water

Article

Technological Innovation in the Traditional Olive Orchard Management: Advances and Opportunities to the Northeastern Region of Portugal

Carlos Silveira [1,2,*], Arlindo Almeida [1,2] and António C. Ribeiro [1,2]

[1] Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
[2] Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
* Correspondence: carlos.silveira@ipb.pt; Tel.: +351-273-303382

Abstract: In Portugal, the olive orchard is the most representative agricultural crop and one of the most impactful on the national economy. Therefore, a production structure accompanying the technological advances in this field would be expected; however, such a structure has not yet been realized, especially within traditional systems. Thus, taking northeastern Portugal as a case study, where a great expression of traditional orchards is visible, the following aspects are addressed within this paper: the region's biophysical framework, the olive orchard's environmental and socio-economic importance and its current management practices and associated pressures. As a result of that assessment, which demonstrates a low level of sustainability for traditional olive orchards, mainly in terms of economic viability, the most effective and simple solution is to act appropriately on factors that interfere with the crop yield, namely, irrigation and fertilization issues. With that purpose, a multiscale precision oliviculture system is also presented that is being developed in order to support decision making in traditional olive orchard management, aiming to obtain economically efficient productions based on eco-friendly cultural practices. Throughout the entire process, it is essential to ensure stakeholder engagement, in particular, olive growers, so that they recognize the effectiveness of potential measures that may avoid the reconversion/abandonment of the traditional olive production system.

Keywords: Trás-os-Montes region; traditional olive orchard; management practices; crop yields; precision oliviculture system; sustainability

Citation: Silveira, C.; Almeida, A.; Ribeiro, A.C. Technological Innovation in the Traditional Olive Orchard Management: Advances and Opportunities to the Northeastern Region of Portugal. *Water* **2022**, *14*, 4081. https://doi.org/10.3390/w14244081

Academic Editors: Nuno Conceição and Guido D'Urso

Received: 15 November 2022
Accepted: 12 December 2022
Published: 14 December 2022

1. Introduction

Given the exponential growth of the world population and technological evolution in recent decades, allied to the concern of environmental sustainability, agriculture is confronted with the societal challenges of increasing food production and improving efficiency in the use of resources (e.g., soil, machinery, manpower) and production factors (e.g., water, fertilizers, agrochemicals). In turn, the high levels of productivity at the optimal minimum cost, as well as the added value of expected product quality, will contribute to maximizing the farm profitability, considering lower environmental impacts per harvested product unit [1–4]. As a response to these emerging issues, the concept of precision farming arises, which consists of using high-tech hardware and software to improve the agricultural sector's competitiveness, thus contributing to monitor, assess and act under the biophysical environment, taking into account spatio-temporal changes from the soil–plant system and the specific needs of each crop. Among the analysed biophysical indicators, particular emphasis has been placed on productivity mapping, since it is the visible result of the entire cultural calendar, and product sales will be the key to assessing the degree of profitability of the production system [5–9].

Concerning these technological innovations, the conjuncture for their use in precision farming is threefold: (i) data collection and regional or in situ monitoring; (ii) integration and data analysis; and (iii) materializing the field activities. For data collection and monitoring purposes, valuable sources of historical, current and static data (e.g., climatological series, land use maps and digital elevation models) and earth observations obtained from field sensors and satellites have been widely adopted to cover multiple scales and applications. In the remote sensing domain for the use in agriculture, vegetation indices and evapotranspiration mapping have been the most investigated drivers in terms of productivity and irrigation water management (e.g., [10–14]). In order to implement the prescribed field activities, variable rate technologies (VRT) combined with global positioning systems (GPSs) have been used for the differentiated and localized application of production factors. However, due to the high cost of VRT controllers, field activities are often implemented using only GPS technology. GPS guidance systems enable a homogeneous agricultural management throughout the area of interest.

Regarding its applicability, the option for this smart agriculture schedule is relatively well disseminated worldwide, with the first developments in the 1990s, when GPSs became available for civilian use. Such high tech-assisted agricultural practices are especially referenced in arable and horticultural crops, where greater effectiveness and increasing economic returns are expected, thus amortizing the investment in equipment, training, technical support, labour, etc. [7,8]. More recently, precision farming has also expanded to woody crops, such as fruit trees, vineyards and olive orchards (e.g., [15,16]).

The olive orchard is one of the most important crops in the Mediterranean, a region characterized by an arid and semi-arid climate with low water availability and reduced soil fertility; these are the main limiting factors of agricultural production. On the other hand, the olive tree (*Olea europaea* L.) is considered resistant to drought and is nutritionally undemanding [4]. This evidence is particularly associated with traditional olive orchards under a rainfed regime (Figure 1), which typically have a low density of trees per hectare and are poorly managed regarding the use of production factors and technological resources, given the farm's structural limitations (e.g., small size, orography and soil type) and the low levels of profitability associated with the production system. However, it remains the most widespread olive production system [4,12,13,17].

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

Figure 1. Traditional olive orchards in northeastern Portugal with (**a**) tilled soil and (**b**) cover crops between planting rows controlled by mowing or herbicides to reduce the olive tree–cover crop competition for soil water (photographs taken in spring).

Despite the advantages in using precision tools to support agricultural management, optimising processes and consumptions, there are still several constraints to their employability. Firstly, the high cost of these technologies and in rehabilitating or modernizing farm infrastructures and equipment (e.g., irrigation systems, machinery) are probably the main obstacles, given the uncertainty in recovering the investment (i.e., without a priori performance guarantees). Beyond the costs, the difficult and slow adaptation to the technological advances is closely linked to other factors, namely: (i) the inherent complexity of these technologies; (ii) the lack of training and technical knowledge of farmers; (iii) the communication, not always clear and easy, involving the governmental entities, associations and the farmers themselves; (iv) the reduced ownership structure; and (v) the spatial and temporal variabilities when mapping the crop's vigour/productivity can present an extremely heterogeneous and random pattern that makes the farm management unfeasible.

Based on this overall framework for the thematics of precision farming, some less-explored research topics are addressed here: (i) the target crop is the olive tree, whose spatial variability of its vigour/productivity using precision technologies has been poorly studied; (ii) within the olive orchard, the focus is the traditional production system mostly conducted under a rainfed regime; therefore, issues related to irrigation and fertilization in order to sustainably improve the productivity should be a priority; and (iii) moving the experiments from agricultural plots (local scale) to a regional dimension, the administrative unit from which many policy decisions are taken. Thereby, after characterization of the reference situation, the main objective is to present a precision farming system that is being developed at the Polytechnic Institute of Bragança, oriented in close collaboration with the stakeholders for the sustainable and cost-effective management of the traditional olive orchard in northeastern Portugal. To reach this goal, the following specific points should be fulfilled:

- To develop a multiscale precision oliviculture system that is able to describe the historical and current biophysical environment and to provide potential eco-friendly cultural recommendations for enhancing the crop yield and quality of its products (olive oil and table olives);
- To apply and assess the system with high spatial and temporal resolutions for particular case studies (i.e., olive plot scale and seasonal monitoring);
- To group the monitored plots when moving from local to regional scales taking into account similar environmental and agronomic characteristics, in order to design deterministic models under unsampled olive growing areas by relating the spatial variability of the target biophysical parameters (explanatory variables) with productivity mapping (dependent variable);
- To produce prescription maps based on integrative analyses of system outcomes to support decision making in traditional olive orchard management activities, focusing on fertilizers and water-use optimisation at the lowest possible cost and while respecting the environment.

The work is organized as follows. Section 2 presents a characterisation of the traditional olive orchard in northeastern Portugal, concerning the biophysical determinants, its environmental and socio-economic importance, and customary management practices and associated pressures. The design of the ongoing multiscale precision oliviculture system and potential simplified cost-effective measures for sustainable irrigation and fertilization management, engaging stakeholders at all stages, is exposed and discussed in Section 3. Finally, the main conclusions are presented in Section 4.

2. Characterization of the Traditional Olive Orchard in Northeastern Portugal

In Portugal, according to the latest Agricultural Census 2019 [18], the olive orchard is the permanent crop present in the largest number of farms (129.8 thousand) and with a greater agricultural surface (377 thousand hectares), intended primarily for olive oil production (98.9%). Within the traditional system, low-density olive orchards cover an area of 138 thousand hectares (37% of the total olive orchard area), with greater expression in the Trás-os-Montes (TM) and Beira Interior regions. Nevertheless, it suffered a decrease of 11% compared with the 2009 census. Focusing on northeastern Portugal, the characterization hereinafter presented for traditional olive orchards corresponds to the TM region, an administrative unit (NUTS III) that largely integrates this broad territory (Figure 2).

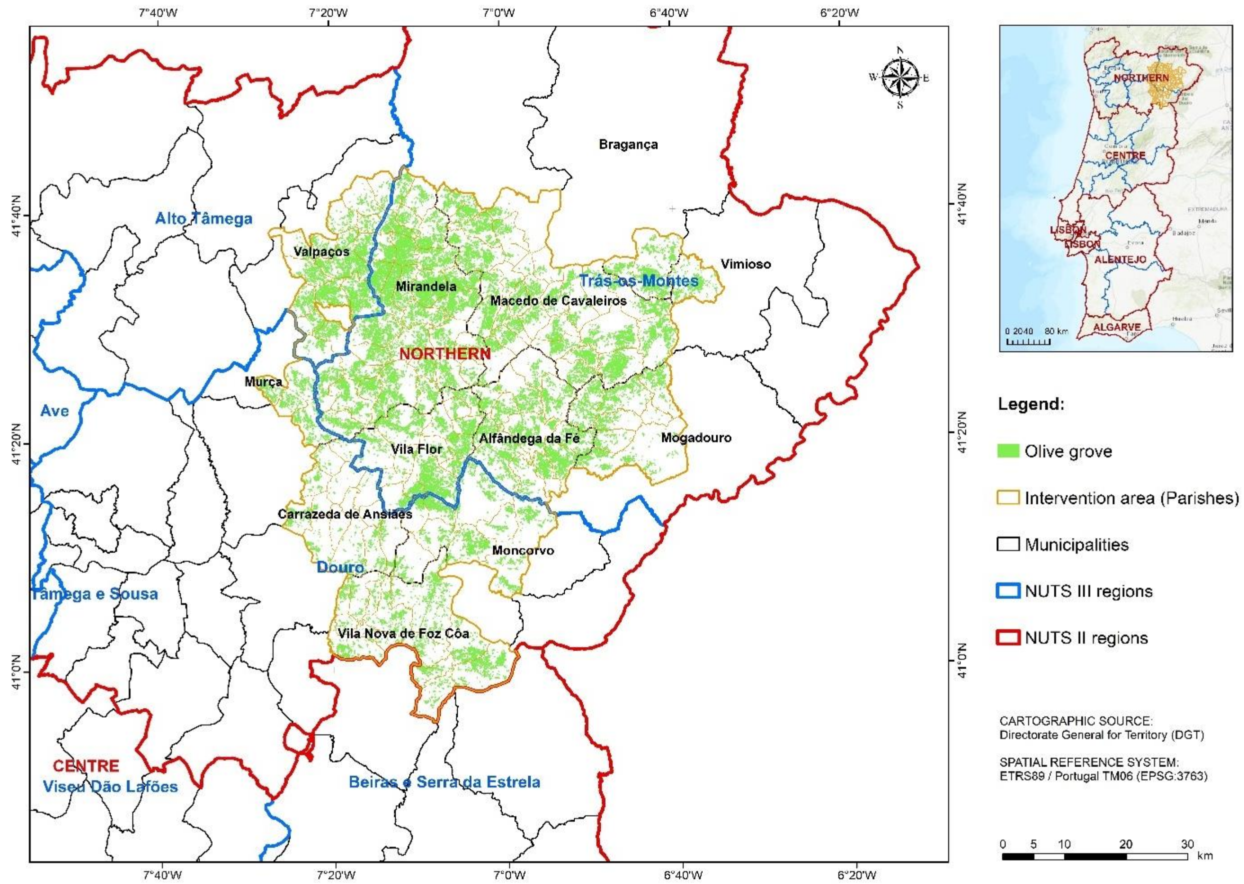


Figure 2. Geographic framework of the Trás-os-Montes olive region (source: A Land Cover/Use Map of Mainland Portugal for 2018 [19]).

The TM olive region is managed almost entirely as a traditional system oriented towards the limited production of the "Azeite de Trás-os-Montes", a Portuguese Protected Denomination of Origin (PDO) for olive oil [20]. PDO labels have been attributed to reward regional endogenous products based on specific varieties, production processes and quality requirements. In the case of olive oils, PDO labelling requires that their production complies with the stipulated specifications concerning the target olive cultivars, harvesting, transport and labouring conditions, chemical and sensory characteristics of the final product, and legal requirements to be marketed [20,21]. To achieve the status of PDO olive oil, the local cultivars Cobrançosa, Cordovil, Madural and Verdeal Transmontana, which spatially cover the entire intervention area, have been preserved. The production system is predominantly extensive under a rainfed regime, in orchards with densities typically between 100 and 240 trees per hectare, with a high number of centenary olive trees. Such longevity, depending on each olive cultivar, is largely related to its adaptability to local environmental conditions and resistance to biotic and abiotic stresses, such as droughts, extreme temperatures and the occurrence of plant pests and diseases [22,23].

The orography of this region is highly diversified (Figure 3; 66–1261 m altitude above sea level), contributing significantly to variations under the local climate and soil formation and, consequently, in the plant physiology. Deep valleys are associated with a dense hydrographic network, where the Douro River, the third-longest river of the Iberian Peninsula, and its major tributaries, namely, the Sabor, Tua, Tâmega and Coa rivers, stand out. On the other hand, the nuances of the terrain relief broadly determine the olive orchard's geographic distribution. Its spatial location is visible at altitudes up to 600 m and on a wide range of slopes. However, a large majority of olive-growing areas have a gentle-to-moderate slope, or even none [20].

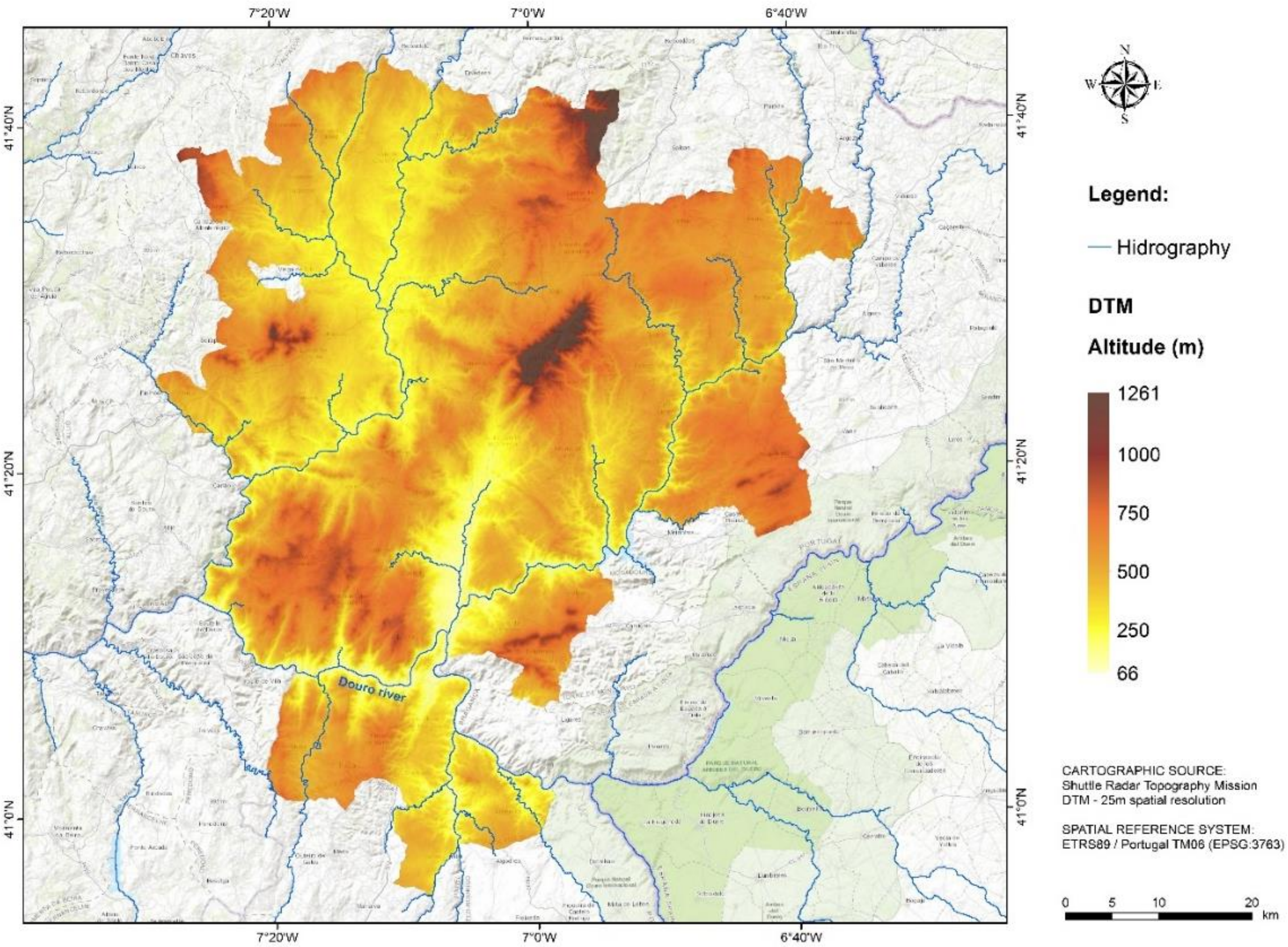


Figure 3. Altimetry (m) of the Trás-os-Montes olive region derived from a digital terrain model with 30 m spatial resolution (source: Shuttle Radar Topography Mission [24]).

With respect to the soils, according to the TM soil map [25], eutric lithosols associated with luvisols prevail, along with some classes of cambisols (I-L-B type FAO-Unesco cartographic representation [26]). Both soil groups, lithosols and cambisols, hold soils with incipient soil formation, i.e., poorly developed and with low organic matter content, and are characteristic of hilly and mountainous areas. From a climatic point of view, the region has a temperate Mediterranean climate with a continental influence, which depends on the atmospheric circulation over the ocean–continent transition zone (CSa-type Köppen–Geiger climate classification [27]). According to 30 years of average climatological normal data (1971–2000) recorded in the Mirandela meteorological station (41°31′ N, 7°12′ W, 250 m altitude), the monthly mean temperature ranges from 1.2 °C in January to 31.8 °C in July and August, whereas the monthly mean precipitation rose from 13.4 mm in August to 72 mm in December (Figure 4), representing an annual average rainfall of 508.6 mm [28].

From a socio-economic perspective, the traditional olive orchard is often seen as having low levels of productivity and profitability; hence, in many regions, it is being progressively replaced by intensive and even super-intensive systems (densities above 300 trees per hectare) [18,21,29]. Nevertheless, traditional orchards still have a wide geographic coverage, given their primordial multifunctional role in preserving the identity and traits of a region. Additionally, due to the use of low-input factors, such as fertilizers, water and energy, and consequent reduction in management operations, their maintenance results in a lower environmental impact than the intensive ones [30,31]. In addition, especially on sloping lands, the olive orchard is maintained with natural vegetation or arranged in small terraces. This common practice contributes to increases in both biodiversity and soil conservation, preventing worrying rates of soil erosion. Indirectly, both natural and cultural heritage could be potentiated through agro-ecotourism [2,21,32,33].

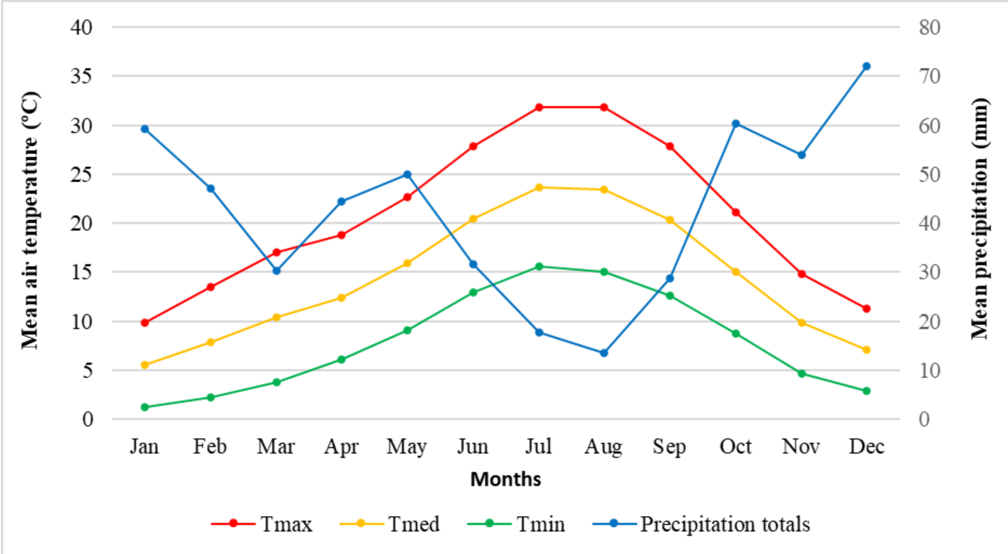


Figure 4. Mean of monthly maximum (Tmax), average (Tmed) and minimum (Tmin) air temperature (°C) and average value of the monthly precipitation totals (mm) recorded in the Mirandela meteorological station (41°31′ N, 7°12′ W) during the period 1971–2000 (source: IPMA—Portuguese Institute for Sea and Atmosphere [28]).

Beyond the relatively low levels of productivity, the reduced farm size is another factor that contributes to the unsustainability of the traditional production system [21,34]. This evidence, somehow, translates the 2019 agricultural census results reported for the TM region, indicating a total standard production value (TSPV) three times below the national average; however, in general, the number of farms and the usable agricultural area have increased by 5.5% and 4.1%, respectively, compared with the 2009 census. TSPV measures the produced quantity based on sales, reflecting stock variations through the transaction of goods and services [18].

Despite the farm's productivity and structural limitations, important economic returns associated with the traditional production system should be highlighted: (i) it is a significant source of income and employment for residents of these rural areas, in particular, for the population fraction that is economically dependent on these agricultural activities; (ii) the excellence of the PDO olive oil allows the olive growers to obtain a better market price, improving the farm profitability (i.e., by overcoming the production costs); and (iii) beyond their incomes from direct production, the olive growers are looking for other economic benefits by offering landscape and social uses [17,21,33,35].

In terms of traditional olive orchard management, semi-mechanized and conventional agricultural practices covering the different cropping phases are adopted. These cultural practices are closely related to the region's biophysical characteristics, such as orography, climate and soil, and take into consideration the evaluation of field measurements (e.g., plant nutritional status, soil water availability). In turn, the environmental impact resulting from the implementation of such practices will depend on the existing biophysical framework [21,31,33,36].

Following the cropping scheme, the traditional olive orchard management practices described below have been implemented in the study region:

Soil Management

This step has been oriented to ensure the productivity and survival of the olive orchard under highly variable and limited environmental conditions. With this purpose, the olive growers seek to adjust the type and number of farm operations according to the terrain characteristics. On hilly and mountainous areas, the most common practice is reduced soil management maintaining cover crops (e.g., natural vegetation, cereals, leguminous) in order to protect against soil erosion, reduce leaching losses of nutrients and improve the soil water holding capacity. Cover crops are often controlled by mowing or herbicides in spring to reduce the olive tree–cover crop competition for soil water. The cut weeds and other agricultural residues are normally left under the surface of the soil (i.e., applying mulching techniques), serving as a protective barrier and a source of nutrients. On the other hand, the implementation of these soil conservation practices brings environmental benefits, since by improving the soil's properties, an enrichment in biodiversity is expected, contributing to increases in the carbon sequestration capacity, and thus mitigating the potential effects of climate change [17,37–41].

Irrigation

As previously mentioned, the traditional olive orchard has been predominantly explored in extensive and rainfed regimes, where a 7 m × 7 m or wider spacing among olive trees (i.e., low water competition) and their high drought tolerance make the need to have the water supply meet potential plant needs a non-priority issue for the vast majority of the farmers, although they recognize that irrigation considerably increases productivity. This view is reinforced by including the implementation and operational costs associated with irrigation systems. When irrigation is applied to olive orchards, the water is supplied from different region's watersheds (e.g., Douro River tributaries, Azibo reservoir), often using the drip irrigation technique. In many cases, irrigation is also combined with fertilization, known as the fertigation method, which aims to incorporate the needed nutrients for the crop through the irrigation water.

Fertilization

Besides the fertigation and incorporation of agricultural residues under the soil surface, the application of other fertilizers to soils is also carried out using animal manure and/or solid inorganic compounds. In chemical terms, the fertilization stage, focused primarily on the main macronutrients (nitrogen—N, phosphorus—P, potassium—K), is usually supported by the result of soil and foliar analyses, which indicate the suitable amount and proportions to apply at the right time. As a general rule, the nutrients should be available in the soil when the plant restarts its physiological activity. Thus, given the high unpredictability of the Mediterranean climate, in traditional olive orchards, fertilization normally occurs in early spring, since the risk of nutrient loss through leaching is reduced and the possibility of the nutrients being efficiently absorbed during vegetative growth is high.

Phytosanitary Treatments

In this domain, the European Directive no. 2009/128/EC of 21 October 2009 established a legal framework for the sustainable use of phytopharmaceuticals, aiming to reduce risks and side-effects of their use on both human health and the environment by promoting the option for integrated protection/production techniques or non-chemical alternatives to pesticides. Nevertheless, olive trees are among the least demanding crops with regard to the application of phytopharmaceutical products, and those used present a low hazard level [4,17,36]. These facts reflect the crop's low weight in the national market of phytopharmaceuticals, even more so in agricultural crops with the largest implementation area in Portugal.

Pruning

Pruning operations are normally biennial and are performed manually, with the pruned material usually being burned; this method takes advantage of the thicker branches for use in residential heating. Regarding both the time taken for pruning and its intensity, this cultural practice is carried out after the harvesting in light-to-moderate regimes in order to favour the fruit yield and quality, and to ensure the survival of the olive trees during drought periods, since water requirements will be further reduced [2,4,21].

Harvesting

The olive harvesting occurs between October and December by semi-mechanized means using manual and mechanical canopy beaters and/or trunk shakers. The typical farm structure, namely, its small size, the low density of trees and their spatial arrangement, and the terrain relief nuances, are aspects that can somehow discourage the bet in more mechanized harvesting. In addition, it is widely proven that the harvesting method and the remaining procedure for olive oil production, from storage to transport and fruit processing, are determinant factors for olive oil quality with respect to acidity and peroxide values [21,30,42–44]. In this sense, the fact that the TM olive region produces olive oil with PDO labelling means that the entire production process meticulously complies with the regulated specifications.

Analysing the associated pressures, namely, the low economic sustainability associated with traditional systems compared with intensive ones, it can be seen that this is the main reason behind the abandonment of many olive-growing areas across the world; even so, such an alarming scenario is not yet visible in the TM region. However, if there are no concerted innovative strategies for the maintenance of this olive growing territory, the abandonment also tends to be a reality. Besides the low productivity and restricted structural features (e.g., small and slopping farms, low density of trees, nutrient-poor soils, no irrigation), according to the national census, 97.1% of the farms belong to individual agricultural producers. Moreover, for the TM region in particular, the average age of farmers increased from 59 to 65 years in the period of 1999–2019 [18]. As a consequence of land abandonment, an increase in fire risk and deep changes in the Mediterranean traditional landscape mosaic will be expected [21,33,45]. This idea is reinforced when considering climate change projections performed by Ascenso et al. (2021) [46] for the study region and its surroundings. For future mid-term (2049 and 2064) and long-term (2096 and 2097) scenarios, the authors point out an increase in the air temperature and intensity/frequency of heatwaves in summer, leading to a decrease in precipitation, and an increasing number of consecutive dry days during that season. Given these projections, the region's climate tends to be warmer and drier, incisively contributing to a decrease in soil water availability, which is the major limiting factor for olive production under rainfed conditions. Accordingly, this water stress can also affect the soil chemical, physical and biological properties essential for plant health. One of the most noticeable drought effects is the reduction in stomatal conductance decreasing carbon assimilation (and transpiration flux) by the plants. Another concern is related to the increase in the soil temperature, which negatively impacts microbial activity in processing nutrients to be assimilated by the plant.

3. Challenges for Improving the Traditional Olive Orchard Sustainability

Once we identified the importance of traditional olive orchards for the TM region and the usual management practices, it was intended to enhance the positive aspects, namely, how to maintain the superior quality of the olive oil (PDO) and low environmental impacts, and present innovative solutions for minimizing the main pressures, which are mainly focused on productivity issues. To that end, in this section an ongoing multiscale precision oliviculture system is designed, along with potential simplified cost-effective strategies for irrigation and fertilization management, and the role of the stakeholders is detailed in two ways: understanding their perceptions, and when implementing the prescribed field activities.

3.1. Development of a Precision Oliviculture System

The transition from the low-resource traditional management model to an integrated and sustainable system, which takes advantage of the available precision technologies and offers the best trade-off between economic and environmental concerns, is being designed for the TM olive region. Thereby, the precision oliviculture system should provide eco-friendly cultural recommendations, i.e., based on optimal amounts of water and fertilizers to be supplied, which ensure an increased and constant annual production, economically persuading the olive growers and young farmers to remain the activity and thus avoid land abandonment. As a starting point, a better understanding of the soil water dynamics optimising the water supply and the fertilization program with the resource to specific and efficient machinery/equipment should be the priorities for cost-effective management of rainfed traditional olive orchards.

The core of the precision system is composed of three modules that are structured as follows (Figure 5):

(i). INPUT DATA—The acquisition, integration, processing and analysis of input data using remote sensing, geographic information systems (GIS) and GPS technologies and ground-based measurements to know and explain both the spatial- and temporal-level crop variability.
(ii). AUTOMATION—The creation of GIS geoprocessing sequences and programming tools/scripts to automate the treatment of the input data, guiding the outcomes to the responses to be given by the system. Lastly, the system will be operationalized as a whole to reproduce local-to-regional scale results that support the decision-making.
(iii). OPERATION—The operationalisation of field activities based on prescription maps (responses) using, if feasible, advanced agricultural machinery in the different cropping phases to increase the field efficiency and capacity.

More details about the methodologies and precision tools to be adopted within each module are exposed in the following sections.

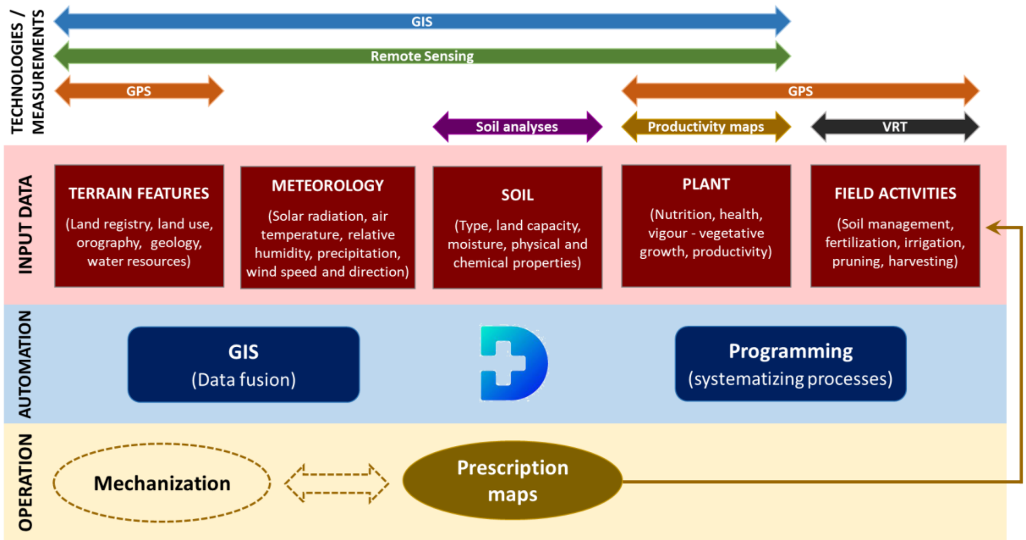


Figure 5. Architecture of the precision oliviculture system that includes the technologies/measurements to be used, input data required, automating the information flow, and operationalising the field activities.

3.1.1. Selecting and Processing the Input Data

As a first step, the survey and processing of biophysical parameters that may influence and/or infer on the productivity of the olive orchard and quality of its products were carried out. These parameters can vary in space and time (e.g., soil moisture, plant vigour); alternatively, only one dimension is relevant (e.g., orography in space and solar radiation in time). Hence, the spatiotemporal analysis is dependent on the variable type. To perform this comprehensive analysis, a remote sensing and GIS-assisted approach to describe local-to-regional scale variations and their temporal evolution has been followed.

From a methodological point of view, at the plot level (local scale), vegetation products derived from aerial images using unmanned aerial vehicles (UAVs), commonly known as drones, and field measurements, have been designed. Regarding the adopted UAV technology, the multirotor drone DJI Matrice 300 RTK [47], to which it was coupled a multispectral camera MicaSense RedEdge-MX covering 5 high-resolution (8 cm per pixel at 120 m above ground level) narrow spectral bands (Table 1) [48], have been used to monitor the selected olive plots. The resulting aerial images are then photogrammetrically processed using the software Agisoft Metashape Professional version 1.8.3 to build orthomosaics using spectral bands and digital elevation models (DEMs) derived from 3D-point clouds. The main vegetation indices (VI) that could be calculated from these spectral bands are presented in Appendix A. For a broader temporal and geographic coverage (regional scale), satellite data and meteorological observations from the Portuguese monitoring network have been compiled. In addition, a comparative analysis involving satellite data and orthorectified mosaics derived from UAV aerial images will be performed. The aim is to evaluate the possibility of using satellite data at the plot level, thus increasing the range of available information (e.g., wider spectral coverage), which could be very useful in gaining more effective support for olive orchard monitoring.

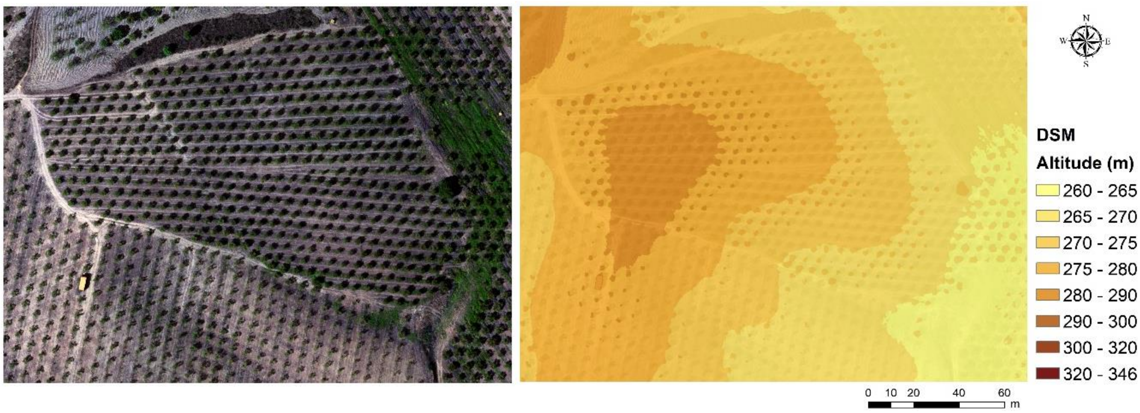
Table 1. Spectral bands covered from the camera MicaSense, model RedEdge-MX (source: MicaSense [48]).

Spectral Band	Central (nm)	Bandwidth (nm)
Blue	475	32
Green	560	27
Red	668	16
Red-Edge (RE)	717	12
Near-Infrared (NIR)	842	57

A brief description by system's input data category and some preliminary results at the plot level are presented below:

Terrain Features

Knowing the terrain features, particularly its orography (elevation, slope and orientation), is crucial to understand local weather fluctuations and evaluate how the surface water flow is affected. For olive orchard productivity purposes, south-facing slopes and low altitudes are generally favourable due to higher levels of solar radiation and consequent rises in air temperature [4]. These topographic attributes are derived from DEM, which represent land surface elevations considering the natural and built environment (digital surface model—DSM), or simply the bare earth, i.e., without man-made features (digital terrain model—DTM). At a local scale, DEMs have been generated from high-resolution aerial images acquired by using the drone DJI Matrice 300 RTK coupled with the camera MicaSense RedEdge-MX (Figure 6).



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

Figure 6. (**a**) Orthomosaic and (**b**) digital surface model of an olive orchard plot (41°21′31″ N, 7°2′22″ W) obtained from monitoring with the drone DJI Matrice 300 RTK using a camera RedEdge-MX (8 cm spatial resolution).

Besides these terrain inputs, other thematic layers, such as land cover [19], geological and hydrographic maps and satellite data/products, have been used in a regional perspective. Remotely sensed data retrieved from the Sentinel-2 are preferably used, because this sensor provides wide spectral coverage (13 spectral bands ranging from 443 nm to 2190 nm) and high spatial resolution (10, 20 and 60 m) [49]. Low-level cloud cover or cloud-free satellite images with radiometric and geometric processing are selected.

Meteorology

Meteorological conditions are a key determinant for the crop yield, even overcoming the effect of the management practices. Overall, they greatly influence the soil properties and the plant growth and production processes, namely, the photosynthetic response, the evapotranspiration rate and crop water requirements [4]. Accordingly, for the existing olive cultivars in the study region, an in-depth assessment of the weather-productivity relationship is required. To this end, high-temporal resolution meteorological data collected from the Internet of Things (IoT) sensors and automatic weather monitoring stations located within the region are used.

Soils

Soils play a very important role in both the growth and productivity of crops, given their intrinsic and dynamic properties, by anchoring the plant roots and regulating water and nutrient supplies. Unlike many fruit tree crops, olive trees can be well established on calcareous soils; however, they can also thrive in moderately acidic soils, with pH levels varying between 5.5 and 8.5. However, olive trees benefit from near-neutrality values due to the increase in nutrient absorption capacity as a consequence of the higher soil microbial activity (i.e., accelerates the mineralization process) [4,32,50]. In terms of physical properties, the soil texture and depth are limiting factors of the olive tree's productive cycle, since they influence the soil water holding capacity, an effect that can be minimized through the implementation of cover crops and/or by adding organic matter. On the other hand, soil fertility management, in addition to contribute for improving the soil structure and crop yield, is advantageous to control the soil porosity, facilitate water and air transport, and reduce the plant competition for nutrients and water [4]. For these reasons, chemical and physical analyses in multiple sampling points of monitored plots should be performed to capture spatial variations of soil properties and relate to the crop yield.

Plant

To evaluate the vegetation characteristics, soil–plant–atmosphere (SPA) interactions should be well understood, namely, soil–meteorology relationships combined with water and nutrient uptake by plants, and the influence of these on the soil structure and weather forecasts. Focusing this assessment on the traditional olive orchard, the aim is to find out how the SPA system behaves in the face of current management practices. Thus, in the first phase, since the research is based on optimising the irrigation and fertilization schemes, particular emphasis has been given to mapping vegetation indices (VIs) and tree heights (Figure 7), and monitoring surface water and energy budgets. For the olive orchard, higher VI values of canopy reflectance are typically observed from January to April and then decrease until August–September, resuming an upward trend in the remaining months [22]. Posteriorly, these biophysical parameters together with tree biomass estimates (delineated from tree crown volume) will be crossed with productivity data in order to find potential statistical correlations that accurately identify how, when and where to act.

To complement the analysis of the plant physiological status, VIs should be combined with surface water and energy budgets, aiming to better understand how the hydrological cycle and the latent heat flux (ΔET) interfere with the crop phenology. Moreover, given the perspective of optimising irrigation management, an accurate estimation of the soil water storage (ΔS) will allow us to effectively know the available water resources and act according to the crop water requirements [10,12,13,29,51]. Equations (1) and (2) illustrate the simplified formulations for calculating ΔET and ΔS, respectively.

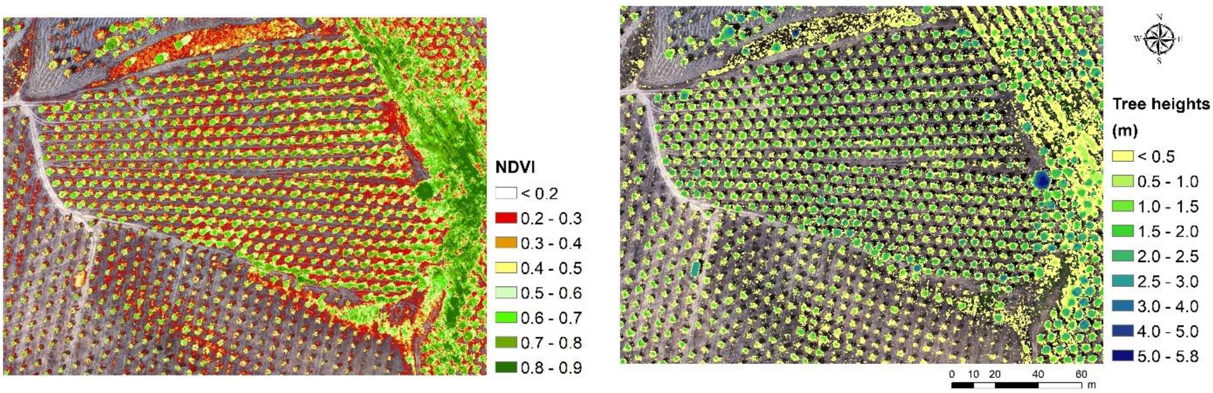
$$\lambda ET = R_n - H - G \tag{1}$$

$$\Delta S = I + P - ET \pm R \tag{2}$$

where

λET—Latent heat flux (energy consumed through evapotranspiration) [W·m^{-2}];
R_n—Net radiative flux [W·m^{-2}];
H—Sensible heat flux (energy convected from the surface to the air) [W·m^{-2}];
G—Soil heat flux (energy conducted to the soil) [W·m^{-2}];
ΔS—Soil water storage [mm];
I—Amount of water used for irrigation [mm];
P—Precipitation [mm];
ET—Evapotranspiration (includes bare soil evaporation and plant transpiration) [mm];
R—Surface runoff (amount of water entering or leaving the system by gravity) [mm].

These parameters can be measured or estimated using different methods and data sources, such as in situ measuring devices and meteorological and remote sensing observations. However, in this paper emphasis is given to the crop ET calculation under standard (ET_C) and non-standard/environmental conditions (ET_R). These ET values are often used to assess the amount of water to be supplied to the plant.



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

Figure 7. (**a**) Normalized difference vegetation index (NDVI) and (**b**) tree heights of an olive orchard plot (41°21′31″ N, 7°2′22″ W), derived from aerial images with the drone DJI Matrice 300 RTK using a camera RedEdge-MX (flight data: performed on 31 August 2021; 100 m altitude; 8 cm spatial resolution).

ET_C represents the latent heat flux density under optimum soil water conditions to the crops' full production, and its estimation results from the product between the reference ET (ET_0) and a standard crop coefficient (K_C). To determine the ET_0, the Penman–Monteith method recommended by the Food and Agriculture Organization (usually called the FAO56 method) [52], which has been widely accepted for estimating ET_0, will be applied.

Regarding K_C, measurements compiled from various olive growing regions show quite a wide range (0.50–0.75) with a recommended average K_C around 0.55–0.65, depending on the ET seasonal pattern, which is mainly based on two factors: green canopy cover fraction (measured through VI), and precipitation variability [11,14,22,29]. Thus, once VI values are mapped and seasonal rainfall patterns are known, efforts will be made to derive K_C coefficients for the studied olive orchards. This approach has been successfully implemented in other research works (e.g., [52,53]). Another possibility for crops' actual ET and/or K_C estimations is its derivation from surface energy balance models (Equation (1)), such as the mapping evapotranspiration at high resolution with internalized calibration (METRIC) and the surface energy balance algorithm for land (SEBAL), which are the most commonly used (e.g., [11,29,54,55]).

Following the general formulation ($ET = ET_0 \cdot K_C$) for actual ET estimation, denoted as ET_R, the K_C should be adjusted to the local environmental and cultivation conditions taking into account the crop, planting density and height. Thus, it is predictable that the ET_R may deviate from the ET_C (i.e., ET_R below ET_C), due to unfavourable environmental conditions (e.g., water scarcity, low soil fertility) that could negatively influence the crop yield [29]. As a complement to these methods, whenever possible, measuring devices should be used for point measurements of ET_R, which will serve to validate the produced ET estimates.

Field activities

Field activities are not properly input into the system; however, the way these relate to the other categories, in particular with the soil and the plant, allows us to measure their effectiveness for olive productivity and quality purposes. Thereby, as a starting point, the impact of the current management practices throughout the production cycle will be evaluated. If a deficit crop yield and/or soil degradation problems are identified, the causes may be in the underlying assessment to the other input datasets (e.g., occurrence of extreme weather events, soil water deficit, low soil fertility). In addition, this cross-analysis will help improve our understanding about the processes that lead to soil heterogeneity and plant physiological response. In such undesirable circumstances, following the general scheme of the precision oliviculture system, new cultural recommendations should be prescribed (Section 3.1.3).

3.1.2. Automatizing the Information Flow

After the input data module is duly consolidated and validated, a data fusion approach in the GIS platform that combines different types of software and geoprocessing and programming tools will be created to systematize and automate the data treatment at local and regional scales. Similarly, the system will be operationalized as a whole to support decision making, guiding the results to the responses required by the stakeholders.

In general outlines, the information flow at a local scale (i.e., plot level) is optimised as follows:

(i). Integration and processing of input data in GIS environment, creating geoprocessing sequences through GIS models (e.g., processing modeller in QGIS software) and R and Python-based programming scripts;

(ii). Spatial interpolation from sampling points (i.e., field measurement locations) using geostatistical extensions that allow the application of deterministic (e.g., IDW—Inverse Distance Weight) and geostatistical (e.g., kriging) methods and statistical analysis of the results (e.g., semivariograms). To enhance the resulting spatial pattern as well as the sampling frequency, reducing uncertainties, a smart sampling technique is being adopted. This technique aims to assess the plot's spatiotemporal variability when, for example, different olive cultivars and experimental treatments are present, in order to define the number of sampling points and frequency. More homogeneous areas require fewer points, whereas high heterogeneity means that a larger sampling density is essential to understand why so much variability. In sampling frequency terms, higher temporal variability justifies collecting a larger number of samples per unit of time;

(iii). Creation of typological relationships between geographic and alphanumeric data, when combining the GIS geodatabases' functionalities with Microsoft Access/Excel table's primary key fields. This Database Management System (DBMS) enables the edition of any information source, preserving the data integrity. Moreover, it is useful for managing a high data volume and when there are many potential end-users, since the theme-structured plot form can be easily consulted (e.g., owner—location—microclimate—soils—plant vigour—productivity—prescriptions).

When moving from local to regional scales, the following procedures are taken into account:

(i). Olive plots monitored from different geographic areas, but with similar environmental and agronomic characteristics, will be grouped to develop deterministic models. This will help to explain the spatial variability in the olive orchard productivity as a function of the analysed biophysical parameters (explanatory variables);
(ii). Multivariate regression analyses will be performed to determine the variables that best account for yield variability and find the best models for describing that variability;
(iii). The selected models will be standardized considering thresholds for the involved variables, aiming the application of the most appropriate ones under unsampled olive plots;
(iv). Beyond the olive yield prediction in non-monitored plots, regression models will be of utmost usefulness for optimising the olive production when playing with the explanatory variables;
(v). For validation of these estimates, real productivity data and literature values reported in other case studies will be used, as long as the crop is developed in similar edaphoclimatic conditions.

3.1.3. Operationalizing the Field Activities

According to the integrated data analysis to be performed from the local to regional scale and known the olive tree's cultural needs and its potential yield, where the actual production is limited, prescription maps will be prepared. In line with these agricultural prescriptions, for their implementation, the resource to precision machinery/equipment that improves the field efficiency and capacity will be encouraged, even more, given the TM region's labour shortages.

Agricultural prescriptions will be focused on optimising the irrigation and fertilization schemes in TM region's traditional olive orchards, taking advantage of the assessment of both field measurements (soil and foliar analyses) and remote sensing-derived products (e.g., VIs and ET). The aim is to apply water and fertilizers in the right locations, in exact doses and at opportune time, rationalizing the consumption of these production factors and, simultaneously, improving the productivity and quality of the final products (olive oil and table olives) in a sustainable way. To implement these prescriptions, especially for olive harvesting, the reinforcement of mechanization could be the key to ensure the survival and profitability improvement (i.e., work rate) of this production system, thus contributing to reduce production costs and increase the environmental efficiency (i.e., lower environmental impacts per harvested product unit). To this end, different technological alternatives to accomplish any agricultural operation should be analysed, considering technical, economic and environmental aspects.

3.2. Definition of Cost-Effective Management Strategies

Promoting knowledge and innovation in olive growing by adopting best sustainable practices and technologies requires a depth analysis of all chains of impact associated with potential changes in the production system. In this context, life cycle assessment (LCA) methodologies have been widely used and recommended for quantifying environmental, social and economic pressures [16,31,34,56]. In environmental terms, soil, water and air pollution problems, soil erosion, biodiversity losses and low energy efficiency are some negative impacts arising from field activities. From a social perspective, issues related to human health and well-being, employment, and local development have often been analysed. On the economic side, costs with labour, machinery, fuel, energy and production factors are often balanced with product sales.

Although, in the first phase, the elaboration of an LCA is not foreseen, cost-effective strategies proposed for sustainable irrigation (soil water) and fertilization management (i.e., maximizing the benefits at the lowest possible cost) as a result of the precision oliviculture system application will be based on LCA studies conducted from traditional olive production systems and in similar environmental conditions.

Irrigation is a relatively recent and not very widespread practice in olive growing, mainly in traditional systems, due to the fact that although it contributes to a significant improvement in productivity, it entails high production costs. Furthermore, the water availability for agricultural use is limited, as it is a scarce natural resource in Mediterranean regions. Accordingly, the implementation and/or operationalization of irrigation systems in traditional olive orchards should be oriented towards efficient water use management. With this purpose, the option for deficit irrigation at the right time, considering the crop water requirements (i.e., ET_C), is recommended. This methodology requires previous knowledge of the olive cultivar and soil water status, which depends on local weather conditions and soil water-holding characteristics. In physiological terms, according to Connor et al. (2014) and Fernández-Escobar et al. (2013) [4,17], the response of olive production to irrigation is linearly proportional for small increments of water, gradually decreasing as the water supply approaches the $\mathrm{ET_C}$. Thus, irrigation below the ET_C may be economically viable when balancing water costs and crop yield, and will allow appreciable water savings.

Nevertheless, for a successful evaluation, following the example of other research works, olive tree responses to different irrigation strategies should be analysed at different phenological stages. Over the period from 2006 to 2007, Ramos and Santos (2010) [12] demonstrated that sustained deficit irrigation regimes ensure high yield and considerable reduction in water consumption. In addition, the authors also experienced that olive trees respond differently to irrigation water and summer rainfall, but other environmental variables, such as radiation and temperature, also markedly influence the plant physiology due to stomatal conductance oscillations. Later, Santos (2018) [13] tested two deficit irrigation (DI) scenarios against full crop water, 50DI and 70DI, corresponding to 50% and 70% of the $ET_{C.}$. Both scenarios contributed to significant water savings with little impact on olive productivity. However, 50DI presented the highest water use efficiency, whereas 70DI was the most productive, being indicated as the preferred DI treatment for Cobrançosa orchards. In turn, full irrigation showed a decline in yield per amount of applied water.

From another perspective, irrigation should increasingly be combined with the use of treated wastewater (fertigation) aiming to: (i) save significant fertilizer amounts; (ii) reduce irrigation water volumes to combat the seasonal water scarcity; and (iii) minimize environmental impacts, otherwise, wastewater would likely be discharged into the environment.

Unlike the irrigation, fertilization is a common practice in olive growing to satisfy the crop's nutritional needs, which depend on the tree age, cultivar and production system [17,32,50]. Normally, it occurs when certain nutrients essential for plant growth are unavailable or in insufficient amount. Thereby, for sustainable and responsible fertilizer applications, a good diagnosis of the olive orchards' nutritional status and proper methods for its application are required.

The nutritional diagnosis is based on soil and foliar analyses that provide important fertilization recommendations to support the olive yield optimisation, tending to reduce production costs, obtain quality products, and minimize the environmental impact and incidence of insect pests when avoiding the excessive application of fertilizers, primarily nitrogen. The fertilization program should be annual and specific to the orchard where the analyses are carried out. In the case of rainfed olive orchards, the option for fertigation and foliar fertilization in small doses during most of the growing season may increase the nutrient use efficiency [4,17].

3.3. Stakeholder Engagement

The effective engagement of stakeholders, where olive growers, associations, research units, policymakers and consumers are included, is of utmost importance for developing, applying and assessing the designed precision oliviculture system. This connection with the society is being worked in two ways: understanding stakeholder's perceptions and through cost–benefit analyses of traditional olive orchard management strategies to be implemented.

When exploring perceptions of the various stakeholders, it is intended to improve the understanding about the concerns of the olive sector, particularly with regard to the traditional production system, in the sense of defining new pathways towards its sustainability. These social perceptions are evaluated following the Q-methodology fundamentals and SWOT (strengths, weaknesses, opportunities and threats) analysis.

Q-methodology is a systematic study of participants' feedback based on qualitative and quantitative analyses to investigate their opinions about possible weaknesses, areas to be improved and receptivity/acceptability to new proposals. The objective is to find sustainable and innovative solutions that can efficiently increase the crop production and economic return, satisfying the environmental protection requirements and market needs by providing a quality product at a fair price. In the perspective of policymakers, this methodology allows more coherent decisions with the local reality, facilitating the resolution of controversial issues in favour of common interests and successful governance [35]. SWOT analysis is also a strategic planning method that relies on the participation of stakeholders to identify the most important problems (weaknesses and threats) and potential solutions (strengths and opportunities) considering the main functions of the olive orchard: productive, ecological, economic and social [33].

In turn, the cost–benefit analysis aims to put into practice, or at least gather an overall net income estimation (Equation (3)) based on ideas/decisions taken together with the stakeholders, in order to determine the best management strategies enhancing the traditional olive orchard sustainability.

$$Net\ Income_f = \left(Sales_f - Production\ costs_f\right)/Area_f \tag{3}$$

For each farm f the net income comprises the earnings from the product sales (olive oil and table olives), to which fixed and variable production costs are subtracted, including the use of specific inputs (e.g., water, fertilizers) and machinery (operationalization, maintenance and rental), energy and fuel consumption, labour (own and hired), material depreciation, insurances, interest rates, overheads, among others. As a result, the net income is expressed per hectare, dividing by the olive orchard area.

In soil management operations focused on different olive production systems, De Luca et al. (2018) [16] mentioned other research studies where labour and fuel consumption were the major cost components. Conversely, mechanized olive harvesting is seen as the most economically sustainable solution, even in traditional olive orchard management. However, operating in hilly areas can result in more costly mechanization and lower yields [30,57].

Beyond the measurable production costs, intangible costs resulting from the implementation of cultural practices should also be considered, such as environmental impact, farmer's satisfaction degree, product quality and side effects on the local economy (e.g., employment, purchasing power, business branches, agrotourism, etc.).

4. Conclusions

Along with other agricultural crops, the olive sector is increasingly associated with the concept of sustainability. This issue is more challenging when the target is to ensure the economic viability of traditional production systems, although environmental protection criteria, such as soil conservation and biodiversity preservation, are largely achieved. Accordingly, the objective of this paper is to present a precision oliviculture system that is being designed and discussed with stakeholders, which takes advantage of technological innovation to become the more productive and profitable traditional olive orchard, seeking to maintain the superior quality of the olive oil (PDO) and low environmental impacts. However, regarding the adoption of precision technologies to support management activities, issues such as encouraging investment policies, farmers' training programs and concerted communication actions should be considered a priority.

From the point of view of cost-effective management strategies, part of the investment for modernizing the traditional olive orchard should be reflected in the expansion of irrigation infrastructures and, consequently, of the irrigated area. Nonetheless, it becomes essential to control and manage the water supply during the cultivation process by testing different irrigation regimes based on crop water requirements, as well as to assess its use efficiency, since this production factor has a high weight in the total production costs and, as mentioned, for agricultural purposes, the water availability is limited. In relation to fertilization, its management could be relatively simpler, due to the fact that fertilizer applications are normally in accordance with the nutrient needs discovered in soil and plant chemical analyses. In order to implement these recommendations or any other cultural operations, the use of appropriate techniques and the right timing are crucial to achieve an optimum production level, rationalize costs and produce environmental advantages.

Notwithstanding the promising challenges addressed here, these will have to be framed considering the observable and predicted effects of climate change; therefore, further efforts to ensure the short–medium-term sustainability of traditional olive orchards will be required. Thus, as a starting point, extensive and reliable agricultural databases that relate climate variability with productivity data in olive plots should be constructed, in order to capture specific effects of regional and local climates on the soils and crop yield. Afterwards, this preliminary analysis should be crossed with other explanatory variables (e.g., terrain orography, soil and olive cultivar types, tree age, current management practices) to comprehensively assess potential causes that could explain the existing spatiotemporal variability. Lastly, the upscaling to the regional scale will be carried out, allowing a broader view of the biophysical environment influence on the olive orchard productivity; however, it is also justified because many political decisions are often taken from this administrative level. To ensure the effectiveness of these policy options in traditional olive orchard management, it is essential that they take into account the concerns of all the agents involved, as well as the guidelines provided from the presented system applications.

Author Contributions: Conceptualization, C.S., A.A. and A.C.R.; methodology, C.S.; formal analysis, C.S., A.A. and A.C.R.; investigation, C.S.; writing—original draft preparation, C.S.; writing—review and editing, C.S., A.A. and A.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support through national funds FCT/MCTES (PIDDAC) to CIMO (UIDB/00690/2020 and UIDP/00690/2020) and SusTEC (LA/P/0007/2020). This work was carried out under the Project "OleaChain: Competências para a sustentabilidade e inovação da cadeia de valor do olival tradicional no Norte Interior de Portugal" (NORTE-06-3559-FSE-000188), an operation to hire highly qualified human resources, funded by NORTE 2020 through the European Social Fund (ESF).

Data Availability Statement: Not applicable.

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

Appendix A

Based on the spectral bands presented in Table 1, the following vegetation indices (VI) can be determined:

Appendix A.1. Normalized Difference Vegetation Index (NDVI)

Among the various VI, the NDVI is the classic and effective indicator in a first assessment about the plant physiological status, arising from spectral reflectance measurements in the NIR and red regions (Equation (A1)). NDVI results vary from -1 to 1, wherein negative values correspond to water bodies, rocks and artificial surfaces; conversely, positive values indicate the presence of vegetation. Healthier and dense vegetation (NDVI closer to 1) primarily reflects NIR radiation, unlike the visible red light, which is strongly absorbed (i.e., low reflectance) due to the high chlorophyll concentration in green plant leaves. In turn, sparse and non-vigorous vegetation presents NDVI values below 0.5. The NDVI is also effective in portraying canopy cover variations during early and mid-development stages and providing a high contrast between the vegetation and the soil [5,58].

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{A1}$$

Appendix A.2. Normalized Difference Red Edge (NDRE)

NDRE is an index similar to the NDVI, which can only be formulated when the RE band is available (Equation (A2)). However, it is more sensitive to high canopy density and leaf chlorophyll levels and in capturing soil background effects; thus,, that could be a better indicator of both vegetation health/vigour and fertilizer (nitrogen) requirements, especially for mid-to-late growth stages. Furthermore, the plant leaves are more translucent to RE light than red; hence, RE is probably less absorbed by the tree canopy [48].

$$NDRE = \frac{NIR - Red\ Edge}{NIR + Red\ Edge} \tag{A2}$$

Appendix A.3. Optimised Soil-Adjusted Vegetation Index (OSAVI)

OSAVI is an extension of the soil-adjusted vegetation index (SAVI) that includes an optimised soil adjustment coefficient (0.16) to minimize the NDVI sensitivity due to variations in soil background effects under a wide range of environmental conditions (Equation (A3)). It can be applied in areas with high vegetation density, where the NDVI saturates, though it is preferentially used to cover relatively sparse vegetation areas, enhancing the soil brightness [59,60]. As in the previous VI, the OSAVI varies from −1 to 1, corresponding higher values to dense and healthy vegetation, whereas low positive values indicate less vigour.

$$OSAVI = \frac{NIR - Red}{NIR + Red + 0.16} \tag{A3}$$

Appendix A.4. Chlorophyll Indices (CI)

CI are produced to monitor the total chlorophyll content present in the leaves as a function of canopy cover and nutrient content changes, being therefore an indicator of the plant's primary production and photosynthetic potential. However, their usefulness is greater for orchards and vineyards since dense tree canopies better differentiate the chlorophyll signal [6,48]. Within these indices, the Green and Red-Edge CI have been widely used, because they are sensitive to small variations in the chlorophyll content (best identified in the NIR region) and consistent for most species [58,61–63] (Equations (A4) and (A5)). In general, low chlorophyll content indicates fertilizer limitation and low vegetative vigour.

$$CI\ Green = \frac{NIR}{Green} - 1 \tag{A4}$$

$$CI\ Red\ Edge = \frac{NIR}{Red\ Edge} - 1 \tag{A5}$$

Appendix A.5. False-Colour Composite (Colour Infrared—CIR)

False-colour composites are not properly VI, but their mapping allows us to visualize light's wavelengths, as the NIR, which are invisible to the human eye, thus facilitating the interpretability of remotely sensed data. The CIR composite presented in Equation (A6) emphasizes the response of the NIR spectral band to the crop vigour/health. Healthy vegetation reflects a high NIR level and appears as red in CIR maps, decreasing the red hue when representing low vigour vegetation. Soils and man-made structures are shown as green or blue (Figure A1) [48].

$$CIR = (\boldsymbol{R} : NIR,\ \boldsymbol{G} : Red,\ \boldsymbol{B} : Green) \tag{A6}$$

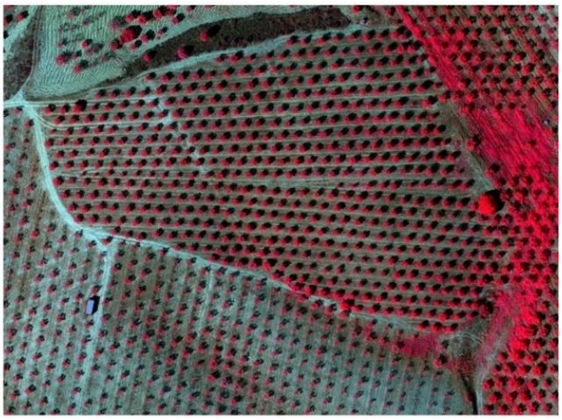


Figure A1. False-colour composite of an olive orchard plot (41°21′31″ N, 7°2′22″ W) derived from UAV images (flight date: 31 August 2021).

References

1. Fernandez, P.; Roque, N.; Lourenço, C. *Gestão e Monitorização do Olival Suportados na Caraterização da Variabilidade Espacial do Olival*; Promoção e Valorização de Azeites de Montanha (CENTRO-01-0246-FEDER-000004/6756); Azeites de Montanha: Castelo Branco, Portugal, 2019; ISBN 978-989-8196-82-8.
2. Palese, A.M.; Pergola, M.; Favia, M.; Xiloyannis, C.; Celano, G. A sustainable model for the management of olive orchards located in semi-arid marginal areas: Some remarks and indications for policy makers. *Environ. Sci. Policy* **2013**, *27*, 81–90. [CrossRef]
3. Bernardi, B.; Falcone, G.; Stillitano, T.; Benalia, S.; Strano, A.; Bacenetti, J.; De Luca, A.I. Harvesting system sustainability in Mediterranean olive cultivation. *Sci. Total Environ.* **2018**, *625*, 1446–1458. [CrossRef]
4. Connor, D.J.; Gómez-del-Campo, M.; Rousseaux, M.C.; Searles, P.S. Structure, management and productivity of hedgerow olive orchards: A review. *Sci. Hortic.* **2014**, *169*, 71–93. [CrossRef]
5. Neto, M.C.; Pinto, P.A.; Coelho, J.P.P. *Tecnologias de Informação e Comunicação e a Agricultura, Cap 4: Agricultura de Precisão*; SPI—Sociedade Portuguesa de Inovação, Principia, Publicações Universitárias e Científicas: Porto, Portugal, 2005; pp. 49–72. ISBN 972-8589-58-1.
6. Bernardi, A.C.C.; Naime, J.M.; Resende, Á.V.; Bassoi, L.H.; Inamasu, R.Y. *Agricultura de Precisão: Resultados De um Novo Olhar*; Embrapa: Brasília, Brazil, 2014; ISBN 978-85-7035-352-8.
7. Braga, R.; Pinto, P.A. Agricultura de precisão: Adopção & principais obstáculos. *Agrotec Rev. Téc.-Cient. Agríc.* **2011**, 84–89.
8. Coelho, J.P.C.; Silva, J.R.M. (Eds.) *Agricultura de Precisão*; Associação dos Jovens Agricultores de Portugal: Lisboa, Portugal, 2009; ISBN 978-989-8319-04-3.
9. Braga, R. (Ed.) *1ª edição, Viticultura de Precisão*; AJAP—Associação dos Jovens Agricultores de Portugal: Lisboa, Portugal, 2009; ISBN 978-989-8319-05-0.
10. Arampatzis, G.; Hatzigiannakis, E.; Pisinaras, V.; Kourgialas, N.; Psarras, G.; Kinigopoulou, V.; Panagopoulos, A.; Koubouris, G. Soil water content and olive tree yield responses to soil management, irrigation, and precipitation in a hilly mediterranean area. *J. Water Clim. Chang.* **2018**, *9*, 672–678. [CrossRef]
11. Pôças, I.; Paço, T.A.; Cunha, M.; Andrade, J.A.; Silvestre, J.; Sousa, A.; Santos, F.L.; Pereira, L.S.; Allen, R.G. Satellite-based evapotranspiration of a super-intensive olive orchard: Application of METRIC algorithms. *Biosyst. Eng.* **2014**, *128*, 69–81. [CrossRef]
12. Ramos, A.F.; Santos, F.L. Yield and olive oil characteristics of a low-density orchard (cv. Cordovil) subjected to different irrigation regimes. *Agric. Water Manag.* **2010**, *97*, 363–373. [CrossRef]
13. Santos, F. Olive Water Use, Crop Coefficient, Yield, and Water Productivity under Two Deficit Irrigation Strategies. *Agronomy* **2018**, *8*, 89. [CrossRef]
14. Steduto, P.; Hsiao, T.C.; Fereres, E.; Raes, D. *Crop Yield Response to Water*; FAO, Land and Water Division: Rome, Italy, 2012.
15. Alamo, S.; Ramos, M.I.; Feito, F.R.; Cañas, J.A. Precision techniques for improving the management of the olive groves of southern Spain. *Span. J. Agric. Res.* **2012**, *10*, 583–595. [CrossRef]
16. De Luca, A.I.; Falcone, G.; Stillitano, T.; Iofrida, N.; Strano, A.; Gulisano, G. Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy. *J. Clean. Prod.* **2018**, *171*, 1187–1202. [CrossRef]
17. Fernández-Escobar, R.; de la Rosa, R.; Leon, L.; Gómez, J.A.; Testi, L.; Orgaz, F.; Gil-Ribes, J.A.; Quesada-Moraga, E.; Trapero, A.; Msallem, M. Evolution and sustainability of the olive production systems. *Options Méditerranéennes* **2013**, *Série A*, 11–41.
18. INE. *2019 Agricultural Census*; INE, Ed.; Statistics Portugal: Lisbon, Portugal, 2021; ISBN 978-989-25-0562-6.
19. DGT. *A Land Cover/Use Map of Mainland Portugal for 2018*; Directorate-General for the Territorial Development: Lisbon, Portugal, 2019.

20. DGADR. Azeite de Trás-os-Montes DOP. Available online: https://tradicional.dgadr.gov.pt/pt/cat/azeites-e-azeitonas/59-azeite-de-tras-os-montes-dop (accessed on 6 November 2021).
21. Duarte, F.; Jones, N.; Fleskens, L. Traditional olive orchards on sloping land: Sustainability or abandonment? *J. Environ. Manage.* **2008**, *89*, 86–98. [CrossRef] [PubMed]
22. Santos, F.L.; Correia, M.M.; Coelho, R.R.; Sousa, A.; do Paço, T.A.; Pereira, L.S. *Efeitos da Rega e do Regime Hídrico em Olival Super Intensivo no Alentejo*; Sociedade de Ciências Agrárias de Portugal: Lisboa, Portugal, 2013; Volume 36.
23. Nissim, Y.; Shloberg, M.; Biton, I.; Many, Y.; Doron-Faigenboim, A.; Zemach, H.; Hovav, R.; Kerem, Z.; Avidan, B.; Ben-Ari, G. High temperature environment reduces olive oil yield and quality. *PLoS ONE* **2020**, *15*, e0231956. [CrossRef] [PubMed]
24. NASA. Shuttle Radar Topography Mission. Available online: https://www2.jpl.nasa.gov/srtm/ (accessed on 5 September 2022).
25. AGROCONSULTORES & COBA. *Carta de Solos, Carta do Uso Actual da Terra e Carta da Aptidão da Terra do Nordeste de Portugal, Escala 1:100 000. Peças Desenhadas e Memórias Descritivas*; Universidade de Trás-os-Montes e Alto Douro: Vila Real, Portugal, 1991.
26. FAO/UNESCO. Soil Map of the World. Available online: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ (accessed on 5 October 2022).
27. Andrade, C.; Fonseca, A.; Santos, J.A. Are land use options in viticulture and oliviculture in agreement with bioclimatic shifts in portugal? *Land* **2021**, *10*, 869. [CrossRef]
28. IPMA. Portuguese Institute for Sea and Atmosphere Climate Normals (1971–2000). Available online: https://www.ipma.pt/pt/oclima/normais.clima/1971-2000 (accessed on 4 June 2022).
29. Paço, T.A.; Pôças, I.; Cunha, M.; Silvestre, J.C.; Santos, F.L.; Paredes, P.; Pereira, L.S. Evapotranspiration and crop coefficients for a super intensive olive orchard. An application of SIMDualKc and METRIC models using ground and satellite observations. *J. Hydrol.* **2014**, *519*, 2067–2080. [CrossRef]
30. Bernardi, B.; Falcone, G.; Stillitano, T.; Benalia, S.; Bacenetti, J.; De Luca, A.I. Harvesting system sustainability in Mediterranean olive cultivation: Other principal cultivar. *Sci. Total Environ.* **2021**, *766*, 142508. [CrossRef] [PubMed]
31. Ben Abdallah, S.; Elfkih, S.; Suárez-Rey, E.M.; Parra-López, C.; Romero-Gámez, M. Evaluation of the environmental sustainability in the olive growing systems in Tunisia. *J. Clean. Prod.* **2021**, *282*, 124526. [CrossRef]
32. Tubeileh, A.; Turkelboom, F.; Al-Ibrahem, A.; Thomas, R.; Sultan-Tubeileh, K. Modelling the effects of soil conditions on olive productivity in mediterranean hilly areas. *Int. J. Agron.* **2014**, *2014*, 672123. [CrossRef]
33. De Graaff, J.; Duran Zuazo, V.H.; Jones, N.; Fleskens, L. Olive production systems on sloping land: Prospects and scenarios. *J. Environ. Manage.* **2008**, *89*, 129–139. [CrossRef]
34. Pergola, M.; Favia, M.; Palese, A.M.; Perretti, B.; Xiloyannis, C.; Celano, G. Alternative management for olive orchards grown in semi-arid environments: An energy, economic and environmental analysis. *Sci. Hortic.* **2013**, *162*, 380–386. [CrossRef]
35. Iofrida, N.; De Luca, A.I.; Gulisano, G.; Strano, A. An application of Q-methodology to Mediterranean olive production–stakeholders' understanding of sustainability issues. *Agric. Syst.* **2018**, *162*, 46–55. [CrossRef]
36. Romero-Gámez, M.; Castro-Rodríguez, J.; Suárez-Rey, E.M. Optimization of olive growing practices in Spain from a life cycle assessment perspective. *J. Clean. Prod.* **2017**, *149*, 25–37. [CrossRef]
37. Russo, C.; Cappelletti, G.; Nicoletti, G.; Di Noia, A.; Michalopoulos, G. Comparison of European Olive Production Systems. *Sustainability* **2016**, *8*, 825. [CrossRef]
38. Rodríguez-Entrena, M.; Arriaza, M. Adoption of conservation agriculture in olive groves: Evidences from southern Spain. *Land Use Policy* **2013**, *34*, 294–300. [CrossRef]
39. Bombino, G.; Denisi, P.; Gómez, J.A.; Zema, D.A. Mulching as best management practice to reduce surface runoff and erosion in steep clayey olive groves. *Int. Soil Water Conserv. Res.* **2021**, *9*, 26–36. [CrossRef]
40. Repullo, M.A.; Carbonell, R.; Hidalgo, J.; Rodríguez-Lizana, A.; Ordóñez, R. Using olive pruning residues to cover soil and improve fertility. *Soil Tillage Res.* **2012**, *124*, 36–46. [CrossRef]
41. Rodrigues, M.Â.; Correia, C.M.; Claro, A.M.; Ferreira, I.Q.; Barbosa, J.C.; Moutinho-Pereira, J.M.; Bacelar, E.A.; Fernandes-Silva, A.A.; Arrobas, M. Soil nitrogen availability in olive orchards after mulching legume cover crop residues. *Sci. Hortic.* **2013**, *158*, 45–51. [CrossRef]
42. De Gennaro, B.; Notarnicola, B.; Roselli, L.; Tassielli, G. Innovative olive-growing models: An environmental and economic assessment. *J. Clean. Prod.* **2012**, *28*, 70–80. [CrossRef]
43. Aiello, G.; Vallone, M.; Catania, P. Optimising the efficiency of olive harvesting considering operator safety. *Biosyst. Eng.* **2019**, *185*, 15–24. [CrossRef]
44. Saglam, C.; Tuna, Y.T.; Gecgel, U.; Atar, E.S. Effects of Olive Harvesting Methods on Oil Quality. *APCBEE Procedia* **2014**, *8*, 334–342. [CrossRef]
45. Stroosnijder, L.; Mansinho, M.I.; Palese, A.M. OLIVERO: The project analysing the future of olive production systems on sloping land in the Mediterranean basin. *J. Environ. Manag.* **2008**, *89*, 75–85. [CrossRef] [PubMed]
46. Ascenso, A.; Gama, C.; Blanco-Ward, D.; Monteiro, A.; Silveira, C.; Viceto, C.; Rodrigues, V.; Rocha, A.; Borrego, C.; Lopes, M.; et al. Assessing Douro Vineyards Exposure to Tropospheric Ozone. *Atmosphere* **2021**, *12*, 200. [CrossRef]
47. DJI Matrice 300 RTK–Built Tough. Works Smart. Available online: https://www.dji.com/pt/matrice-300 (accessed on 10 October 2021).
48. MicaSense RedEdge MX. Available online: https://support.micasense.com/hc/en-us/articles/360011389334-RedEdge-MX-Integration-Guide (accessed on 15 September 2022).

49. USGS. USGS EROS Archive-Sentinel-2. Available online: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-sentinel-2?qt-science_center_objects=0#qt-science_center_objects (accessed on 10 November 2021).
50. Lopes, J.I.; Gonçalves, A.; Brito, C.; Martins, S.; Pinto, L.; Moutinho-Pereira, J.; Raimundo, S.; Arrobas, M.; Rodrigues, M.Â.; Correia, C.M. Inorganic Fertilization at High N Rate Increased Olive Yield of a Rainfed Orchard but Reduced Soil Organic Matter in Comparison to Three Organic Amendments. *Agronomy* **2021**, *11*, 2172. [CrossRef]
51. Palese, A.M.; Vignozzi, N.; Celano, G.; Agnelli, A.E.; Pagliai, M.; Xiloyannis, C. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. *Soil Tillage Res.* **2014**, *144*, 96–109. [CrossRef]
52. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56*; FAO—Food and Agriculture Organization of the United Nations: Rome, Italy, 1998.
53. Salgado, R.; Mateos, L. Evaluation of different methods of estimating ET for the performance assessment of irrigation schemes. *Agric. Water Manag.* **2021**, *243*, 106450. [CrossRef]
54. Shamloo, N.; Taghi Sattari, M.; Apaydin, H.; Valizadeh Kamran, K.; Prasad, R. Evapotranspiration estimation using SEBAL algorithm integrated with remote sensing and experimental methods. *Int. J. Digit. Earth* **2021**, *14*, 1638–1658. [CrossRef]
55. Awada, H.; Di Prima, S.; Sirca, C.; Giadrossich, F.; Marras, S.; Spano, D.; Pirastru, M. Daily Actual Evapotranspiration Estimation in a Mediterranean Ecosystem from Landsat Observations Using SEBAL Approach. *Forests* **2021**, *12*, 189. [CrossRef]
56. Guarino, F.; Falcone, G.; Stillitano, T.; De Luca, A.I.; Gulisano, G.; Mistretta, M.; Strano, A. Life cycle assessment of olive oil: A case study in southern Italy. *J. Environ. Manag.* **2019**, *238*, 396–407. [CrossRef]
57. Gómez-Limón, J.A.; Picazo-Tadeo, A.J.; Reig-Martínez, E. Eco-efficiency assessment of olive farms in Andalusia. *Land Use Policy* **2012**, *29*, 395–406. [CrossRef]
58. Nolè, G.; Pilogallo, A.; Lanorte, A.; De Santis, F. Remote Sensing Techniques in Olive-Growing: A Review. *Curr. Investig. Agric. Curr. Res.* **2018**, *2*, 205–208. [CrossRef]
59. Rondeaux, G.; Steven, M.; Baret, F. Optimization of soil-adjusted vegetation indices. *Remote Sens. Environ.* **1996**, *55*, 95–107. [CrossRef]
60. Steven, M.D. The Sensitivity of the OSAVI Vegetation Index to Observational Parameters. *Remote Sens. Environ.* **1998**, *63*, 49–60. [CrossRef]
61. De Araujo Barbosa, C.C.; Atkinson, P.M.; Dearing, J.A. Remote sensing of ecosystem services: A systematic review. *Ecol. Indic.* **2015**, *52*, 430–443. [CrossRef]
62. Behling, R.; Bochow, M.; Foerster, S.; Roessner, S.; Kaufmann, H. Automated GIS-based derivation of urban ecological indicators using hyperspectral remote sensing and height information. *Ecol. Indic.* **2015**, *48*, 218–234. [CrossRef]
63. Lausch, A.; Erasmi, S.; King, D.; Magdon, P.; Heurich, M. Understanding Forest Health with Remote Sensing-Part I—A Review of Spectral Traits, Processes and Remote-Sensing Characteristics. *Remote Sens.* **2016**, *8*, 1029. [CrossRef]