt, and CHemical industry
BRR-FRF	blue-green to far-red fluorescence ratio
CHM	canopy height model
CON	conventional management
DOY	day of year
DSS	decision support system
FLAV	flavonol
MFA	multiplex force-A
NBI-G	nitrogen balance index on green excitation channel
NBI-R	nitrogen balance index on red excitation channel
NDVI	normalised difference vegetation index
ORG-I	organic annual management
ORG-II	organic biennial management
PA	precision agriculture
PPP	plant protection product
SFR-G	sample fluorescence emission ratio on green excitation channel
SFR-R	sample fluorescence emission ratio on red excitation channel
UAS	unmanned aerial system

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