Review

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Sustainability of Olive Modern Planting Systems and Potential Mitigation Strategies against Climate Change

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Review

Sustainability of Olive Modern Planting Systems and Potential Mitigation Strategies Against Climate Change

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Abstract: Climate change related issues, such as yield decline, quality losses, accelerated phenology, extreme abiotic stress, pose growers new challenges in olive growing areas. Main cultural solutions that could alleviate stress and improve long-term sustainability of modern olive orchards are here briefly reviewed. Selecting varieties that are more resistant to drought or high temperatures would be the optimal solution to mitigate the effects of climate change, but the available scientific information is relatively scarce. Sustainability of irrigation implies that the less water is used, the better. Best results in terms of saving water and uniform application are obtained using micro-irrigation methods. Water can also be saved by not fully satisfying the tree water needs and different deficit irrigation strategies have been developed and tested for olive orchards. The use of green covers and the application of organic mulches and shredded pruning materials should be encouraged as these practices tend to stock carbon, increase organic matter content and water holding capacity of the soil. Olive orchards are efficient CO_2 sinks as they can store considerable amounts of carbon in their organs and permanent structures. Using environmental friendly practices improves the ecosystem carbon budget and contributes to mitigate climate change.

Keywords: olive; planting systems; climate change

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1. Introduction

Olea europaea L. is a widely cultivated tree crop. The Mediterranean basin accounts for about 95% of world olive production, but cultivation in this area is currently facing major challenges. The Mediterranean region is environmentally fragile and particularly susceptible to the ravages of climate change according to the most recent report from the Intergovernmental Panel on Climate Change, which foresees that the rate of temperature rise in this area will continue to be higher than in the rest of the world and especially in the summer [1]. There is clearcut evidence for global heating: it has been shown that surface temperature in the 2001-2020 period has been 0.99 °C higher than that in the 1850-1900 period, and in the 10-year period 2011-2022 the increase rose to 1.09 °C [1]. Scientists have recently named 'Great acceleration' the rapid growth rate of temperature and other physical and socio-economic indexes related to human activities since the 1950s [2].

New problems due to climate change are also emerging for olive plantations, such as yield decline due to severe and long droughts, quality losses, changes in phenology induced by high temperatures, more frequent extreme events (heat waves, strong winds, torrential rains, low temperature) during flowering, fruit set and the first few weeks of fruit development, that is the most vulnerable stages of the annual reproductive cycle. While the extent of climate change induced yield decline is yet to be precisely quantified, it has been estimated that an increase of 1.5-2 °C in temperature could decrease olive production by up to 21%, while with an increase of 3 °C could bring about drops of 15 to 64% under rainfed conditions [3].

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2. Evolution of planting systems

The wide distances at which olive trees have been traditionally planted allow large volume of soils to be explored by root systems and good yields even under rain-fed conditions. Yet, to increase production and cut down costs olive cultivation has evolved from traditional, low-density and low-input systems to more intensive ones. The underlying principle behind increasing planting density is that smaller trees intercept more light per unit area than large, sparse ones, thus increasing yield [4,5].

Modern planting systems include medium/high density (240-600 trees ha^{-1}), and very high density orchards (over 1000 trees ha^{-1}) often named superintensive. The 600-1000 trees per hectare density range is uncommon and limited to experimental trials. It is estimated that about 500.000 ha (equal to less than 5% of world olive growing area) of superintensive plantings produce about 30% of global production, proving more effective than traditional systems (less than 240 trees ha^{-1}) in contributing to the world's supply of olive fruits and oil. While productivity of medium or high density orchards seldom exceeds 10 t of fruit per hectare, superintensive plantations can produce annual yields of 10-15 t ha^{-1} (fruit) and 2-2.5 t ha^{-1} (oil) annually under optimal conditions for several years [6-10]. Although olive trees are well known to withstand dry summers, high evaporative demand, and high UV-visible radiation levels throughout the growing season [4,11], the limited soil volume explored by root systems in very high-density orchards makes these planting systems more sensitive to abiotic stresses (Gucci and Caruso, 2011; Gucci et al., 2012b) and irrigation becomes virtually indispensable. Irrigation also allows early onset of production and less variability due to alternate bearing. The widespread use of irrigation in modern plantations further increases the demand for water in relatively arid areas where olive trees are usually grown. Yet, irrigation also plays an important role in traditional groves present in dry areas, soils with limited water storage, and in the years of low rainfall. In areas of annual rainfall greater than 600 mm, production can be quite high in soils with good water holding capacity even under rain-fed conditions [4,12,13,9].

The aim of this article is to review the current knowledge on modern planting systems with an outlook to major threats and challenges posed by climate change scenarios and potential cultural solutions that could alleviate stress and improve long-term sustainability of modern olive orchards.

3. Climate change enhancement of abiotic stress

Consequences of climate change often include limitations in water and nutrient availability, as well as temperatures and salinity exceeding the optimum range for vegetative growth and production. When stress develops cultivation becomes more expensive and less profitable. In general, adaptative changes to abiotic factors include selection and transmission to the progeny of genetic traits that confer better fitness to the changing environment [14]. Besides genetic adaptations, physiological and morphological ones are developed in response to repeated exposure to stressful conditions and they can also be reversed upon relief of stress. The combination of adaptation and acclimation processes contribute to the overall resistance to abiotic stress for individual species [15]. A brief review of the main mechanisms involved in resistance of olive trees to drought and temperature stress is reported below.

Drought. Olive trees have developed several traits and mechanisms whereby they can cope with drought: anatomical (multicellular trichomes, thick cuticle, hypostomatous leaf, xylem vessels of small diameter), physiological (decrease in water potential, osmotic adjustment, turgor maintenance, stomatal closure), and biochemical (biosynthesis of compatible solutes, changes in carbon partitioning; enzymatic activity against reactive oxygen species) [16,12,11,17,18,19].

At the onset of water deficit olive trees regulate water loss by partial stomatal closure and continue to uptake water by establishing and maintaining a steep water potential gradient between leaves and roots despite the progressive decrease in soil water content. In this way, cell turgor is preserved while cells start losing water and the concentration of osmotically active compounds increases [4,17]. There is some evidence that the rate of stomal closure in response to water deficit is cultivar dependent [20], but more work is needed to further document varietal differences.

The main molecules that olive cells accumulate are soluble carbohydrates (mannitol, glucose), inorganic cations, and organic acids or amino acids [21]. [22] reported an osmotic adjustment ranging from 2.4 MPa to 3.8 MPa in severely stressed trees and estimated that the sugar alcohol mannitol contributed to active osmotic adjustment by 0.45-0.8 MPa in leaves and 0.75-1.42 MPa in roots. Compatible solutes play a protective role in the dehydrated cell and they are synthetized and accumulated in response to drought or salinity [23,21].

As water deficit becomes more severe, cellular dehydration occurs with multiple effects such as the reduction in cell turgor potential and cell volume, an increase in hydraulic resistance, root shrinkage, cavitation of xylem vessels, reduced leaf expansion, stomatal closure, photosynthetic inhibition due to non stomatal components, leaf abscission, reactive oxygen species production, membrane destabilization, protein denaturation, and finally cell death [24,25,17,18]. The metabolism of olive cells is evidently compatible with severe dehydration although mechanisms are yet to be fully elucidated.

From the practical point of view, visible symptoms of lack of water appear late in field-grown trees and, therefore, they cannot be safely used as stress indicators. Severely stressed plants show chlorosis, bronzing, and blade folding of leaves, shoot wilting, and shriveled fruits [11,19]. Water deficit determines abnormalities in flower formation, reductions in the number of flowers and fruits, fruit fresh weight, endocarp weight, and mesocarp cell size [26,27,19,28] (Costagli et al., 2003; Gucci et al., 2009; Rapoport et al., 2004a; 2004b). The effects of water scarcity on olive production largely depend on the phenological stage. Most sensitive stages are flower bud differentiation, flowering, fruit set, the first few weeks of fruit development, during fruit cell expansion and at the beginning of fruit ripening [19,28] (Rapoport et al., 2004a; 2004b).

An implication of the capacity of the olive tree to uptake water at low soil water potential is that the permanent wilting point for an olive orchard can be set at -2.5 MPa rather than -1.5 MPa like for most other crops, which means that the extractable water reservoir is substantially greater than in other crops. The safe interval of pre-dawn leaf water potential for yield components such as oil accumulation and fruit size is above -1.5 and 2.5 MPa, respectively [29,27].

Temperature. Temperature and water availability largely determine the world distribution of plant species and crops [15]. Being the olive tree an evergreen plant, low winter temperatures used to limit its cultivation to mild climates of the Mediterranean region [4,12]. Temperatures below -10 °C for several hours permanently damage vegetative organs [30]. Instead, at flowering, just few degrees above zero are sufficient to damage inflorescences, flowers, fertilization, and fruit set; similarly, a few degrees below zero are enough to freeze fruits at ripening and alter olive oil quality.

In recent years the temperature rise is contributing to modify the area where olive trees can be grown. Summer highs are starting to cause concern for the stress they impose during certain phenological stages and the negative consequences on yield and oil quality. Several days at temperatures close to or over 40 °C cause stomatal closure, tissue dehydration and shriveling, leaf chlorosis, and accelerated fruit ripening. Under these conditions evapotranspiration is enhanced and, other things being equal, the negative effects of drought become more severe. High temperatures during flowering and fruit set can nullify abundant blooms. Research carried out in Israel has shown that the duration of stigma receptivity, pollen viability, pollen tube development, fruit weight, mesocarp layers are negatively influenced by high temperatures [31,32] with unfavorable repercussions on pollination, fertilization, fruit set and, consequently yield. [33] compared the temperature response of pollen germination and pollen tube length *in vitro* and classified Mastoidis and Kalamata as tolerant cultivars, Koroneiki and Amygdafolia as intermediate ones at 30 °C.

As for oil quality, high temperatures during fruit development influence the fatty acid composition. Hot climates lead to modifications especially in some varieties, that is the percentage of oleic acid is lower while the polyunsaturated fatty acids (especially linoleic acid) and palmitic acid increase [34,32]. High temperatures have been shown to decrease the concentration of phenolic compounds in the oil [32]. The effect of high temperatures on oil quality is cultivar dependent: cv. Souri proved more tolerant than Barnea, Coratina, Koroneiki and Picholine [32].

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Selecting varieties that are more resistant to high temperatures is the best solution to mitigate the effects of climate change. However, there is a dearth of scientific studies on resistance to high temperatures and most information is derived from field observations after heat waves or comparing performance of different cultivars at locations differing in temperature [32]. Furthermore, many studies have only focused on one or two phenological stages, while resistance should be ascertained over the entire growing season to provide growers useful information.

The combined effect of multiple stresses

Drought stress seldom occurs as a single stressing factor in olive growing regions and it is more frequently associated with high temperatures and high radiation levels [14]. Drought and salinity are often present in coastal areas and some of the earlier effects of high salt concentrations are reflected in changes in the tree water relations and soil water availability [35, 12]. Salinity causes an acceleration of fruit ripening and induces some physiological changes similar to those induced by water deficit [35,29,36].

Few studies have investigated the interactions derived from the concomitant occurrence of abiotic stresses. Light exposure affects fruit development and modifies fruit temperature. Fruits receiving high levels of light have a greater fresh weight than those present in less illuminated zones with evident differences in the degree of pigmentation of the epicarp, whereas fruits with little exposure to light are green with delays in ripening and little oil content [37]. The abundance of light and the lack of water lead to a higher concentration in phenolic compounds, but not in lignans [38,37]. Slight variations in the acid composition and better sensory characteristics are found in oils from fruits well exposed to light compared to those produced from olives in the most shaded part, while the position in the foliage does not influence the parameters used for the EU classification of the oils. These effects of light are mediated by the degree of water deficit experienced by trees during fruit development [38,37].

4. Irrigation management

Irrigation is the obvious remedy to alleviate water deficit and high temperature in the canopy. The advantages of irrigation in olive orchards have been widely documented: irrigation increases vegetative growth and yield in traditional groves, it is highly recommended in high-density plantings and indispensable in superintensive ones [39,40,29,41,13,42]. The correct application of water is fundamental to match tree requirements and reduce water consumption [43,44]. Restricting the volume of water supplied decreases vegetative growth, but not necessarily oil production [39,29,42]. Significant economic benefits are also achieved through the improvement and diversification of olive oil quality obtained by selecting appropriate irrigation regimes [45,46,47,48].

Sustainability of irrigation implies that the less water is used, the better. Best results in terms of saving water and uniform application are obtained using micro-irrigation methods. Other methods distribute water over a larger area with greater water losses due to evaporation and less water use efficiency [43]. Besides the use of micro-irrigation methods, water can be saved by not fully satisfying the tree water needs. Many different deficit irrigation strategies have been tested in olive orchards [12]. In the most common ones the deficit is distributed evenly throughout the entire irrigation season (sustained deficit irrigation) or the deficit is concentrated from the pit hardening stage through the end of the summer (regulated deficit irrigation). There is not yet evidence that shows the superiority of one strategy over the other, as they both seem to give good results depending on precipitations and soil water holding capacity [12]. Nevertheless, in order to have good flower fertility and fruit set, it is important that the water supply be adequate 2-3 weeks before and after flowering.

The overall water consumption in deficit-irrigated orchards is very limited. Most studies report that strategies supplying only between 30 and 70% of the volume needed for fully-irrigated trees are effective in maintaining yield and tree health [39,49,50,40]. Under dry conditions and low annual precipitation, irrigation volumes ranging 20-50% of evapotranspiration can be sufficient for some vegetative growth and production in medium- or low-density orchards). In Tunisia irrigation volumes of only 20% of evapotranspiration determined increases of water productivity of local and

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international cultivars even at the lower water supplies [51]. As little as 50 mm of irrigation water annually are sufficient to increase yields significantly in sub-humid climates compared with rain-fed conditions, whereas about 100 mm are needed in drier climates. These amounts are much less than those used in most other crops. Superintensive olive orchards have higher water needs than systems with fewer trees per unit area because of the limited soil volume explored by the fine roots of each tree [49,9,52]. Irrigation volumes may be as high as 600 mm in arid climates, but deficit irrigation strategies can be used to reduce water consumption [49,40].

Irrigation increases yield, fruit size, pulp-pit ratio, mesocarp cell size and oil content [46,27]. The sensitivity to water deficit of each cultivar in a given environment is critical for the development of an adequate deficit irrigation strategy [53,54,55]. Irrigation does not affect the analytical parameters used to classify olive oils according to EU regulations, such as free acidity, absorbance in the ultraviolet (K_{232} and K_{270}) and number of peroxides [46,48] As irrigation volumes increase, the ripening index, total polyphenols, oxidative stability mono-unsaturated fatty acids and the oleic-linoleic acid ratio decrease, while polyunsaturated fatty acids generally increase, although sometimes the differences are negligible [46,56,47,48] In arid climates water deficit can lead to significant changes in fatty acid composition [34].

Using deficit irrigation is the best compromise for the production of quality oils, as it allows higher efficiency and a considerable increase of oil yield in comparison with rain-fed trees and a small or null decrease in yield along with substantial water savings compared to fully-irrigated trees [39,12,47]. To target quality and develop tailor-made protocols for cultivars and locations, it is important to monitor tree water status and determine the water use efficiency and needs of different cultivars. For example, differences in the response to irrigation between cv. 'Arbequina' and 'Coratina' have been reported [55](Vivaldi et al., 2013).

5. Soil management

Managing the orchard floor with a grass cover is more sustainable than periodic tillage or herbicide applications [9] Advantages of grass cover include an increase in the total and organic carbon content, improvement of soil structure, increased water infiltration rate and a more favourable pore distribution pattern for water and gas flows [41,57]. The improved chemical and physical soil properties are also beneficial for the biomass and diversity of microbial communities and microarthropods [58,59].

The interactions between soil texture, growth of tree and grass root systems, abundance of food and mineral sources for micro organisms, and the spatial variability caused by the grass cover across the orchard determine a patchy distribution of soil resources (organic matter, humidity, nutrients) and biological components that makes the entire system complex and resilient. On the other hand, the absence of a grass cover in the inter-row of tilled soils can dramatically lower the orchard sustainability by increasing soil erosion, diminish the carbon input, and deplete the microbiological component [58] (Simoni et al., 2021).

The use of green covers and the application of organic mulching materials and shredded pruning residues should be encouraged as these practices tend to increase the organic matter content of the soil which, in turn, improves soil water holding capacity [60,61]. The application of organic matter, that can also be derived from tree prunings, stabilized olive pomace and wastewater from the olive mill, is an effective way to supply nutrients and fertilize the orchard at a lower environmental cost than by using mineral fertilizers [61,9]. In addition, the carbon sequestration of non tilled soil with a cover crop in olive orchards is well above 1 t C ha^{-1} per year [9]. The negative effects of green covers on tree growth during the training phase of the young orchard can be overcome by putting off the cover crop establishment to the third or fourth growing season after planting.

6. Carbon sequestration

Olive groves provide a number of services besides production of fruits and oils. These ecosystem services include soil conservation, hydrological regulation, maintenance of biodiversity and landscape, recreational use, and contrast to climate change not to mention cultural and historical heritage. Since most groves are on slopes, olive growing areas are vulnerable to soil erosion and landslides, excessive water runoff, loss of fertility and degradation. Biodiversity and landscape can be maintained if proper management is conducted, but in many instances the lack of revenue generated from olive cultivation results in land neglect and abandonment.

One important service provided by olive orchards is carbon sequestration. The carbon balance is highly variable depending on site, year, planting density, irrigation and orchard management [60,62]. In most cases carbon uptake prevailed over carbon emissions resulting in less CO_2 released in the atmosphere [61,62]. The annual net carbon fixation measured in traditional rain-fed, traditional irrigated, and intensive olive orchards in Andalusia was 4183, 6290, and 4070 kg CO_2 ha^{-1}, respectively [60]. In general, productivity affected carbon fixation so that high yields resulted in more carbon fixed by trees [60]. It has been estimated that olive orchards accumulate carbon in their woody structures at an annual rate of 0.58 t ha^{-1} and pruning residues provide an additional 2 t ha^{-1} per year [9]. The net ecosystem productivity of an irrigated orchard was positive, although the actual balance depended on annual yields, that is on carbon exported to fruits [62]. The overall carbon stock in European olive trees was estimated to be 0.22 Gt CO_2. Green practices such as cover crops and distribution of pruning residues could sequester additional 0.03 Gt CO_2 per year [61]. In this respect, the carbon dioxide removal potential of olive orchards plays an important role in mitigating the climate change effects and reaching the carbon neutrality target, provided conservation management practices are implemented. Nevertheless, recent models foresee that a temperature rise of 2 °C will bring about a decrease in net ecosystem exchange and net primary production [63,64]. An additional factor that may upset the sequestration potential is the occurrence of heat waves that increase actual evapotranspiration. In an irrigated apple orchard [65] recently reported that gross primary production and net ecosystem exchange patterns showed significant reductions in the assimilation capacity of the orchard in South Tyrol in two hot years (2013 and 2015), but there are no experimental results for olive groves.

7. Conclusions

The Mediterranean area is considered a secondary hot spot in climate change scenarios, that is an area where the effects of climate change are evident, but unable to influence the dynamics of the phenomenon [1]. The main critical environmental issues can be summarized as follows: temperature, erosion and sea level increase, precipitations, flows from water basins, and production of non-irrigated crops decrease.

One of the key questions about sustainability of high– and very high-density olive orchards lies in their water consumption. Although some controversial results have been reported, most published studies agree that increasing tree density increases water needs and that superintensive orchards are the most demanding systems in terms of water and other inputs [43,66,8,42,9,]. Thus, the intensification process of olive growing that is taking place worldwide involves serious environmental concerns about the use of groundwater for irrigation in arid areas where governance is needed to preserve water and other natural resources. Under all circumstances, the use of deficit irrigation to optimize yield, oil quality, and save water should be recommended [45,38,43,12]. Optimizing quality of virgin olive oil (VOO) is an additional key point to emphasize for a general and modern concept of sustainability because of the scientific evidence about the benefits for human health provided by high quality VOO [67].

The sustainability of agro-ecosystems largely depends on how cultural practices are compatible with soil conservation issues. Crop management profoundly affects biodiversity, physical and chemical properties, and equilibria in the soil, that are all crucial for safeguarding ecosystem services and the integrity of natural resources. Soils of the Mediterranean area, where olive growing is one of the main cropping systems, are fragile and subject to desertification. Climate change effects may further exacerbate risks of loss of fertility if conservative practices are not adopted.

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