

Review

# Mediterranean Olive Orchards under Climate Change: A Review of Future Impacts and Adaptation Strategies

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**Abstract:** The olive tree (*Olea europaea* L.) is an ancient traditional crop in the Mediterranean Basin. In the Mediterranean region, traditional olive orchards are distinguishable by their prevailing climatic conditions. Olive trees are indeed considered one of the most suitable and best-adapted species to the Mediterranean-type climate. However, new challenges are predicted to arise from climate change, threatening this traditional crop. The Mediterranean Basin is considered a climate change “hotspot,” as future projections hint at considerable warming and drying trends. Changes in olive tree suitability have already been reported over the last few decades. In this context, climate change may become particularly challenging for olive growers. The growing evidence for significant climate change in the upcoming decades urges adaptation measures to be taken. To effectively cope with the projected changes, both short and long-term adaptation strategies must be timely planned by the sector stakeholders and decision-makers to adapt for a warmer and dryer future. The current manuscript is devoted to illustrating the main impacts of climate change on olive tree cultivation in the Mediterranean Basin, by reviewing the most recent studies on this subject. Additionally, an analysis of possible adaptation strategies against the potentially negative impacts of climate change was also performed.

**Keywords:** Mediterranean olive orchards; olive trees; climate change; climate impacts; adaptation measures



**Citation:** Fraga, H.; Moriondo, M.; Leolini, L.; Santos, J.A. Mediterranean Olive Orchards under Climate Change: A Review of Future Impacts and Adaptation Strategies. *Agronomy* **2021**, *11*, 56. <https://doi.org/10.3390/agronomy11010056>

Received: 1 December 2020

Accepted: 24 December 2020

Published: 29 December 2020

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## 1. Olive Orchards in the Mediterranean Basin

The olive tree (*Olea europaea* L.) is an ancient, traditional crop in the Mediterranean Basin [1,2]. It is believed that the olive tree originated in the Mediterranean region and has been cultivated since 4800 B.C. [3]. Today, this perennial evergreen tree has great socio-economic importance for many countries in southern Europe [4], which jointly produce roughly 95% of the world’s supply of olive oil [5]. The world’s production of olive oil is approximately 2.5 million tons (Figure 1), and the main producers are Spain (38%), Italy (11%) and Greece (11%) (Table 1). From 1990 to 2018, olive oil production underwent an upward trend ( $36 \times 10^3$  t/yr), mostly driven by the increases in Spain [6], although the effect of biennial or alternate bearing is apparent (high/low yield years). About 90% of the world’s olive production is for oil extraction, whereas the remaining 10% is for table olives [7]. Since olive oil is traditionally exported worldwide, this crop has become the foundation for the economic development in many of these agrarian regions [6].

Figure 2 depicts the current olive orchard land cover in the Mediterranean Basin. The olive tree area worldwide is approximately 10 million hectares—more than 90% is located in the Mediterranean Basin, mainly in Spain (25%), Tunisia (13%), Italy (11%), Morocco (10%) and Greece (9%) [7]. The growing awareness of olive oil’s nutritional value has been helping with the expansion of olive tree cultivation area over the last few

decades [6]. Some of the most important olive-growing regions in Europe are Andalucía, Extremadura and Castilla/La Mancha, in Spain; Sardegna, Sicily and Puglia, in Italy; and Crete and Peloponnese, in Greece [6].

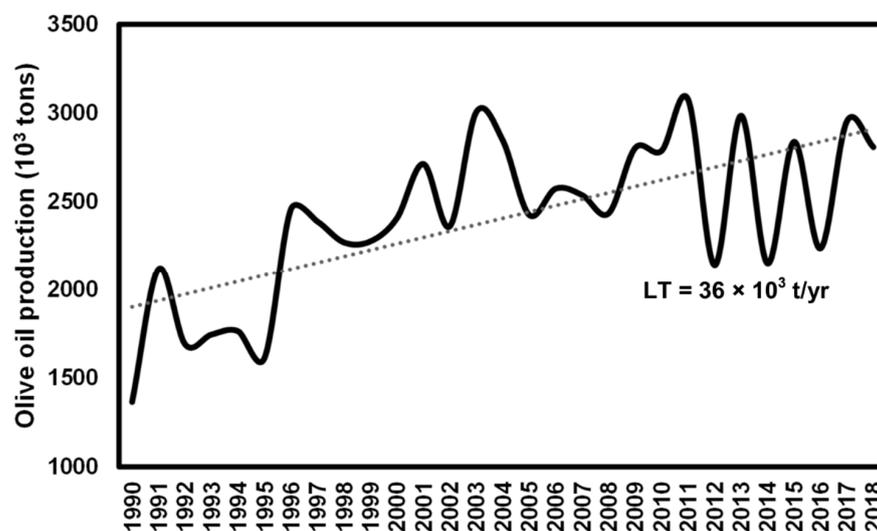


Figure 1. Olive oil production (tons) from 1990 to 2018 along with the linear trend (LT), adapted from [8].

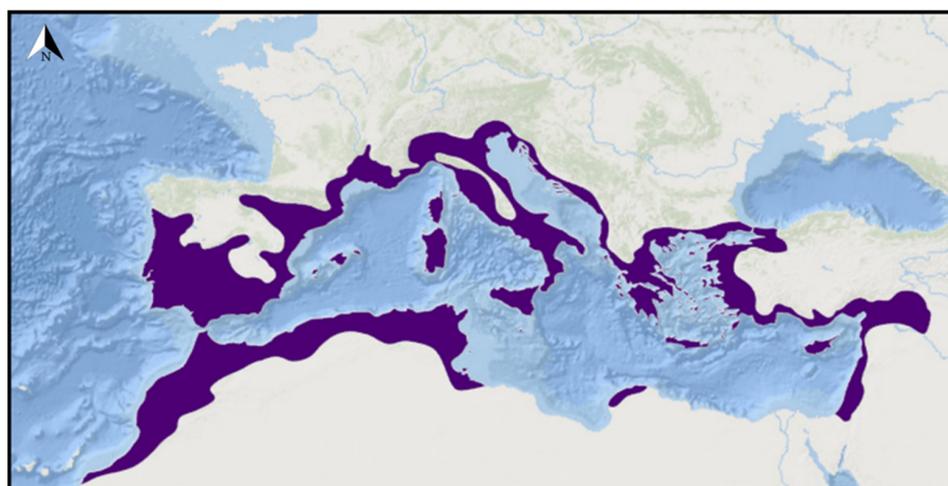


Figure 2. Distribution of the olive orchards in the Mediterranean region according to [9].

In the recent past, most of the Mediterranean olive orchards were grown under rainfed conditions and low-density management systems (<100 plants/ha) [10], mostly exploiting marginal areas characterized by shallow soils and steep terrain that could not easily be used for other crop cultivation [11]. Under these circumstances, while playing a significant role in local economies [12,13], olive cultivation may indeed contribute to the preservation of natural resources of the ecosystem through soil protection, enhanced soil water retention and carbon sequestration [11,14–18].

Nonetheless, a recent increase in global food demand, lack of human labor and other socio-economic constraints, such as the need to increase profitability, are promoting a shift toward intensive (200–500 plants/ha) or even super-intensive (up to 2500 plants/ha) cropping systems. Therefore, crop profitability through the reduction of costs per unit yield is the main reason for the change in crop management. These changes also entail that large areas need to be irrigated and fertilized to increase yield per area [19]. Additionally, olive trees need to be adapted to mechanical pruning and harvesting [20].

The large expansion area and long life of the olive tree explain the vast number of existing cultivars, over 2600 [3] (Table 1). The behavior of each variety in each region results from genetic determinism, which is expressed in the characteristics of each cultivar [3]. These genetic traits are then expressed in phenology, fruit ripeness, resistance to stress, resistance to pests and diseases, final yield and oil quality. Despite the different characteristics of each cultivar, it is known that most of these expressions are also strongly conditioned by the pedoclimatic conditions prevalent in each olive grove.

**Table 1.** List of the top countries regarding olive tree production and area (2016–2018) [7], and also the list of the most used cultivars in each country [3].

Country	Prod. (t)	%	Area (ha)	%	Main Cultivars
Spain	7,817,206	38	2,551,841	25	Arbequina, Aloreña, Cornicabra, Empeltre, Farga, Gordal Sevillana, Hojiblanca, Lechín de Sevilla, Manzanilla de Sevilla, Morisca, Negral, Nevadillo, Picual, Picudo
Greece	2,224,096	11	851,194	9	Anphissis, Chalkidiki, Conservolia, Kalamon, Koroneiki, Kolybada, Lianolia, Mastoidis, Megaritiki
Italy	2,171,166	11	1,144,782	11	Ascolana, Bella di Cerignola, Biancolilla, Bosana, Canino, Carolea, Casaliva, Coratina, Frantoio, Leccino, Moraiolo, Nocellara del Belice, Nocellara etnea, Ogliarola, Pendolino, Peranzana, Taggiasca
Turkey	1,776,822	9	852,011	8	Ayvalik, Domat, Erkence, Çakir, Memecik, Memeli, Uslu, Izmir Sofralik, Gemlik
Morocco	1,338,896	7	1,024,707	10	Picholine Marocaine, Dahbia, Haouzia, Menara, Meslala
Egypt	912,549	4	81,523	1	Aggizi Shame, Kosiem, Maraki, Meloky, Hamed, Sebhawi, Sinawy, Toffahi, Wateken
Algeria	747,225	4	429,217	4	Aaroun, Azeradj, Blanquette, Bouchouk, Chemlal, Ferkani, Khadraya, Hamra, Limli, Mekki, Sigoise, Roulette
Portugal	697,456	3	358,647	4	Galega, Corbrançosa, Cordovil, Verdeal Transmontana, Carrasquenha, Lentrisca, Madural
Tunisia	675,156	3	1,372,104	13	Chétoui, Chemlali, Oueslati, Chemlali Tataouine, Zalmati, Gerbouli, Baroni, Rkhami
World	20,337,435		10,185,151		

In the Mediterranean Basin, traditional olive orchards tend to have distinctive climatic conditions [4]. Olive trees are considered one of the most suitable and best-adapted species to the Mediterranean-type climate [21,22]. Long, warm and dry summers, with mild and wet winters, are general features of this climate [23,24]. Additionally, olive orchards in the Mediterranean are usually exposed to high levels of solar radiation, particularly during spring and summer. Nowadays, olive trees face new challenges and threats, some of the most important being related to climate change. Increased warming and drought, and increases in the frequency of the occurrence of extreme weather events, such as heatwaves, are some of the problems that growers will have to deal with in the upcoming decades.

The present review intends to provide clues on how climate change may impact olive tree cultivation in the Mediterranean Basin, and also provide an overview of the suitable adaptation measures available for growers. Therefore, a discussion on the interconnections between olive trees and climate is presented in Section 2. The climate change projections and their impacts on the olive cultivation are presented in Section 3. Section 4 is devoted to adaptation strategies. Finally, Section 5 outlines the main conclusions.

## 2. The Olive Tree Cycle and Climatic Influences

Globally, the olive tree cultivation is approximately limited by the 30° to 45° parallels [3] (Figure 2). This latitudinal belt suggests that climatic conditions are a key factor for olive tree cultivation, and for its development cycle, and the link between climate and olive

cultivation was recognized very early on. Theophrastus (as reported by Pliny the Elder [Plin. Nat. 15.1]), for example, identified its geographical limits, indicating that the olive tree had to be cultivated at no more than 300 stages (53 km) from the Mediterranean coast. Pliny the Elder observed that the climatic limits were imposed by the sensitivity of the plant to low temperatures, winter frost and extremely high temperatures in summer ("*Fabianus negat provenire in frigidissimis oleam neque in calidissimis*"; Fabiano stated that the olive tree will not grow either in very cold climates or in very hot ones [Plin. Nat. 15.2]). In other words, Pliny the Elder roughly indicated that the most suitable climatic conditions for the cultivation of the olive tree are represented by what today is called a typical Mediterranean climate, which represents the transition between the arid climate of Northern Africa and the temperate rainy climate of Central Europe [25]. As a matter of fact, an olive tree typically cannot withstand temperatures below  $-8\text{ }^{\circ}\text{C}$  for more than one week [26]. Very high summer temperatures may also limit its yield performances, namely, maximum temperatures higher than  $\sim 30\text{ }^{\circ}\text{C}$  [27], and its photosynthetic rate when exceeding  $40\text{ }^{\circ}\text{C}$  [28]. A comprehensive climatological analysis over the Mediterranean Basin indicated that olive cultivation areas are nowadays constrained by temperatures of the coldest (mean monthly temperature of January) and warmest months (mean monthly temperature of July), where the optimum monthly mean temperatures for its cultivation are centered on  $\sim 7\text{ }^{\circ}\text{C}$  in January and  $\sim 25\text{ }^{\circ}\text{C}$  in July [25].

Temperature acts as the main driver of olive tree phenology by regulating the release from the endo-dormancy period, after the accumulation of adequate cold units during winter-time (chill units), and the release from the eco-dormancy period, whose duration is dependent on forcing units cumulated from the end of endo-dormancy to flowering stage [29–31]. The transition between the growing and rest period is triggered by temperatures below  $14.4\text{ }^{\circ}\text{C}$  [32]. The fulfillment of the chilling requirement plays a major role in determining olive flowering [33], since the accumulated exposure to cold temperatures enables plants to properly set inflorescence production when warmer temperatures arise [3]. Accordingly, olive trees planted under tropical conditions do not usually produce fruits, mostly due to the lack of sufficient chilling accumulation [33]. Both chill and forcing unit accumulation have metrics that are generally consistent in the literature. Rallo and Martin [34] and De Melo-Abreu et al. [35] indicated that the best hourly temperature for chilling accumulation is just above  $7\text{ }^{\circ}\text{C}$  (accumulation of temperatures below  $7.2/7.3\text{ }^{\circ}\text{C}$ ), while base temperature for thermal unit accumulation ranges between  $8$  and  $9.2\text{ }^{\circ}\text{C}$  [35].

Another very important climatic factor is precipitation. About 90% of the olive trees grown in the Mediterranean Basin are primarily under rainfed conditions [36,37]. Although olive trees are drought-tolerant species, their distribution in arid zones is limited by annual precipitation lower than  $350\text{ mm}$  [38], and water availability is still considered an important resource to improve final yields. For this reason, olive growers employ management practices, such as sparse plantings and heavy pruning, to avoid severe water stress. This highlights the key role played by precipitation in the economic viability of this crop, which is exacerbated by the typically dry summers in their cultivation areas [21]. Hence, growers strongly depend on the efficient use of winter and spring rainfall for their orchard productivity. However, soil properties, such as soil water holding capacity, also play noteworthy roles in olive tree development. Despite being well adapted to low fertility, shallow and poor soils, the best conditions for olive trees are deep and fertile soils with moderate water contents [3].

Other atmospheric factors, such as solar radiation, relative humidity and wind, also influence the productivity of olive orchards. For example, wind-affected areas should not be used for olive tree cultivation, since cold and moist winds during spring reduce flower fertilization and fruit growth [3]. Furthermore, hot winds during the summer instigate fruit drop, while dry winds seem to result in early maturation and fruit shriveling [3]. Furthermore, since wind plays a fundamental role in olive tree pollination [39], dry and hot winds may damage pollen grains. Along these lines, olive tree development is very sensitive to climate and weather conditions, and hence is exposed and vulnerable to climate

change. Therefore, it is imperative to determine the extents of the likely impacts of climate change on this crop.

### 3. Climate Change Projections and Olive Growing Conditions

Climate change is an undeniable fact that is challenging society and every economic sector, including agriculture. In the Mediterranean region, recent reports show that significant warming has occurred in the last 40 years and annual temperatures are now about 1.5 °C higher with respect to the preindustrial period (1880–1899) and well above current global warming trends (+1.1 °C), and since 2014, we experienced the six warmest years on record, globally [40]. Increasing temperatures were accompanied by a series of extreme heat events that occurred at an unprecedented trend in terms of duration, intensity and frequency [41,42], and there has been a substantial decrease in the frequency of cold extremes [43,44].

In the Mediterranean Basin, the observed precipitation regime is characterized by high variability in space and in time. The overall analysis of extreme precipitation indices reveals that decreasing trends are generally more frequent than increasing trends [45]. Indeed, a more noticeable decreasing tendency in the annual total precipitation is projected, especially over the west-central Mediterranean area [46] and the southern shores of the Mediterranean region [45], though with different local rates [47].

According to the Intergovernmental Panel on Climate Change (IPCC), climate change projections point out that temperatures will continue to rise and precipitation patterns will shift [48]. Although several future scenarios or representative concentration pathways (RCP) have been projected, with different degrees of severity, all point to an overall increase in temperature, though its magnitude is highly dependent on the emission scenario [48]. Although these projections still have high uncertainties, mostly due to climate model limitations and their parameterizations [49,50], it is becoming clear that these projections for future decades tend to be consistent with the recent-past trends [50]. It is worth mentioning that the regional impacts may be stronger/weaker than the global mean signal. Each socio-economic sector, namely, in agriculture, will reveal non-linear responses to changes in temperature, besides their limited ability to adapt to new forcing conditions.

For the Mediterranean region, future climate projections tend to be particularly severe. In this region, precipitation projections point to an overall decrease, which will lead to a lowering of soil water availability. The Mediterranean region is already characterized by plant heat and water stresses, due to the harsh summertime weather conditions, including low precipitation, excessive heat and high solar radiation. Moreover, nocturnal temperatures will also tend to increase, leading to an even higher thermal stress level. Another manifestation of climate change is the modification in the frequency of the occurrence of extreme weather events, such as heatwaves, hail, floods and wildfires, amongst others [51–54]. These events are projected to increase in frequency and magnitude under climate change scenarios, leading to a rise in the severity of drought and heatwave spells over the Mediterranean Basin.

Future climatic changes have great importance for the agricultural sector as a whole, and the olive tree sector in particular. Regarding perennial crops, such as olive trees, under future climatic conditions these projections are expected to cause severe adverse effects, particularly on water relations [55–57], oxidative pathways and other physiological processes [58–60], phenological timings [19,29,61], final yield [19,62–65] and quality attributes [66].

Recent studies applied to olive trees have shown that this crop can be strongly affected by climate change [31,38,67], particularly under the Mediterranean type-climates [61,68]. For instance, rising temperatures may have a strong impact on this crop. The expected increase in temperatures may increase the growing season's length [69]. This will also lead to changes in the phenological timings, particularly in flowering, with potentially detrimental impacts [31,61,68,70,71]. Furthermore, higher temperatures and enhanced evapotranspiration also accelerate fruit ripening, invoking the need for early harvests, though at lower maturity levels [72]. The rise in temperatures could also result in a decrease in chilling conditions [29,73].

Insufficient chilling results in a low fruit setting with detrimental consequences on final yields, as some olive varieties produce deformed floral buds and fruits under these circumstances [74].

Apart from the aforementioned warming effects, water availability also represents a critical issue, particularly for achieving reasonable yields [75]. However, change in water availability is also a major challenge under future climates in the Mediterranean Basin. Nowadays, drought is considered a key limiting factor for agricultural productivity [76]. Although olive trees are a drought-tolerant species [38], water stress may result in a wide range of negative impacts [77], such as a low flower-setting and fruit-setting, low leaf area, limited photosynthesis, flower abortion and cluster abscission. Fraga et al. [57], in a study for Alentejo (the main olive producing region in Portugal), depicted decreases in precipitation (−80 to −90 mm) and actual evapotranspiration (−50 to −70 mm) following two future scenarios (RCP4.5 and RCP8.5). These projections may lead to a general decrease in yields until 2080 due to increased water stress conditions. These impacts are particularly important when considering that traditional olive groves are strictly rainfed [37].

Other studies suggest a decrease in the suitability of the current olive orchards in southern Europe, owing to excessive heat and water stress [25,78,79]. These studies indicate that climate change impacts may be very heterogeneous, since their magnitudes can be quite different from one region to the other [80]. As an example, a study by Ponti et al. [38], concerning future climatic projections, pointed to high economic losses for small olive farms in Italy and Greece, while for some other regions in Europe, these authors pointed to increases in productivity. These outcomes were corroborated by other studies. Orlandi et al. [81], for Italy, suggest that the increase in aridity during the summer signifies an important risk of decreasing olive production. Nonetheless, the authors also recognize that the effect of climate change on the olive yield trend is still mostly unclear, due of the possible interactions between human and environmental factors, and some areas may indeed undergo an increase in productivity in the future. Fraga et al. [64], using an ensemble of regional climate models coupled with a dynamic crop model for olive trees, found similar results, and highlighted heteronomous climate change impacts on yield over southern Europe. These studies indicate the need for regional-to-local climate change impact assessments, as local specificities in climatic conditions may affect the outcomes. Nonetheless, all these studies agree that climate change will negatively impact olive tree yields in some of the warmest and driest regions of the Mediterranean Basin. Another aspect of climate change is related to the impacts of pests and diseases. In fact, studies are reporting that climate change is already affecting Mediterranean areas and enhancing the susceptibility of local olive tree cultivars to certain diseases [82]

One positive aspect of climate change should also be mentioned, i.e., the possible beneficial effect of higher CO<sub>2</sub> atmospheric concentrations in the future. It is known that the increase in CO<sub>2</sub> levels under future climates may have a positive influence on plants, mostly by increasing biomass under CO<sub>2</sub>-enriched environments [60]. This effect may partially counteract climate change's detrimental impacts resulting from enhanced heat and water stresses [83,84]. The widespread distribution of olive groves in the Mediterranean Basin can be also exploited for their important carbon sequestration capacity to mitigate the impact of climate change. Reference [16], following a modelling approach, evidenced the reduction of net primary production and productivity of extensive management of olive groves in warming scenarios of +1.5 and +2 °C, as expected for Mediterranean areas. For contrasting the decrease of olive grove's productivity and improving their mitigation capacity, the same authors pointed out the importance of adopting practices for increasing soil water content and reducing evapotranspiration.

#### 4. Adaptation Strategies

Crop responses to adverse conditions are strongly tied to the implemented adaptation measures. Although the olive tree is a well-adapted species to adverse environmental conditions, suitable adaptation strategies need to be identified and implemented by the sector to face the negative impacts of climate change. Generally, the efficiency of each

measure is strongly governed by the local specificities and regional-to-local climate change signals. Therefore, these responses need to be timely planned at regional/local scales, particularly in the most affected regions. Proper management of the negative impacts of climate change may provide competitive advantages to early-adopting growers [85].

#### 4.1. Short-Term Adaptation Strategies

Short-term adaptation strategies may be considered as the first option against climate change and tend to be focused on specific threats. Short-term adaptation strategies are hereby defined as orchard interventions that can be applied within one or two seasons. These measures mostly imply changes in management practices that can be adopted by growers. Some of them are briefly outlined in the following sub-sections.

##### 4.1.1. Irrigation Management

Even though olive trees are resistant to aridity [20], Tanasijevic et al. [78] claim that the higher frequency and severity of droughts in the future would result in an average increase of 18.5% of the irrigation demand over the Mediterranean, and that the olive tree cultivation characterized by rain-fed conditions may not be feasible under climate change. In line with these projections, Fraga et al. [57] state that, although water resources are limited under warmer and drier future climates, irrigation may be a suitable climate change adaptation strategy for olive tree growers. Mairech et al. [86], using a modelling approach, showed that despite the high climatic variability of the Mediterranean Basin, deficit irrigation may be considered a sustainable management option at the present conditions, by reducing irrigation requirement and increasing crop water use efficiency. In a warmer and drier climate, as projected for the future, although maximum water requirement will increase, especially in the southern Mediterranean regions, irrigated olive orchards will be able to perform satisfactorily, even applying the current amounts of water.

In this context, irrigation is undoubtedly one of the most important options for climate change adaptation. The irrigation timing is crucial to minimize yield losses [87]. Growers are now exploring new ways of optimizing crop water use efficiency by using new irrigation techniques, such as regulated deficit irrigation (RDI) and partial root drying (PRD), amongst others [3]. As an illustration, the RDI strategy uses the knowledge of the crop response to water stress at different phenological phases to identify the periods when fruit trees are less sensitive [88]. For olive trees, water stress early in the season tends to reduce yields, due to interference with flowering and fruit setting, and the pit hardening stage is the most resistant to water deficit [89]. Iniesta et al. [87] state that this technique is a viable alternative to full irrigation. PRD is an irrigation technique that requires a specialized irrigation system, in such a way that 50% of the root system is irrigated and 50% is dry, in any given period [90]. PRD increases root growth in deeper soil layers. Fernandez et al. [91] suggest that similar benefits are achieved in olive orchards with either RDI or PRD.

Despite all the benefits of these techniques, it should be noted that most of the current traditional orchards are mainly rainfed. Applying an irrigation system will thereby bring extra costs for growers. Additionally, the effect of irrigation on the quality of olive oil should also be considered, even though Tovar et al. [92] showed that deficit irrigation does not affect the quality parameters of olive oil in commercial grades. These authors conclude that deficit irrigation results in important savings when compared to full irrigation, without detrimental influences on olive oil quality.

##### 4.1.2. Soil Management and Cover Crops

Michalopoulos et al. [93] proposed replacing the traditional soil tillage with no-tillage soil management, which allows a reduction of soil CO<sub>2</sub> emissions triggered by soil tillage, reductions of economic and environmental costs related to fuel consumption required by traditional practices and the promotion of cover crop development. On the same subject, these authors proposed the use of seed-mix cover crops instead of the traditional

spontaneous vegetation, which may increase soil coverage by up to 100% and promote flora biodiversity. Correia et al. [94] claimed that leguminous cover crops improve the profitability and the sustainability of rainfed olive orchards. Although the use of cover crops is growing in olive orchards [95], certain types of cover crops can compete with the main crop for nutrients and water during some stages of the growing season [96]. Thus, the selection of seed-mixes should be carefully considered [97].

Cover crop management should also be envisioned, e.g., by implementing livestock grazing [98]. No-tillage is also beneficial because bare soils have higher temperature during summer and cooler temperatures during winter, in comparison with that covered by vegetation. Additionally, the application of mulching can also improve soil water reserves, due to reduced evaporation from the bare soils [99], and protect against soil erosion [100,101], which will be of foremost relevance under more frequent and severest precipitation extremes.

Soil fertility is also an important factor that should be considered as a climate change adaptation strategy. As an example, Michalopoulos et al. [93] reveal that future improved soil fertility is an important pillar of climate change adaptation in olive orchards.

#### 4.1.3. Pruning

Michalopoulos et al. [93] state that pruning techniques should be focused primarily on enhancing within-canopy light distribution (photosynthesis oriented), aeration of the foliage and good development of bearing shoots. This should promote a reduction of the “alternate bearing—high/low yield years” phenomenon and the achievement of stable yearly production, with stable labor employment. Moreover, the same authors encourage the mulching of pruning residues, instead of burning, for improving soil fertility. Indeed, the recycling of pruning residues can improve soil organic carbon [102] to avoid direct emissions of CO<sub>2</sub> into the atmosphere due to burning, increases soil organic matter [103] and provides huge potential as a source of energy [104], which should be explored, whenever possible, for improving the future sustainability. However, the use of the pruning residual for mulch may increase the risk of pests and diseases and should be carefully used [105].

#### 4.1.4. Protection against Extreme Weather

The negative effects of extreme heat, water shortage and high solar radiation in olive orchards urge short-term adaptation strategies. The application of spray compounds that can mitigate the negative effects of excessive heat and sunburns is one example. Kaolin clay particles reduce canopy temperature, heat stress and sunburn impacts [106]. Denaxa et al. [107] showed that when kaolin sprays were applied to drought-stressed olive trees, the corresponding negative effects are alleviated. Reference [108] suggested that kaolin or salicylic acid sprays might be effective in mitigating the adverse environmental conditions, without substantial changes in fruit and olive oil quality. Further, kaolin clay has also shown protective properties against pests and diseases [109,110]. On the other hand, spraying olive trees with copper may also give protection against frost [3].

### 4.2. Long-Term Adaptation Strategies

Long-term adaptation options are actions taken by growers, sector stakeholders and decision-makers to adapt to climate change over three or more seasons. The adoption of some long-term adaptation measures may be crucial, though their application may also imply significant socio-economic costs. Although shifts in bioclimatic conditions are expected to occur in the future, the potential of the different adaptation strategies may still prevent more dramatic changes in the suitability of a given region to grow olive trees. Some examples of long-term adaptation strategies are provided in the following sub-sections.

#### 4.2.1. Varietal/Clone Selection

Olive growers have selected the most well-adapted varieties for each location and climate over the centuries. Under future climate change, it is expected that growers will need to replace susceptible varieties with more climate-resilient ones. The distribution of olive tree varieties may be significantly altered due to climate change [1,111]. The vast number of varieties (over 2000) can be a valuable resource against climate change. For this reason, it is of utmost importance to maintain the large genetic pool. As an example, Cabezas et al. [80] recommended the use of cultivars with an earlier flowering date in Seville. Zaied and Zouabi [112] encouraged the use of drought-tolerant olive tree varieties in Tunisia. Furthermore, the implementation of suitable breeding systems is central to this adaptation strategy [1]. Breeding systems should focus on selecting clones with high tolerance to water and heat stress. Certain olive tree clones/varieties have proved to be more resilient to high temperatures and/or to water stress conditions [113]. Tolerance to diseases and insects may also be a major aspect of the varietal and clonal selection, thereby avoiding the excessive use of pesticides and herbicides that can threaten drinking water quality.

#### 4.2.2. CO<sub>2</sub> Effect

Lobell et al. [114] stated that actual yield variability reflects the combined influence of climatic factors and the potentially positive effects of management, technology and increased atmospheric CO<sub>2</sub> concentration. Exposure of olive plants to elevated CO<sub>2</sub> can have a positive effect on plant growth and physiology, namely, enhanced net photosynthesis and decreased stomatal conductance [60,115] leading to increased radiation and water use efficiency [116]. The CO<sub>2</sub> atmospheric concentration has increased from 310 to 410 ppm since the mid-twenty-first century, and it is expected to reach 650–700 ppm by the year 2075 [3]. This may cause a positive impact offsetting some of the negative impacts of other atmospheric factors, such as the warming and drying trend [18] or reduced water requirement for irrigation. Nevertheless, higher CO<sub>2</sub> concentrations may also promote weed growth, increasing the competition for water resources and soil nutrients, depending on the weed species. Therefore, knowledge about the effect of CO<sub>2</sub> influence on primary plant production is of utmost importance for climate change impact assessment.

#### 4.2.3. Relocation

Warmer conditions in Europe will determine a possible northerly shift of olive tree cultivation into regions where nowadays excessively low temperatures are commonly a limiting factor for olive growth [35,117]. It is expected that Atlantic-facing areas may become viable in the near future, due to the increasingly mild winters and warmer and dryer summers [118]. Recent reports indicate that it is now conceivable to plant olive groves in the UK [3] and future projections highlight that potentially cultivable areas for olive groves are expected to extend northwards and towards higher elevations, increasing by 25% in 50 years [78]. Rodríguez Sousa et al. [79] projected that by 2050, in the Mediterranean Basin, a displacement towards lower temperatures and higher moisture areas is expected. This climate-driven shift may lead to the abandonment of some olive orchards in the Mediterranean region, as more areas that are northerly will become more economically viable and profitable. Nonetheless, changes in the northern African part of the Mediterranean Basin may become even more dramatic, as there is no space for relocation (bioclimatic niche extinction) [25]. Therefore, using other adaptation measures is crucial for the olive sector in these areas.

#### 4.2.4. New Crops

Olesen and Bindi [119] defined that one of the consequences of climate change for European agriculture could be the introduction of new crop species. In fact, the identification of vulnerable areas and sectors and assessments of needs and opportunities for changing crops and varieties are valuable responses to climate change trends [120]. New crops should be able to provide food security, especially in future climate scenarios. For instance, ref [121] proposed

several crops, such as quinoa and chia, which are well adapted to harsh environments. Jacobsen [122] also addressed this issue and identified the faba bean, chickpea, lentil and quinoa as crops with improved abiotic stress resistance, and thus possibly good performances in the Mediterranean region. This shows that innovative crops, well adapted to the future warmer and dryer Mediterranean region, can be viable alternatives to current crops.

## 5. Conclusions

The Mediterranean Basin is considered a climate change “hotspot” [123], since future projections hint at considerable warming trends and an increase of consecutive dry days [124], leading to an overall increase in aridity. In this context, climate change may become particularly challenging for olive growers [21]. The growing evidence for substantial climate change in the upcoming decades urges adaptation measures to be taken. As such, the development of future climate projections, based on feasible future socio-economic storylines, is of great value, as they provide objective information that can be used in developing suitable adaptation/mitigation managements to minimize climate change’s impacts on the environment and human activities. In effect, a single adaptation strategy may not be sufficient to counteract the negative impacts of climate change [99]. In a study by Lorite et al. [18], the authors indicated that the best adaptation measure was a combination of using cultivars with early flowering dates and regulated deficit irrigation. Nevertheless, to effectively cope with the projected changes, short and long-term strategies deserve much greater attention in future research [125]. Although the adaptation potential of the different strategies to cope with climate change impacts is still unclear [114], they can be highly beneficial for the agricultural sector as a whole [126].

**Author Contributions:** Conceptualization, H.F.; resources, H.F.; data curation, H.F.; writing—original draft preparation, H.F.; writing—review and editing, M.M., L.L. and J.A.S.; visualization, H.F., M.M., L.L. and J.A.S.; supervision, H.F.; project administration, H.F.; funding acquisition, H.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** The work was supported by the CoaClimateRisk project (COA/CAC/0030/2019) financed by the Portuguese Foundation for Science and Technology (FCT). This work was also funded by European Investment Funds (FEDER/COMPETE/POCI), POCI-01-0145-FEDER-006958, and by the FCT (UID/AGR/04033/2013 and UIDB/04033/2020). Helder Fraga thanks the FCT for contract CEECIND/00447/2017.

**Acknowledgments:** M.M. and L.L. acknowledge the OLIVE2REC project, Giovani @RicercaScientifica number 9/2018, Fondazione Caript; and the project CATChCO<sub>2</sub>-live olive grove Contrast and Adaptation to Climate Change, PSR-FEASR 2014–2020 Regione Toscana.

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

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