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Review

Sustainability of High-Density Olive Orchards: Hints for Irrigation Management and Agroecological Approaches

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Abstract: The production of olive oil in Portugal and other countries of the Mediterranean region has greatly increased in recent years. Intensification efforts have focused on the growth of the planted area, but also on the increase of the orchards density and the implementation of irrigation systems. Concerns about possible negative impacts of modern olive orchard production have arisen in the last years, questioning the trade-offs between the production benefits and the environmental costs. Therefore, it is of great importance to review the research progress made regarding agronomic options that preserve ecosystem services in high-density irrigated olive orchards. In this literature review, a keywords-based search of academic databases was performed using, as primary keywords, irrigated olive orchards, high density/intensive/hedgerow olive orchards/groves, irrigation strategies, and soil management. Aside from 42 general databases, disseminated research, and concept-framing publications, 112 specific studies were retrieved. The olive orchards were classified as either traditional (TD) (50–200 trees ha^{-1}), medium-density (MD) (201–400 trees ha^{-1}), high-density (HD) (401–1500 trees ha^{-1}), or super-high-density (SHD) orchards (1501–2500 trees ha^{-1}). For olive crops, the crop coefficient (Kc) ranges ranges from 0.65 to 0.70, and can fall as low as 0.45 in the summer without a significant decrease in oil productivity. Several studies have reported that intermediate irrigation levels linked with the adoption of deficit irrigation strategies, like regulated deficit irrigation (RDI) or partial rootzone drying (PRD), can be effective options. With irrigation, it is possible to implement agroecosystems with cover crops, non-tillage, and recycling of pruning residues. These practices reduce the soil erosion and nutrient leaching and improve the soil organic carbon by 2 to 3 t C ha^{-1} year^{-1}. In this situation, in general, the biodiversity of plants and animals also increases. We expect that this work will provide a reference for research works and resource planning focused on the improvement of the productive and environmental performance of dense irrigated olive orchards, thereby contributing to the overall enhancement of the sustainability of these expanding agroecosystems.

Keywords: irrigated olive orchards; high density; hedgerow; irrigation strategies; soil management

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1. Introduction

The world's olive cultivation area was about 10.3 Mha in 2021, yielding 23 million tons of olive fruits. From 2015 to 2021, the top European olive producers were Spain (32%), Greece (13%), Italy (10%), and Portugal (4%) [1]. Portugal is the fourth olive producer in Europe and the eighth in the world. Despite only representing 4% of the total olive cultivation area and 4% of the total production worldwide, the Portuguese olive sector is an important source of income for the country.

In Portugal, the Southern region of Alentejo is the main production province, comprising 52.4% of the total Portuguese area (377,234 ha), with a large part occupied by dense irrigated plantations (Figure 1). Irrigated orchards cover 31.7% of the total Portuguese olive tree area, 13.8% corresponding to super-high-density orchards, with over

1500 trees ha^{-1} [2] (Figure 1). The olive harvest occurs every year from early October to January. The oil content of Portuguese olives varies from 14% to 20% of the fruit fresh weight, depending on the cultivar and harvest date. Normally, early harvesting leads to lower oil content of the fruits [3–10].

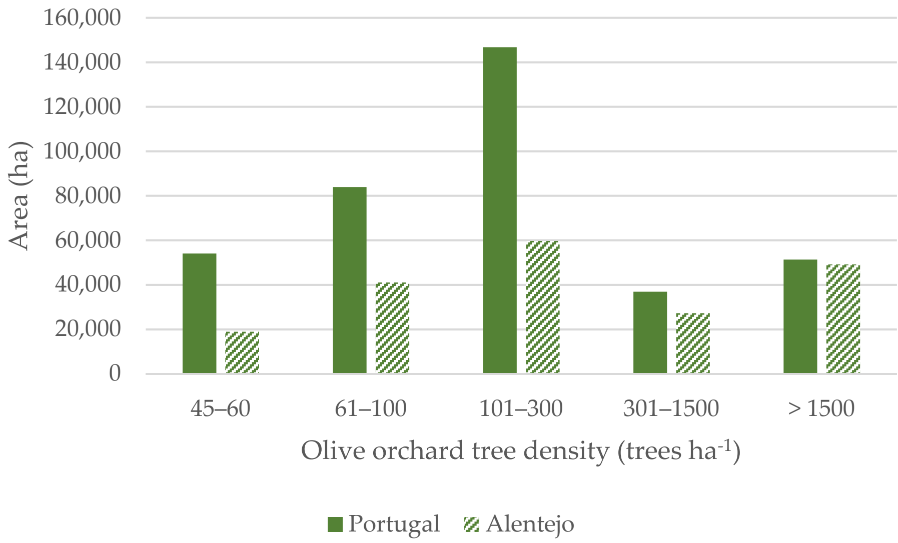

Figure 1. Comparison between olive orchard area (ha) in Portugal and the Portuguese Alentejo region by tree density classes [2].

Traditionally, olive trees have been grown in the region surrounding the Mediterranean, mainly as a rainfed crop with low productivity given the typical dry environment of this region. In recent years, the expansion of olive oil and table olive production has been achieved through both an increase in the planted area and through intensification within and beyond the Mediterranean countries by increasing the orchards' density and via the introduction of irrigation [11–13]. In fact, in the last two decades, high-density (HD; 401 to 1500 trees ha^{-1}) and super-high-density (SHD; 1501 to 2500 trees ha^{-1}) orchards, known as hedgerow olive orchards, have been developed to further reduce harvesting costs using over-the-row harvesting machines [14–16]. Because of the higher water demand of the dense canopies and the low soil volume available for each tree, irrigation is usually needed [12,17,18]. The current water scarcity in traditional olive-growing regions, like Alentejo, along with the expected increase in heat waves and droughts caused by climate change [16,19,20], imply an urgent need to reduce the use of water for irrigation of crops in these regions and to adopt measures to avoid the degradation of soil resources and biodiversity.

The adoption of management practices that maintain ecosystem services (SE), like soil and water conservation practices for the regulation of SE, or biodiversity preservation [15] for the support of SE, is a key aspect of modern agriculture [21,22]. The olive-growing sector is no exception to this premise. In fact, the increase in irrigated dense plantations of olives has led to relevant changes in the landscapes of some regions, and the risk of negative impacts of this agricultural intensification on the environment must be avoided [14,23,24].

The target of this review is to focus on the sustainability of high- and super-high-density olive orchards.

We aim to contribute towards an optimized system in terms of water management, with a focus on irrigation strategies and agroecological practices to enhance the health of these agroecosystems. It is our objective to provide: (i) a systematization of the type of olive orchards that can be found regarding their tree density; and (ii) an overall research output regarding water-saving irrigation strategies and agroecological options in irrigated dense olive orchards.

For this purpose, we applied a keywords-based search of academic databases. The primary keywords used were irrigated olive orchards, high density/intensive/hedgerow olive orchards/groves, irrigation management, and soil management. Within these, the secondary keywords used were water requirements, deficit irrigation strategies, erosion, infiltration rate, surface temperature, pesticides, herbicides, diseases, cover crops, pruning residues, organic matter, organic carbon accumulation, nitrogen accumulation, and biodiversity.

2. The Olive Orchard Mosaic

2.1. The Traditional Olive Orchards

When traveling in the Mediterranean area, one can often find olive orchards planted in the XIXth century or up to the mid-XXth century, with fewer than 50 trees ha^{-1} to a maximum of 200 trees ha^{-1}, that are still productive today. These were sometimes planted on sharp slopes or small and narrow terraces made with stone walls, as can mainly be observed in the north of Portugal, providing landscapes of great beauty.

In traditional olive orchards (TD), the management of cover crops is conducted by tillage or total herbicide coverage. Grain crops were traditionally grown within olives as primary sources of farmers' income. In these situations, the soil erosion can be quite dramatic [25–27], and at the same time, the temperature of the soil's top layer is quite high in the summer (over 40 °C). Although olive is a well-adapted species to drought conditions, the soil's exposure to direct sun and the lack of canopy shade over the tree root zone leads to water and heat stress, and can induce summer dormancy in the trees [28–30].

The farmers use few fertilizers and apply a reduced number of chemical pest and disease treatments in the olive groves. They are pruned every four years by chain saw, and the pruning residue is generally burned. The alternate bearing is very strong, with a sparse yield in the year following pruning [14]. Since these orchards are rainfed, the biodiversity of species is sometimes low due to the lack of water and cover crops [31–33].

Traditionally, the harvest is performed by hand with wood sticks, although nowadays, some growers use portable backpack shakers with or without nets covering the floor. The net production of these olive ecosystems is less than 3 t ha^{-1} of fruits. The quality of the oil produced is often affected by diseases like anthracnose (*Colletotrichum* sp.) [34] or by contamination of the fruit through direct contact with the orchard floor [35]. The overall sustainability of this traditional olive system is currently compromised due to the lack of workers and the labor price [36] (Table 1).

2.2. The Medium-Density Olive Orchards

The most common olive orchards in the Mediterranean area are those with medium density (MD; 200–400 trees ha^{-1}), which are very likely to be observed in lime soils of the southern parts of Portugal or Spain. They are rainfed or little irrigated, and the soil is kept weed-free by tillage or by partial (in the rows) or total herbicide application. Many have spontaneous cover plants, mainly in the interrows, which are used to some extent as grazing lands. In this case, animal manure provides some nutrient recycling for the ecosystem and complements the annual fertilization. The pruning is carried out in alternate years and is less intense than in the traditional orchards. The pruning residue is often burned.

The sun exposure of the soil is lower due to the improved tree shade, resulting in better development of resident herbaceous vegetation that increases insect populations, improving biodiversity, and provides more protection against soil erosion than in the TD systems.

The harvest is carried out by tree shaking using floor nets or wraps around the trees as collecting systems. These orchards have been upgraded over time by increasing plant density and providing better irrigation. This agricultural system is undergoing a fast transition to a higher-density system [37–39].

Table 1. Systematization of the most common olive orchards' agricultural systems in the Mediterranean climate and their features. Traditional (TD), medium-density (MD), high-density (HD), and super-high-density (SHD).

Orchard Type	Spacing Inter-row × Row (m)	Tree Density (trees ha^{-1})	Productivity (t ha^{-1})	Soil Conservation	Tree Architecture	Pruning	Irrigation and Soil Management	Harvest	Common Cultivars
Traditional (TD)	8–15 × 6–15	50–200	0.5–3	Slopes: 0 to 30%. Strong erosion.	Trichotomic vase canopy. Strong alternate bearing.	Every 4 years. Chain saw. Pruning residue is burned.	Non-irrigated. Soil tillage, inter-row grain crops. Herbicides.	Hand branch shakers, with or without floor nets.	Galega, Verdeal, Cordovil.
Medium-density (MD)	7–8 × 3.5–6	201–400	3–6	Slopes: 0 to 15%. Some erosion.	Trichotomic vase canopy. Alternate bearing.	Every 2 years. Chain saw. Pruning residue is burned.	Non-irrigated or low-irrigated. Soil tillage, herbicides, or spontaneous weed cover, some used for animal pasture.	Trunk shaker, floor nets. Wrap around the tree collector.	Galega, Verdeal, Cordovil, Cobrançosa, Picual, Frantoio
High-density (HD)	4–7 × 1.7–3.5	401–1500	6–12	Slopes: 0 to 10%. Low erosion.	Dichotomic vase or hedge row. Some alternate bearing in orchards over 20 years old.	Every 1–2 years. Manual shears, electric or air compressed. Tractor disc trimmers. Pruning residue is shredded on site.	Drip irrigation—250–500mm $year^{-1}$. Spontaneous or sowed cover crops. Herbicide in the tree rows or no herbicide.	Trunk shaker and wrap around the tree collector, or over-the-row.	Cobrançosa, Picual, Arbequina, Frantoio.
Super-high-density (SHD)	3.5–4 × 1–1.7	1501–2500	12–22						Arbequina, Arbosana, Koroneiki.

2.3. The High- (HD) and Super-High-Density (SHD) Olive Orchards

The success of the higher-density olive agricultural systems is based on water availability [12,40]. The olive tree is an evergreen species with a remarkable water control process that manages water losses, requiring less water in the summer than in the remaining period of the year [41–43]. Nevertheless, in a region with 562 mm year^{-1} of average rainfall [44], 250 mm to 500 mm year^{-1} of supplemental irrigation water are the necessary values for the trees to achieve their maximum productivity. This demand is lower when compared to the 500–800 mm year^{-1} required by other perennial species (Figure 2). Under these conditions, higher densities lead to increased productivity. The HD and SHD olive orchards are planted with 401–2500 trees ha^{-1}. Plantation is sometimes conducted in ridges of 1.0 m × 0.5 m (width × height) that are meant to prevent waterlogging and improve soil temperature in the early spring. These ridges must be made with special care; otherwise, they can prevent the natural rainfall flow and worsen the waterlogging [45].

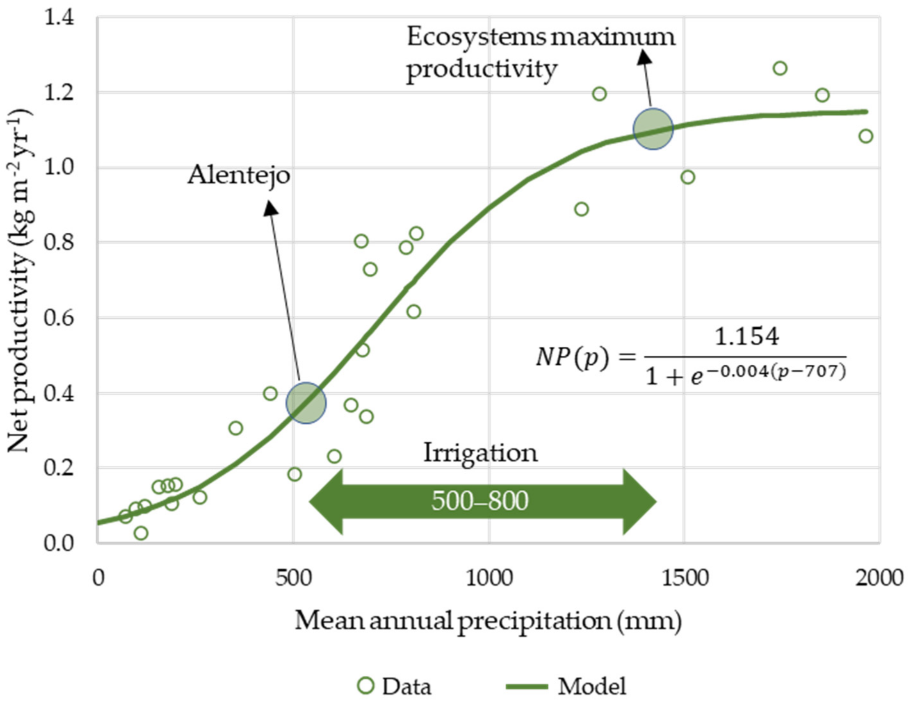

Figure 2. Biomass productivity by world ecosystems. The Mediterranean rainfall in Alentejo is signaled as well as the irrigation requirements, calculated as the difference between the ecosystem's maximum productivity and the average Alentejo rainfall. (Data from Taiz et al. [46]). NP—net productivity (kg m^{-2} year^{-1}), p—precipitation (mm).

Considering soil management, the soil is normally covered with spontaneous or sowed herbaceous vegetation to minimize soil erosion. The sowed cover species could be *Fabaceae* sp., like *Medicago sativa*, *Vicia* sp. or *Trifolium* spp., which are quite important nitrogen recyclers (Table 2). Every 2–8 t ha^{-1} of olive fruits extract 7–28 kg ha^{-1} of N, 2–8 kg ha^{-1} of P_2O_5, and 12–48 kg ha^{-1} of K_2O [47]. The cover species can provide an important contribution in the form of nitrogen balance in the cases of HD and SHD olive orchards. The spontaneous or sowed cover crops are also important refuges for beneficial insects or pollinators, which improve the general biodiversity of HD and SHD orchards [48–54]. Inter-row weed management is usually carried out by shredding 3 to 5 times a year to keep the weeds below 0.5 m in height. The shredding also recycles the pruning residues left in the topsoil of these orchards. The recycling of pruning residues is a good practice which allows the reposition of 2.9 kg t^{-1} N, 1,1 kg t^{-1} P_2O_5, and 2.9 kg t^{-1} K_2O [47], apparently without side effects related to the improvement of orchard diseases [55]. Nevertheless, soil diseases caused by *Verticilium dahliae* may occur [56].

Table 2. Seed quantity necessary to establish the cover crop and nitrogen fixed by hectare with *Fabaceae* species (Adapted from [47]).

Species	Sow Seed Quantity ($kg\ ha^{-1}$)	Nitrogen Fixed ($kg\ ha^{-1}\ yr^{-1}$)
Alfalfa (*Medicago sativa*)	10–25	114–223
Broad bean (*Vicia faba*)	150–200	160–216
Common vetch (*Vicia* sp.)	40–60	90–155
Crimson clover (*Trifolium incarnatum*)	10–20	20–64
Eggs and Bacon (*Lotus corniculatus*)	4–6	49–112
Lentil (*Lens culinaris*)	60–80	15–85
Pea (*Pisum sativum*)	70–140	37–185
Red clover (*Trifolium pratense*)	4–10	68–113
Sub clover (*Trifolium subterraneum*)	10–20	48–183
White clover (*Trifolium repens*)	8–12	165–188

If irrigation lines are directly on the soil surface, they do not allow for weed mowing in the tree lines. Therefore, weed control in the tree row normally requires herbicide application. This issue should be addressed in the near future, as the herbicide glyphosate could be banned, and other chemical solutions are currently less economical [57,58].

One advantage of HD and SHD olive orchards is the soil temperature. In the same location, the temperature of the topsoil in the summer, measured with a FLIR (Forward Looking InfraRed) device, was about 20 °C lower at the top of the cover grass when compared to bare topsoil [59,60].

Finally, HD and SHD olive orchards are more regular in yield, but do not show evidence for strong alternate crop behavior when compared with the other systems [12,14]. The cultivars in use have less vigor and, therefore, provide more regular production, at least during the first 20 years of the orchard's life [14,16,61–63].

Harvests in HD and SHD olive orchards require tractor trunk shakers with wraps around the tree collectors or over-the-row self-propelled machines. The latter can harvest up to one hectare per 1 h (12–22 t of fruits). As the fruits are never in contact with the ground, they are quite suitable for virgin or extra-virgin oil production [39]. In Portugal, the harvest is restricted to the period from sunrise to sunset in order to prevent involuntary bird losses, since these animals often use olive trees as refuges overnight [64].

3. Water Management

3.1. Water Use and Irrigation Requirements

Crop water requirements (CWR) are defined as the amounts of water needed to replace the water lost through evapotranspiration by a disease-free crop growing in large fields under no limitations regarding soil conditions, including soil water and fertility, and achieving full production potential in the given growing environment [65]. This water loss is defined as the crop evapotranspiration (ET_c) under standard conditions, given by Equation (1):

$$ET_c = ET_0 \times K_c \quad (1)$$

where ET_0 is the reference evapotranspiration of a grass-like reference crop, and K_c is the crop coefficient [66,67]. In fact, ET_0 represents an index of climatic demand, and K_c represents the influence of the specific crop characteristics [68]. The K_c in olive orchards is affected by several factors, including the canopy architecture, the fraction of ground covered by the vegetation, crop management practices, and rainfall variability [42]. In the case of olive growing under standard climatic and agronomic conditions, the Kc values recommended by FAO vary between 0.65 in the initial phase and 0.70 in the intermediate and final phases of the development cycle [67]. The monthly Kc values proposed by Pastor and Orgaz (1994) [69] vary between 0.45 in July and August and 0.65 in March and May.

To meet the reduction in the fraction of soil covered by vegetation, or the fraction of shaded area (C, in %) in an olive grove, Fereres and Castel (1981) [70] proposed that ET_c be estimated by Equation (2):

$$ET_c = ET_0 \times K_c \times K_r \tag{2}$$

where K_r should be used when the coverage fraction is less than 50% and corresponds to a reduction coefficient, obtained by Equation (3):

$$K_r = \frac{2\,C}{100} \tag{3}$$

In the case of irrigated crops, the concept of irrigation water requirement (IWR) must be considered. The IWR is the amount of water that is required to be applied to a crop to fully satisfy its specific crop water requirement whenever rainfall, soil water storage, and groundwater contributions are insufficient [68].

Olive's water requirements are a function of cultivar characteristics, management, and environmental demands. Olive trees withstand long periods of drought and can survive in very sparse plantings, even in climates with very low annual rainfall: values of 150–200 mm year^{-1} are indicated in Steduto et al. (2012) [17] and Carr (2013) [11] refers to 200–250 mm year^{-1}. However, as referenced in Section 2.3, for economic production, much higher precipitation or irrigation are required: Carr (2013) [11] states that an average annual precipitation or irrigation above 600 mm year^{-1}, in soils with good water-holding capacity, is needed for successful cultivation; Beede and Goldhamer (2005) [71] found values of around 950 mm year^{-1} for mature olive trees in clean cultivated orchards with 60% or higher shaded areas.

Olives are perennial trees that retain their canopies and use water during the entire year, but, regardless of the growing conditions affecting seasonal water use, they have different sensitivities to water deficits depending on their development stage. While water stress during the period of flower bud formation can lead to a reduced number of flowers, thereby affecting the year's yield, when it occurs during periods of shoot growth, it can affect the next year's yield, which is formed on 1-year-old shoots [45,71,72].

For olive oil production, fruit sets should be managed to maximize oil extractability and quality. Several studies have reported that intermediate irrigation levels linked with the adoption of deficit irrigation during certain stages of fruit development can increase the fruit and oil quality [13,73–76]. Additionally, the slowing of fruit development—known as the pit hardening phase—is considered as the less sensitive period of olive trees to water deficit, when it is possible to reduce or interrupt irrigation without a significant reduction in yield or in oil quality [77–80].

3.2. Irrigation Strategies

The management of irrigation in olive trees following schedules to optimize water productivity can be an effective option to balance vegetative development, yield, and fruit quality while ensuring water conservation [81–83]. These irrigation regimes include supplemental irrigation (SI) and deficit irrigation (DI) strategies. The former is used by applying irrigation in selected phenological stages and is responsible for remarkable responses even with low irrigation supplies. Its goals include achieving maximum yields and eliminating yield fluctuations caused by water deficits [83,84]. The latter are widely adopted in other drought-resistant crops, the most relevant example being grapevine (*Vitis vinifera*) [85–87], where they are commonly supported by physiologically based and soil-based monitoring tools [88–91].

Supplemental irrigation can be defined as the application of a limited amount of water to increase and stabilize crop yields when rainfall fails to provide sufficient water for plant growth [92]. Studies concerning the effect of supplemental irrigation on olive trees' productive responses involve mostly TD and MD orchards in semi-arid conditions (e.g., [76,93–95]).

Deficit irrigation strategies are based on supplying irrigation volumes lower than the irrigation crop requirements under non-limiting growing conditions, that is, below the potential ETc, allowing for water savings in regions with present or future limited water resources without compromising production [96]. Three DI strategies can be considered: (i) sustained (or continuous) deficit irrigation (SDI), (ii) regulated deficit irrigation (RDI), and (iii) partial root-zone drying (PRD). Selected research regarding the use of DI strategies in MD, HD, and SHD olive orchards is summarized in Table 3.

3.2.1. Sustained Deficit Irrigation

In SDI, the irrigation water used at any moment during the season is below the crop evapotranspiration demand. This is based on the idea of allotting the water deficit uniformly over the entire growing season [97]. Thereby, the water deficit increases progressively as the season advances due to a combination of the uniform application of a reduced amount of water and the depletion of available soil water. This allows water stress to develop slowly and for the plants to adapt to the water deficits when the soil presents significant water storage capacity [96]. One of the first and most well-known studies on the effects of SDI in olive trees was published by Goldhamer et al. (1994) [98], which tested eight irrigation rates, ranging from 232 mm (Kc = 0.16) to 1016 mm (Kc = 0.85), in mature olive trees, cv. 'Manzanillo', planted with a density of 239 trees ha^{-1}, in Madera County, California. They reported tree water stress occurring for Kc values of 0.55 or less, and a strong correlation between fruit value (USD/ha^{-1}) and applied irrigation (mm) up to 950 mm, indicating that higher amounts of irrigation water do not correspond to increased economic water productivity when a threshold value is exceeded. Grattan et al. (2006) [74], by studying the effect of different water-application treatments on oil yield in a SHD olive orchard, cv. 'Arbequina', found that oil yields can be maximized over a rather broad range of applied water, since increases in fruit yield with higher irrigation levels are offset by the reduction in the percentage of oil extracted. In a MD orchard, cv. 'Cobrançosa', in Northern Portugal, Fernandes-Silva et al. (2010) [82] reported that the oil yield increased to more than double with SDI treatment when compared to rainfed conditions. Santos et al. (2018) [99] studied the water use and productivity of the same cultivar in an orchard with 300 trees/ha^{-1}, located in Alentejo, under two deficit irrigation treatments, and found that the 70% of ETc strategy presented a higher yield and increased water use efficiency. Other studies on the SDI technique applied in medium-to-dense olive orchards usually consist of comparisons with other DI strategies, like RDI, and the reported results point to similar yield responses [78,81,100].

3.2.2. Regulated Deficit Irrigation

The RDI strategy consists of reducing or withholding irrigation water during specific periods to manipulate plants' vegetative and reproductive growth [13,101]. The less sensitive period for olive trees to water deficits is midsummer, when it is possible to reduce or interrupt irrigation without a significant yield reduction nor decreased oil quality [72,77,100] (Figure 3). However, during certain stages of the growth cycle, irrigation supplies must balance, or be close to, the crops' water needs (Figure 3). According to Fernández et al. (2013) [102], these periods are:

- From the last stages of floral development to full bloom, normally in mid-April, when water stress can affect flower fertilization.
- At the end of the first stage of fruit development, normally in June, when water stress causes reductions in fruit size.
- After the midsummer period, normally from late August to mid-September, when a marked increase in oil accumulation occurs.

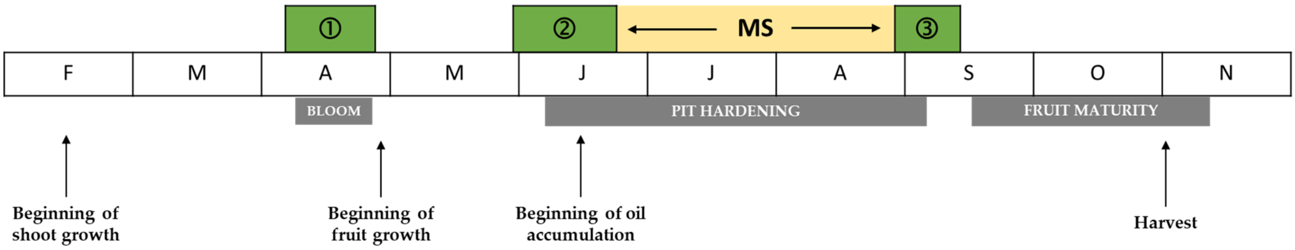

Figure 3. Olive growth cycle and periods at which olive trees are most sensitive to water stress, indicated as ①, ②, and ③. MS is the midsummer period, normally from late June to late August, during which olive trees are resistant to drought and irrigation can be reduced or withdrawn (adapted from Fernández et al. (2013) [102]).

The studies regarding RDI strategies are usually based on timing the withdrawal of or reduction in irrigation during midsummer and/or immediately before and after this period [75,81,100,102]. Usually, different percentages of reduction in irrigation are tested with the aim to understand the threshold at which the reduction in fruit yield caused by stress can be offset by the maintenance/increase in the percentage of oil extracted, as well as in the oil quality [75,102,103]. Additionally, trees' water statuses are monitored, and these measurements are used to define thresholds for irrigation scheduling. The most frequently used physiological parameters are leaf (Y) or stem water potential (Y_{Stem}), measured at different times of the day, normally at predawn or midday [80,102,104–106]; stomatal conductance (g_S); net photosynthesis (A_N); and evapotranspiration rate (E) at the leaf level [82,105,107].

3.2.3. Partial Rootzone Drying

The PRD technique requires that approximately half of the root system be maintained in a drying state while the remainder of the root system is irrigated [85,101,108,109]. The theoretical background of PRD is that irrigation of part of the root system keeps the upper part of crops in favorable water conditions, while the drought in the other part of the roots induces the formation of root chemical signals, mainly abscisic acid, which are transported to the upper parts of the plants to induce reductions in stomatal conductance and shoot growth [110–112]. The aim of PRD would then be to reduce water losses by transpiration without affecting the yield. However, as stated by Fernández et al. (2006) [107], the studies carried out to date have not always supported this hypothesis, and PRD and RDI do not differ significantly in terms of water productivity [113].

In general, studies of the effects of PRD on olive trees grown under semi-arid conditions have in common a slight PRD-induced yield reduction, although with high water productivity and no reduction in oil yield [114–116].

Table 3. Summary of selected studies on the effect of irrigation strategies on olive production in medium- to super-high-density olive orchards.

DI Strategy	Cultivar	Location	Annual Rainfall (mm)	Orchard Type	Irrigation Treatments	Main Results	Reference
SDI	Arbequina	California, USA	533 (3-year average during the experiment)	30-month commercial orchard (1709 trees ha^{-1})	7 treatments: 1–15 (28), 2–25 (33), 3–40 (55), 4–57 (75), 5–71 (93), 6–89 (117), and 7–107 (140)% ETc [(1)] (SDI in treatments 1 to 6 and 1 to 5 in the first and second year of the trial, respectively)	SDI treatments of 70–75% ETc did not reduce oil yields significantly; sustained season-long irrigation deficit of approximately 33–40% ETc maximized oil quality (chemical parameters, flavor, and stability).	Berenguer et al. (2004) [73] Grattan et al. (2006) [74]
SDI	Cobrançosa	Vilariça Valley, Portugal	520	10-year-old commercial orchard (278 trees ha^{-1})	3 treatments: R 30% ETc (SDI) FI	With SDI treatment, the oil yield increased to more than double that of rainfed conditions; 25% oil yield reduction in SDI compared to FI.	Fernandes-Silva et al. (2010) [82]
SDI	Frantoio	Venturina, Italy	635	10-year-old experimental orchard (513 trees ha^{-1})	3 treatments: FI 46–52% ETc (SDI) 2–6% ETc (SI)	The fruit yield of the SDI trees was 68% of that of FI; the fruit sets and numbers of fruits of the FI trees were similar to those of SDI trees and significantly higher than the SI trees; the oil yield of the DI treatment was 82% that of FI trees.	Caruso et al. (2013) [117]
SDI and RDI	Picual	Cordoba, Spain	602	18-year-old experimental orchard (278 trees ha^{-1})	5 treatments: FI 75% ETc and no irrigation from mid-July to mid-September (RDI) 75% ETc (SDI) Adaptation to alternate bearing habit: R during years of few or no crops and FI during heavy crop years R	Responses to deficits were similar for SDI and RDI; yield responses to FI during the bearing year and R in the nonbearing year were less favorable than those observed in SDI and RDI.	Moriana et al. (2003) [81]
SDI and RDI	Arbequina	Cordoba, Spain	502 (3-year average during the experiment)	12-year-old experimental orchard (408 trees ha^{-1})	3 treatments: FI 25% IWR (SDI) 25% IWR and no irrigation in midsummer (RDI)	RDI and SDI caused higher reductions in fresh fruit yield than oil yield due to a higher oil concentration in deficit-irrigated trees	Iniesta et al. (2009) [100]
SDI and RDI	Koroneiki	Nicosia, Cyprus	428	17-year-old commercial orchard (278 trees ha^{-1})	2 treatments: 70% ETc (SDI) 70% ETc ② → 35% ETc MS → 70% ETc ③ → 35% ETc during maturity (RDI)	No significant differences between the two irrigation treatments were found in terms of morphology, physiology, fruit yield, or oil quality; water productivity was 1.4 and 1.0 kg oil m^{-3} in SDI and RDI, respectively.	Siakou et al. (2021) [78]
RDI	Arbequina	Seville, Spain	534	4-year-old commercial orchard (1667 trees ha^{-1})	3 treatments: FI 60% IWR ② → 10% IWR MS → 30% IWR ③ (RDI1) 80% IWR ② → 20% IWR MS → 100% IWR ③ (RDI2)	RDI1 treatment showed the best balance between water saving (72%), tree vigor, and oil yield (26% reduction) when compared to FI.	Fernández et al. (2013) [102]

Table 3. *Cont.*

DI Strategy	Cultivar	Location	Annual Rainfall (mm)	Orchard Type	Irrigation Treatments	Main Results	Reference
RDI	Arbequina	Toledo, Spain	395	10-year-old commercial orchard (1250 trees ha^{-1})	4 treatments: FI 30% IWR in July and FI in the remaining growth period (RDI1) 30% IWR in August and FI in the remaining growth period (RDI2) 50% IWR in July and August and FI in the remaining growth period (RDI3)	FI trees produced more oil and fruit with higher oil percentages than RDI trees; the oil yield with RDI1 was not significantly reduced compared with FI and the oil percentage was higher; RDI1 was the most effective strategy, with 16% less water applied relative to FI.	Gómez-del-Campo (2013) [75]
RDI	Arbequina	Pencahue Valley, Chile	620	6-year-old commercial orchard (1333 tress ha^{-1})	4 treatments: FI Irrigation cut-off from fruit set until Ψstem = −3.5 MPa (RDI1) Irrigation cut-off from fruit set until Ψstem = −5.0 MPa (RDI2) irrigation cut-off from fruit set until Ψstem = −6.0 MPa (RDI3)	Fruit yield, fruit weight, and fruit diameter decreased in RDI2 and RDI3; total oil content and pulp/stone ratio were not affected by the different irrigation strategies; RDI treatments averaged 83% to 53% of applied water compared with FI.	Ahumada-Orellana et al. (2017) [104]
PRD	Picholine marocaine	Station Saada, Morocco	250	13-year-old experimental orchard (278 tress ha^{-1})	4 treatments: FI (100% ETc on both sides of the trees) 50% ETc on one side, switching every irrigation (PRD1) 50% ETc on one side, switching every two-irrigation (PRD2) 100% ETc on one side, switching every irrigation (PRD3)	Slight yield reduction (15–20%) under PRD1 and PRD2 was mainly due to a decrease in fruit number; oil percentage and oil acidity in the fruits did not show any significant differences between PRD treatments and the control; water use efficiency increased (60–70%) under PRD1 and PRD2 treatments.	Wahbi et al. (2005) [114]
PRD	Chemlali	Sfax, Tunisia	220	9-year-old experimental orchard (625 trees ha^{-1})	4 treatments: FI (100% ETc on both sides of the trees) 50% ETc on one side, switching every 15 days (PRD1) 50% ETc on one side, switching every 30 days (PRD2) R	PRD2 achieved a slight cumulative yield reduction (11%) compared to FI while applying half of the irrigation quantity; oil content showed an improvement with increasing deficits.	Ghrab et al. (2013) [115]
PRD	Arbequina, Arbosana, and Chetoui	Sidi Bouzid, Tunisia	240	11-year-old commercial orchard (1250 trees ha^{-1})	4 treatments: FI (100% ETc on both sides of the trees) 100% ETc on one side, switching every 2-weeks (PRD1) 75% ETc on one side, switching every 2-weeks (PRD2) 50% ETc on one side, switching every 2-weeks (PRD3)	Shoot length was lower under PRD irrigation treatments, mainly for Arbequina and Chetoui; reducing irrigation volumes by 25% and 50% with PRD strategy compared to the control increased oil yield and water productivity, mainly for Arbequina cultivar, without significant reductions in yield components.	Abboud et al. (2019) [116]

Notes: (1) Values between brackets were used in the second year of the trial. R: rainfed; SI: supplemental irrigation; SDI: sustained deficit irrigation; RDI: regulated deficit irrigation; PRD: partial rootzone drying; FI: full irrigation; IWR: irrigation water requirements (ETc—Crop evapotranspiration); MS: midsummer (late June to late August); ②—period that occurs at the end of the first phase of fruit development (normally in June) (Figure 3); ③—after the midsummer period, around 3 weeks prior to ripening, when a marked increase in oil accumulation occurs (normally from late August to mid-September) (Figure 3). Ψ_{stem}: stem water potential.

4. Agroecological Practices

4.1. Non-Tillage, Cover Crops and Herbicide Reduction

Semi-arid Mediterranean regions are among the most productive areas in the world [118]. However, the soil has a low carbon content and is susceptible to degradation [119–121]. Semi-arid soils are exposed to erosion by random and heavy precipitation, absence of herbaceous plant cover, and high rates of carbon mineralization related to high temperatures and high soil pH [45,122,123]. Intensive tillage in olive farming promotes soil organic matter degradation and general nutrient losses [124] (Table 4). Thus, tillage increases CO_2 emission at the expense of organic matter, contributing to global climate change. In irrigated olive orchards such as HD or SHD, it is possible for non-tillage practices to be implemented, fully mitigating these side effects. Normally, the organic matter in non-tillage orchards is about 0.8% or more higher than tilled ones [125]. The contribution to carbon sequestration of a non-tillage system with cover crops is 1.23 t C ha^{-1} year^{-1} [126] or 1.34 t C ha^{-1} year^{-1} [123] compared with bare soil. Non-tillage system avoids the propagation of soil-borne diseases such as *Verticillium dahliae*, the main soil-borne disease for this perennial species worldwide [56,127]. Preventing soil disturbance and minimizing the contact of fungus mycelia from root to root decreases the infection rate.

Herbaceous vegetation can have a positive impact on erosion reduction, especially in orchards planted on slopes [31], contributing to carbon and nitrogen sequestration and acting as a nutrient buffer. Herbaceous cover also provides shelter and food for many beneficial and pollinator insects. Nevertheless, vectors for the bacteria *Xylella fastidiosa* could also live and feed on orchard weeds. Late in the spring, as the weeds dry out, these vectors could fly from weeds to the olive canopy and infect the olive trees [128,129].

The generalized application of herbicides dramatically decreases the number of species, plants, animals, and other living organisms present in an olive orchard ecosystem [125]. For instance, the abundance and diversity of nematodes is lower in bare soils treated with herbicides, and is intermediate in non-herbicide areas [125]. Normally, tillage reduces the number of arthropod species [130,131].

The use of herbicides in the total area of an orchard increases the rainwater runoff and contributes to faster soil erosion and lower nutrient availability [132]. The use of herbicides sprayed in stripes, as in rows of trees, seems to have a lower impact on soil erosion. Weed species present on an olive orchard's floor, like *Conyza* sp., present significant challenges nowadays, as they are not effectively controlled by glyphosate spray treatment [133,134]. The eventual withdrawal of this herbicide will lead to the implementation of other non-herbicide solutions for orchard floor management [135].

4.2. Pruning Biomass Recycling

Olive orchards show a carbon accumulation rate in tree structures of 0.58 t C ha^{-1} year^{-1}, whereas the maximum potential rate is around 1 t C ha^{-1} year^{-1} for perennial crops; 20 year-old olive orchards can have up to 11.7 t C ha^{-1} in the trees' permanent structures, and pruning residues represent an additional 2 t C ha^{-1} year^{-1} [123]. The annual olive orchard carbon sequestration is higher than the amount denoted for vineyards and lower than that mentioned for other fruit trees [123].

In HD and SHD olive orchards, the pruning wood is normally shredded together with the cover weeds, and its nutrients are slowly released over time. This is a way to recycle nutrients and organic matter [136]. The presence of chopped wood pieces and weed residues on the orchard floor has four main benefits. First, it decreases the rainwater runoff speed and helps to prevent erosion [137]. Second, it promotes the rainwater infiltration rate, which is quite important in the case of heavy rain events [136]. Third, it improves machines' traction, preventing tractor or harvesters' wheels from sliding. Fourth, crossed chopped wood pieces act as a physical barrier over the floor, preventing soil compaction [138]. The last two benefits are often disregarded.

Table 4. Summary of selected studies on the effect of agroecological practices on soil factors in high-density orchards.

Soil Factor	Tillage	Pruning Residues	Herbicide	Cover Crops	Organic Farming	Main Results	Reference
Erosion	+	−	+A −P	−	+T −NT	Cover crops can reduce soil loss by more than 92% compared with tillage. The annual water runoff increased with tillage (highest runoff: tillage or full herbicide coverage; lowest runoff: cover crops and pruning residues).	Repullo−Ruibérriz de Torres et al. [139] Novara et al. [51]
Resistance to penetration	+	−	=	−	+T –NT	With cover crops, the compaction decreased at a depth of 0.3 m. Tillage reduced compaction just at the first 0.1 m of depth. Water availability improved in the soil with cover crops. However, the infiltration rate decreased.	Sastre et al. [140]
Water evaporation	−	− or =	−A =P	+	–T +NT	Cover crops increased the water consumption compared with tillage.	Novara et al. [51]
Pesticide accumulation	=	=	+	=	+Cu – Other	Total Cu in olive orchard and vineyard soils is about 5–10 times the concentration found in forest soils. Organic vs. integrated pest management: the use of fewer pesticides, but more cooper fungicides, is recommended.	Viti et al. [141] Miloš and Bensa [142]
Biodiversity	−	=	−	+	–T +NT	Tillage and herbicides decrease soil biodiversity. Tillage reduces the abundance of microarthropods.	Sánchez−Moreno et al. [124] Vignozii et al. [131] Velázquez−Martí et al. [143] Repullo et al. [136]
Organic matter and carbon accumulation	−	+	−	+	–T +NT	Tillage negatively affected soil organic carbon pools in the interrow. Cover crops vs. bare soil: increase of 1.23–1.34 t C $ha^{-1}year^{-1}$. Pruning residues vs. removal: increase of 1–2 t C ha^{-1} $year^{-1}$.	
Nitrogen accumulation	−	+	−	+	–T +NT	The N in pruned residues from a SHD orchard was 59 kg ha^{-1}. The N contained in fruits was 7 kg t^{-1}.	Zipori et al. [144]
Waterlogging	+	− or =	=	−	+T −NT	The olive trees survived if soil salinity was <4 dS m^{-1}. Wet flat land increased tree mortality due to hypoxia. Ridge plantation can prevent this.	Aragüés et al. [145]
Diseases	+	− or =	−	−	+T −NT	Tillage vs. cover crops or herbicides: verticillium wilt increased. Drip irrigation increased verticillium wilt.	Calderón et al. [127] López−Escudero and Blanco−López [146]

Notes: + Increase, − decrease, = equal. A—total coverage, P—stripes of 1 m, T—organic farming with tillage, NT—organic farming with cover crops, IPM—integrated pest management.

4.3. Adaptation of Cultivars

Due to the longevity of olive trees and the adaptation to the cultivation system, the TD and MD olive orchards present different cultivars than the HD or SHD [14]. Therefore, one can wonder whether old traditional varieties could be adapted to HD or SHD systems. According to Marino et al. [147] some old Italian cultivars can be suitable for these systems. In Portugal, the 'Cobraçosa' cv. seems to be adaptable to high-density systems. The introduction of new cultivars suitable for SH or SHD orchards has a positive impact, improving the overall genetic pool of olive orchards [14,148,149]. The use of rootstocks with low vigor makes the adoption of traditional cultivars to SH or SHD systems possible. This is a promising option for decreasing the high vigor normally associated with these cultivars. Traditional cultivars grafted on such rootstocks could live together at a high density, be adaptable to higher soil variability conditions, and present improved pathogen-resistant patterns [150].

Some authors have also referenced the negative impact of tree density on biodiversity, as in the case of bird population reduction [65,151]. Heavier machinery and increased fertilizer, pesticide, and water usage are also said to negatively impact ecosystems' biodiversity [24,152,153]. The generalized adoption of drip irrigation increases the *Verticillium dahliae* in the soil. The inoculum density in all experiments was higher in wet than in dry areas, and after 4 months of watering, the soil pathogen population increased considerably in both wet and dry areas [146]. The inoculum density remained higher in the wet soil.

5. Conclusions

The target of this work was to focus on the sustainability of high- and super-high-density olive orchards.

The increase in tree densities, the introduction of irrigation, and the development of new training systems to facilitate mechanical pruning and harvesting have contributed significantly to the intensification and expansion of olive oil and table olive production. In recent years, concerns about the potential detrimental impacts of high-density olive cultivation have emerged, bringing into question the trade-offs between production benefits and environmental costs. Water-saving irrigation practices and more sustainable soil management or other agroecological practices can mitigate the negative effects of climate change and improve the ecosystem services of dense irrigated olive cultivation.

The systematization of the various olive cultivation systems allows us to gain a better understanding of the olive orchard cultivation mosaic. The review and summary of studies and publications on deficit irrigation strategies and agroecological practices in dense olive orchards can contribute towards optimized options in terms of water, soil, and biodiversity management in order to enhance the health of these types of agroecosystems.

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