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Review

Climate Change Impacts on *Pinus pinea* L. Silvicultural System for Cone Production and Ways to Contour Those Impacts: A Review Complemented with Data from Permanent Plots

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Abstract: Umbrella pine (*Pinus pinea* L.) cones take three years to develop. With the increasing frequency of extreme droughts, water available for trees has decreased—climate change is a reality. The cone's survival in its first two years of development and the average cone weight during its last year of maturation is affected, thus, reducing kernel quantity and quality. Climate change has resulted in forest fires becoming an inescapable issue in forest management planning. A literature review was carried out, focusing, on one hand, the predicted climatic changes for the Mediterranean basin and, on the other hand, the umbrella pine silvicultural mechanisms at tree, stand, and landscape levels that may help to face these constraints. Finally, the Portuguese case was focused, describing the management practices that are being adopted to achieve, even when the period of cone formation and growth include dry years, one to six tons of cones per hectare per year in adult stands.

Keywords: umbrella pine; cone production; climate change; water availability; forest management

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1. Introduction

Umbrella pine (*Pinus pinea* L.) is widely distributed throughout the Mediterranean basin, where it is native, covering more than 700,000 ha as the dominant species [1], with a recent increasing expansion owing forest restoration or farmland afforestation [1,2]. Pine nuts are currently highly prized in international markets. The cones have become the most important product of umbrella pine forests, providing higher incomes to their owners than any other forest resource (timber, grazing, hunting rights, and so on) [3]. It is one of the most important non-wood forest products that can be obtained from the Mediterranean forests [4].

Spanish natural stands are mostly located in four regions: Northern Plateau, Central Range, West Andalusia, and Catalonia, with most of the natural umbrella pine stands being managed for the production of both timber and pine nuts [5]. The first region is the most studied region in Spain concerning umbrella pine development and cone production [4,6]. It is characterized by an average altitude between 700 and 850 m and a Continental Mediterranean Climate, with very cold winters (average annual temperature 11.7–13.7 °C, minimum absolute temperature below −10 °C), often snowings, and very hot summers and very low rainfall (average annual rainfall: 440 mm, ranging from 220 to 620 mm), and summer drought (average rainfall of 54 mm between July–September) [6,7], which can negatively influence cone production even in the absence of inter-tree competition.

In Portugal, there are seven provenance regions and two restricted areas [8] of which the most important for cone production is undoubtedly the region of provenance V, which covers the entire district of Setúbal and part of the districts of Évora, Portalegre, and Santarém [9]. Its stands are predominantly managed for nut production and, secondarily, for timber production. This region, at the Portuguese southeast cost, with an altitude lower than 200 m, has a markedly Mediterranean climate with hot, dry summers and winters milder than in the Continental Mediterranean Climate, water shortage being a more limiting factor than winter temperature. In this region, umbrella pine has an increasing importance, with a 54% increase in area between 1995 and 2010 [10]. Freire [9] point out the main reasons for this increase in area.

1. Cones represent an annual income for forest owners with increasing importance;
2. The substitution of maritime pine as a consequence of high mortality of this species caused by the nematode (*Bursaphelenchus xylophilus* (Steiner et Buhrer) Nickle); and
3. The plantation of umbrella pine inter-mixed within cork oak sparse stands.

In southern Portugal, umbrella pine growth correlates positively with precipitation, spring growth being highly sensitive to previous autumn and winter rainfall [11]. Other authors consider that winter and spring rainfall is crucial in explaining the variability in tree growth [12]. Calama et al. [6] consider that the total rainfall occurring between October of the previous year to September of the current growth year, as well as the mean temperature in May and June, are the main climatic factors driving secondary growth in *Pinus pinea*, Mutke et al. [13] found a highly significant correlation between June rainfall and shoot length and between flower bearing in the next year and current needle and branch diameter growth.

Water stress seems to be the most notable limiting factor in umbrella pine cone-yield [3], as seen both in exponential yield response to rainfall amounts during different cone development stages and in the negative effect of hot midsummers on cone setting [14].

Forestry adapted to climate change, or adaptive forest management, aims to propose technical responses to mitigate the impacts of the expected climate change [15].

This paper starts with a literature review, combined later with information from data available in Portugal. The objective is to use the available research results to provide some guidance for umbrella pine stands for cone production management established at the Mediterranean climate zone in order to face climate changes. It considers different aspects such as umbrella pine development, cone production management, and landscape resilience to fire spread. Special emphasis is given to the case study of Portuguese silvicultural system to characterize the relationship between cone number and weight, and the average weight of a cone and the inter-tree competition, since it was possible to use available data covering:

1. Cone production from plots established in stands whose trees were subject to numerous levels of competition and
2. A wide cone production range in number and weight at tree and stand level. At some situations those were much higher than the ones presented for other countries. These differences may be explained by the favorable site conditions in the country and/or stand management practices.

Finally, some suggestions for adaptive forest management are brought into context with the results of other studies.

2. Umbrella Pine Ecology for Cone Production

Umbrella pine in Europe is distributed mainly in Spain (450,000 ha), Portugal (90,000 ha), Turkey (50,000 ha), and Italy (40,000 ha) [16,17]. It can grow on almost all soil types, including very poor soils, but grows better on sandy substrates [18].

Umbrella pine presents a remarkable degree of phenotypic plasticity [19,20], despite the low genetic variability [19–22]. This may be due to gene expression regulation [20] and/or environmental constraints [19,23]. However, the protein profile analysis allowed differentiating umbrella pine growth macrozones in Chile [24]. In light of these conclusions, it might be possible to achieve a different outcome if the methodology applied in Chile would be tested to the diverse Mediterranean basin umbrella pine provenances.

Umbrella pine fruiting starts at 15 to 20 years old, without being abundant for several years [25]. There is an extremely large variability in cones production between years and trees [3,9,25–32] and between the various Mediterranean basin countries. It is in Portugal where the highest cone production per tree and hectare is achieved, both in weight and number.

The species is characterized by a long cone development cycle, leading to the coincidence of cones one, two, and three years old in the tree, making nutritional and water management more complex than in other cultivated trees [33]. From the beginning of primordia until cones are harvested there is a lag of four years. Between April and May, three years before cone harvest, female flowers appear in the upper part of the crowns, and these flowers are fertilized in May of the same year. Fecundation takes place one year before cone harvest, between May and June. Most of the growth occurs between March and June in the year before cone harvesting, and maturation occurs between October and December [3,34,35].

Umbrella pine is a typical masting habit species, showing huge interannual variability in fruit production mainly ruled by climate factors, especially rainfall events occurring at key moments [17]. The hot points of cone development are bud formation and flower survival, both of which are closely related to rainfall [3]. The sum of May and June and of October and November rainfall three years before maturation are respectively related to bud formation and the differentiation of buds into flowers and buds growth; summer rainfall after flowering conditions flowers survival; the sum of winter–spring months rainfall before maturation influences cone weight [36].

3. Umbrella Pine Nut Production and Productivity in Mediterranean Countries

Gonçalves et al. [29] carried out a literature review of umbrella pine cone production per tree, both in number and weight, in the Mediterranean basin countries. The average cone fresh weight was also characterized (Table 1).

Table 1. Average tree cone number and weight and average fresh weight of a cone at Mediterranean basin countries (Adapted from [29]).

Countries	Tree Cone Number		Tree Cone Weight (kg)		Cone Average Fresh Weight (g)	
	Values	References	Values	References	Values	References
Portugal (overall)	100–120	[37]			286 122–300	[26,38]
Portugal (Setúbal distric)	200–250 >2000	[37]	15 0.06–390	[9]		
Spain (overall)	1–473	[39–41]	0.2–160	[39,42]	29–852	[39,40]
Spain (Northern Plateau)	9	[4]	2.4	[4]		
Spain (Central Region)	15	[4]	4.6	[4]		
Italy	1–305	[25,43]			344–423	[43]
Turkey	146,300	[25,43,44]	100–120	[44]		
Tunisia	7	[45]			60–389	[45]
Greece					101.2–162.5	[30]

Evaristo et al. [38] found that cones tend to be heavier in low-density stands but did found no clear trend between umbrella pines diameter at breast height and the average fresh cone weight.

4. Analysis of Portuguese Silvicultural Systems for Pine Nut Production Using Permanent Plot Data

4.1. Traditional Umbrella Pine Silvicultural Systems for Cone Production

Table 2 shows the traditional umbrella pine silvicultural systems for cone production [46] as proposed by three different authors [47–49]. The three systems recommend an initial stand density of more than 400 trees ha^{-1}, between two and four thinnings during the stand life, the first between 10 and 15 years, and the last one between 20 and 40 years of age. They also propose a rotation age between 80 and 100 years with a final density between 100 and 225 trees ha^{-1} that correspond, respectively, to a mean distance between trees (Mdist) [50] of 10 and 6.7 m.

$$\mathrm{Mdist} = \sqrt{\frac{10000}{\mathrm{N}}}, \tag{1}$$

where N is stand density (trees ha^{-1}).

In short, the traditional guidelines support decisions relative to initial density in plantations (including beating-up), pruning and thinning and age for the final cut. They do not describe the regeneration method in existing stands (including new plantations when they get old) and time/age to start regeneration treatments [46]. At these silvicultural systems, if crown diameters exceed 6.7 to 10.0 m, they will start to compete strongly.

Table 2. R2_3 Traditional forestry systems for umbrella pine [46].

Operation	Traditional Silvicultural Systems		
	[47]	**[48]**	**[49]**
Initial density	625 Trees ha^{-1}	500 till 600 Trees ha^{-1}	208 till 400 Trees ha^{-1}
Pruning	Removal of branches without female flowers (without indication of periodicity)	1/3 branches removal: Between 8 and 12 years Between 20 and 25 years Removal of branches without female flowers: Between 35 and 40 years Between 50 and 60 years	1/3 till 2/3 branches removal: Between 5 and 6 years Between 10 and 12 years Between 20 and 25 years
Thinning	At 10 years till 500 Trees ha^{-1} At 15 years till 300 Trees ha^{-1} At 31 years till 100 Trees ha^{-1}	Between 15 and 20 years till 440 Trees ha^{-1} Between 20 and 25 years till 352 Trees ha^{-1} Between 25 and 30 years till 281 Trees ha^{-1} Between 35 and 40 years till 225 Trees ha^{-1}	Between 10 and 12 years Between 20 and 25 years No information on density after thinning
Final density	100 Trees ha^{-1}	225 Trees ha^{-1}	Between 100 and 120 Trees ha^{-1}
Mdist	10.0 m	6.7 m	Between 10.0 and 9.2 m
Revolution	At 80 years	Between 80 and 100 years	No information about the revolution

4.2. Impact of Competition on Cone Production at Portuguese Umbrella Pine Stands

4.2.1. Description of Data Used

The data available for this analysis come from 100 permanent plots established in southeastern Portugal, the most appropriate Portuguese region for cone production, considering a diverse range of development stages, stand structures and stand densities. Part of the data used is available at https://doi.pangaea.de/10.1594/PANGAEA.895267 and was used by Freire [9], Carrasquinho et al. [51], and Rodrigues et al. [28]. The present data set includes information from more plots and more remeasurements of the initial plots.

4.2.2. Methodology

Cone collection is performed since 1 December of a year till 30 of April at the year after. Thus, when cone production from a specific cone collection campaign is characterized, it is usually designated considering both years. For example the 2004-2005 cone collection starts on 1 December of 2004 and ends on 30 April of 2005.

The analysis of the data available is based on a graphical characterization of the relationship between cone production, tree, and competition measures. First, the correlation between tree cone production and tree diameter at breast height and crown diameter were analysed. Then, the relationship between the production of cones per hectare and stand basal area and number of trees per hectare. Finally, the impact of basal area on the average weight of a cone was analysed.

Cone yield and stand structure are very heterogeneous in permanent plots. Therefore, cone production in the 20th most productive Portuguese permanent plots was analysed separately for even-aged stands, two storied uneven-aged stands, and selection forests. The production was analysed by quadratic mean diameter (dg) classes with 30 cm of amplitude.

The total and umbrella pines average, minimum and maximum basal area, crown cover and density from the 20th most productive Portuguese permanent plots were also analysed, as well as the respective umbrella pine mean, minimum and maximum mean height and quadratic mean diameter.

Additionally, the average, maximum and minimum annual cone weight and the number per hectare at each harvest campaign (from 2004-05 till 2007-08) were also analysed. Finally, the carbon sequestration from dry cones without seeds was evaluated.

4.2.3. Results

The data available show that higher cone productions occur in trees with large diameter at breast height (d) and large crown diameter (Figure 1) [46]. They can be frequently found in highly sparse mature stands, with umbrella pines with d between 75 and 100 cm, and crown diameter between 18 and 24 m, producing more than 400 kg year^{-1} of cones. Those stands in good crop years produce more than 6 Mg of cones ha^{-1} year^{-1} [46]. The cone production variability shown in Figure 1 is due to the masting habit [46]. Larger trees show greater variability of cone production [46]. Nevertheless, plots with very big sparse trees are always the ones with higher cone production per hectare, despite the average production for the year [46]. In order to obtain trees with crown diameter sizes that correspond to large cone productions, the stands, when mature, must have a stand density between 15 and 30 trees ha^{-1} [46]. Figure 1 also shows a number of overmature trees, with a d greater than 1 m, growing with little or without competition but with small cone production [46]. This information suggests that the rotation length in even-aged Portuguese *Pinus pinea* stands for cone production should be around 90–100 years and that the maximum diameter in selection forests should be around 1 m [46].

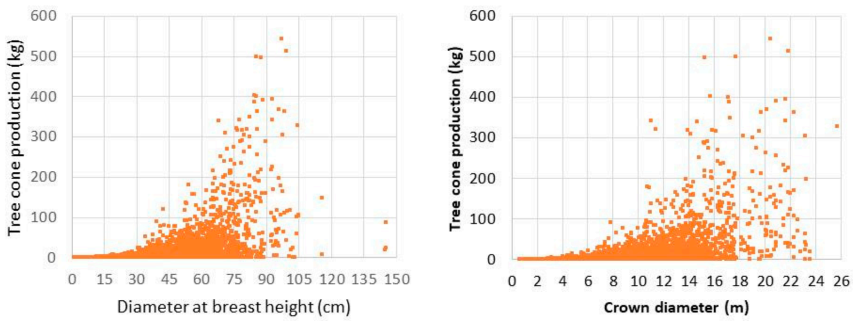

Figure 1. Cone production per tree in relation to the diameter at breast height and crown diameter [46].

Cone production per hectare increases with basal area until a threshold is attained from which cone production starts to decrease, most probably due to competition (Figure 2) [46]. The threshold is between 14 and 18 m^2 ha^{-1} independently of the stand structure. Thus, thinning should take place before this threshold is reached [46].

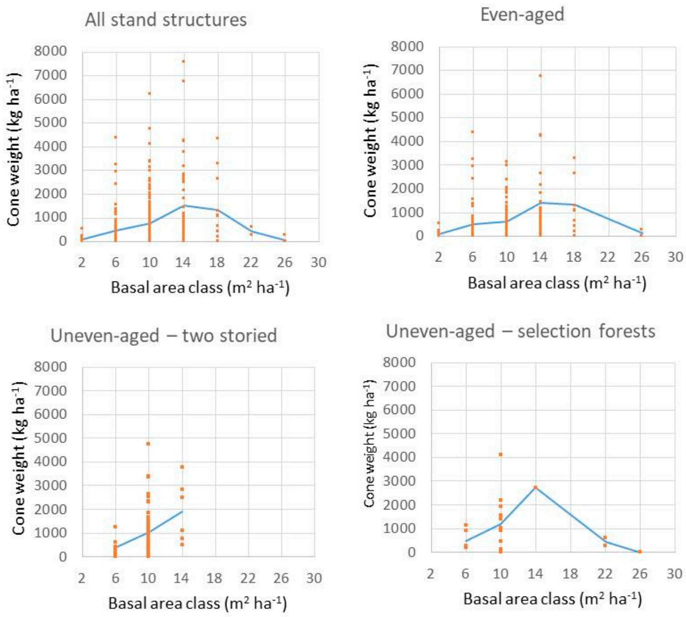

Figure 2. Impact of basal area on cone production for the different Portuguese stand structures analysed. The blue line represents the average production (all plots in all sampled years) [46].

Freire et al. [46] also analysed the relationship between cone production per hectare and stand density. It was found that higher cone production occurs, despite the stand structure, in extremely sparse stands with a stand density between 15 and 30 trees ha^{-1} (Figure 3).

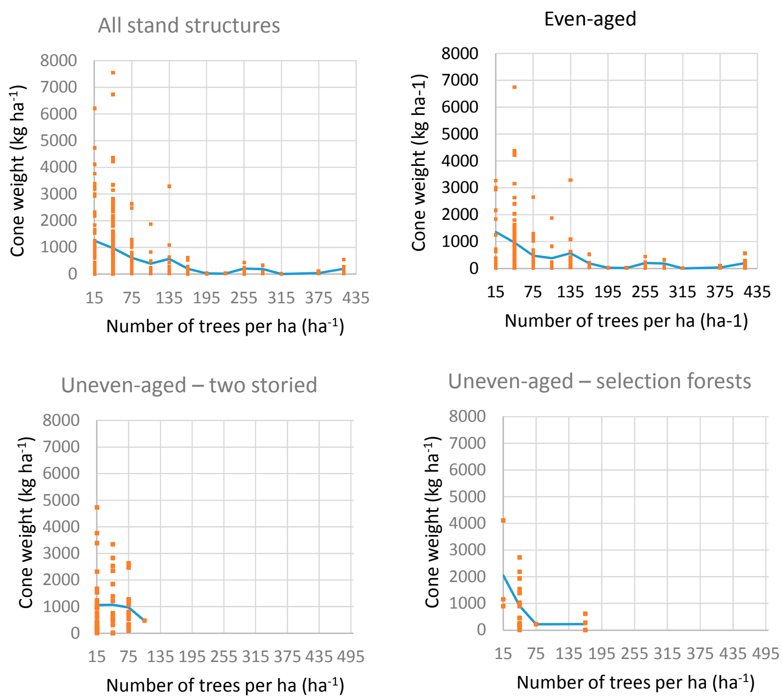

Figure 3. Relationship between cone production and number of trees ha^{-1} for the different stand structures considered [46]. The blue line represents the average production (all plots in all sampled years).

Table 3 shows that the highest productions in even-aged stands umbrella pine occur for an average basal area (GUp) of around 12 m^2 ha^{-1} for plots with a dg higher than 30 cm [46]. An easy way to manage *Pinus pinea* stands in Portugal for cone production could be to maintain basal area into an interval of 8 to 14 m^2 ha^{-1} (Table 3) [46]. Whenever the above limit will be reached, thinning should take place in order to achieve the bellow limit. This is a way to deal with the problem that in good sites trees grow faster than in poor ones [46].

Table 3. Minimum (Min), average (Avg) and maximum (Max) cone yield and respective umbrella pines basal area (GUp) and density (Nup) by mean square diameter classes (dg) at the most productive Portuguese permanent plots [46].

Stand Structure	dg	Cone Yield (kg ha^{-1} year^{-1})			GUp (m^2 ha^{-1})			NUp (ha)		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Even-aged	]0,30]	1.4	302.9	553.8	3.8	7.2	12.1	60	220	509
	]30,50]	319.2	1631.1	3335.9	6.1	12.9	24.7	39	96	215
	]50,70]	7.1	2593.0	6349.0	5.6	11.0	18.4	18	44	88
	]70,90]	3261.5	4819.7	7550.8	7.2	12.5	15.3	18	28	32
Uneven-aged two storied	]30,50]	463.9	1560.8	3161.0	10.0	13.4	26.9	60	102	297
	]50,70]	175.5	1365.0	3344.1	6.5	8.8	11.5	21	31	56
	]70,90]	35.8	1501.8	4731.8	2.5	8.1	10.9	6	18	28
Uneven-aged selection forests	]30,50]	329.1	880.9	1706.5	12.5	16.3	20.7	127	133	151
	]50,70]	109.0	842.1	1538.0	8.8	10.5	11.6	35	42	50

Umbrella pine trees per ha (NUp) is another stand variable that has to be taken into consideration. The average data from these permanent plots show that higher cone productions per hectare in Portugal occur in much less dense stands than the ones referred in the traditional guidelines [46]. For the higher dg classes, on average, it is possible to achieve more cone production per hectare in even-aged stands than in uneven-aged ones [46]. Cone production decreases even more if a stand structure near the selection forest is considered [46]. Another conclusion is that, on average, it is possible to attain more cone production per hectare in Portugal than in Spain [46]. The number of thinnings to be held in a stand will depend upon initial stand density and site quality [46].

Landowners in Portugal usually prune the remaining trees after a thinning justifying this practice with an increase in cone production after the operation. However, no research results are available on the influence of pruning over cone production and landowner's income [46]. Evidence shows that it is important to reach equilibrium when pruning is carried out. Trees should not be pruned too much in order not to promote height growth and pollen depletion, but pruning should be carried out when there are dead, sick, or leaning branches or with a low number of alive second order branches in order to concentrate potential productive growth in cones in healthy branches.

Besides cone production, cone quality is a parameter that has an increasing importance. Cone quality can be evaluated by mean cone weight due to the relationship between kernel production and cone dimension [46]. The medium weight of a cone decreases with basal area, the decrease being higher for basal areas greater than 14 m^2 ha^{-1} (Figure 4) [46]. This result is not so clear for the plots classified as uneven-aged selection forests [46].

Freire [9] has studied Portuguese umbrella pine cone production for four campaigns in stands with different ages and competition status, which is included in the data base used here. Table 4 lists the average, minimum, and maximum basal area (G), crown cover (Cc), and stand density (N) from umbrella pine (Up) and the respective total values (including other species, usually cork oak) as well as umbrella pine quadratic mean diameter (dg) and medium height $\left(\overline{\mathrm{h}}\right)$ for the 20th most productive permanent plots. Despite the huge heterogeneity, it is clear that stand density in these productive stands is much lower than in umbrella pine traditional forestry systems [52].

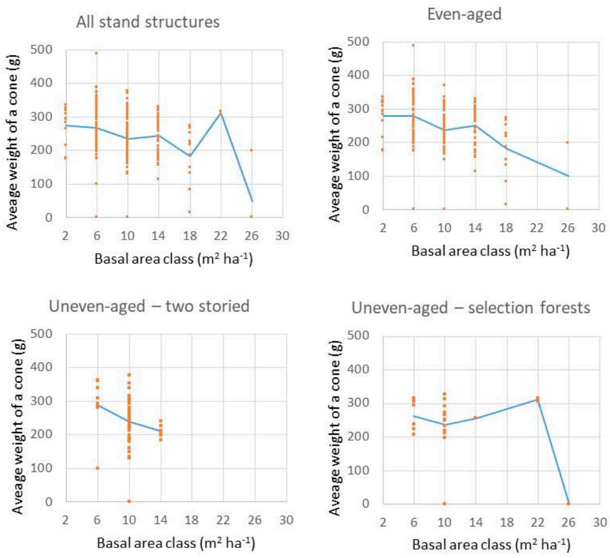

Figure 4. Impact of basal area on cone quality (using average cone weight as a proxy for cone quality) for the different stand structures analysed [46]. The blue line represents the average production (all plots in all sampled years).

Table 4. Umbrella pines (Up) and total basal area (G), crown cover (Cc) and density (N) and umbrella pines quadratic mean diameter (dg) and medium height $\left(\overline{\mathrm{h}}\right)$ from the 20th most productive Portuguese permanent plots [52].

	G		Cc		N		Up	
	(m^2 ha^{-1})		(%)		(ha^{-1})		dg	$\overline{h}$
	Up	Total	Up	Total	Up	Total	(cm)	(m)
Average	10.1	11.6	55.7	61.3	50	67	54.8	13.8
Minimum	6.6	6.6	25.5	25.9	18	21	36.6	9.4
Maximum	17.0	17.7	75.2	79.6	141	152	74.7	17.2

The annual cone production by hectare in weight and number between 2004-05 and 2007-08 campaigns for the same plots is shown in Table 5. The cone production in the 2004-05 campaign was quite high in some plots, with the most productive one with almost 7000 km of cones per hectare [52].

Table 5. Cone production at the 20th most productive Portuguese permanent plots [52].

	Cone Weight (10^3 kg ha^{-1} $year^{-1}$)				Cone Number (10^3 ha^{-1} $year^{-1}$)			
	2004-05	2005-06	2006-07	2007-08	2004-05	2005-06	2006-07	2007-08
Average	2.794	0.937	1.779	0.264	8.412	4.318	6.55	1.267
Maximum	6.739	1.538	4.256	0.504	21.146	7.516	14.487	1.981
Minimum	1.247	0.548	0.54	0.063	3.597	1.687	2.423	0.34

It is important to emphasize that the higher cone production occurred in adult, naturally regenerated or seeded mixed stands which are dominated by umbrella pines with large crowns, without any traces of resin extraction, mixed with cork oak trees. These stands had around 20 umbrella pines ha^{-1} and basal area around 10 m^2 ha^{-1}, and the understory consisted of permanent fertilized pastures, subjected to extensive cattle agroforestry systems [9], with around 0.3 individuals per hectare.

As an exercise, considering the cone productions listed in Table 4, an average cone moisture content of 30% [29], a seed in shell yield of 8.5% [53] and an average carbon content of the cone without seeds of around 42.62% [54], an estimation of the average annual carbon storage in the cones without seeds, using equation 1, is between 164.9 and 896.2 kg ha^{-1} year^{-1} (Table 6), which is not negligible.

$$\mathrm{Cdw} = \mathrm{Cfw}\left(\frac{100-30.0}{100}\right)\left(\frac{100-8.5}{100}\right)\frac{42.62}{100}, \tag{2}$$

where Cdw (kg ha^{-1}) is the dry carbon weight of cones without seeds and Cfw (kg ha^{-1}) is the fresh weight of cones with seeds.

Table 6. Carbon sequestration from dry cones without seeds.

	Carbon Sequestration (kg ha^{-1} year^{-1})				Average
	2004-05	**2005-06**	**2006-07**	**2007-08**	**(kg ha^{-1} year^{-1})**
Average	768.2	257.6	489.2	72.6	396.9
Maximum	1853.0	422.9	1170.2	138.6	896.2
Minimum	342.9	150.7	148.5	17.3	164.9

Cones without seeds may be used, for example, in the manufacture of wood-based composites such as medium density fiberboards (MDF) [55], allowing carbon sequestration for some time and the production of additional income for the landowners.

5. Climate Change Impacts on Mediterranean Forests

5.1. Climate Changes on Mediterranean Basin

The strong irregularity of rainfall in Portugal, which can for instance trigger severe/extreme droughts and floods, results in a high vulnerability to interannual rainfall variability and extreme event occurrence. Increase drought and extreme rainfall are predicted in the future [56,57]. In recent years, there has been a systematic reduction of rainfall during the spring, accompanied by a small reduction in winter and a slight increase in the remaining seasons. However, Miranda et al. [58] observed that only the rainfall reduction in spring is statistically significant. In turn, Soares et al. [59] predicted the occurrence of important losses in rainfall in spring, summer, and autumn, varying from 10% to 50% in Portugal. It was considered that rainfall loss will be more severe in the country southern basins in all seasons.

In addition to decrease in rainfall, there is a general trend towards an increase in the average annual air temperature at surface. This trend is highly consistent, appearing both in the country's average temperature and in the time series of individual stations, which agrees quite very well with the findings on a global scale [58,60,61]. This increase in temperature leads to an increase in evapotranspiration and a consequent decrease in the available water, especially in summer [62], leading to a water deficit increase [15].

The Portuguese Institute of the Sea and the Atmosphere (IPMA) analysed the information obtained in the national observation network (period 1941–2007) and highlighted the following evolution for some of the most relevant impacts of climatic changes on agriculture and forests [63]:

- An annual average temperature increase of 0.5 °C per decade;
- Decrease in thermal amplitude due to a more pronounced increase in minimum temperature;
- Increase in the number of extremely hot days;
- Reduction in the number of cold days;
- Increase in the frequency of heat waves;
- Total rainfall decrease in about 80% of the meteorological stations;
- Spring rainfall decrease, coinciding with major cone growth one year before harvest, and increase in autumn;

- Increase in the frequency and intensity of droughts.

According to [63], this climatic evolution leads to an increase of the Aridity Index, the ratio between annual precipitation and annual potential evapotranspiration [64], 36% to 58% at Portuguese continental surface (mean of 1960–1990 and 1980–2010, respectively). The Aridity Index serves as a basis to identify areas more susceptible to desertification.

5.2. Impacts of Climate Change on Mediterranean Forests

The expected medium-term climate change impacts on Mediterranean forests are the following:

- Displacement and migration of forest species from south to north and from the inland to the coast [15,65];
- Possible extinction of some species and species replacement [15,65];
- Increase of dieback processes (growth reduction, loss of vegetative vigor, defoliation, mortality) associated with the occurrence of drought processes and higher summer temperatures [15];
- Action of harmful agents, such as pests and pathogens [15,65], that may be favored by the new environmental conditions and by a longer duration of the vegetative period [15];
- Increase of abiotic disturbances, such as large fires (associated with heat waves), lower relative humidity, and convective winds that give impetus to higher probability of occurrence [15,65]; and
- Decrease of net primary productivity of Mediterranean forests, which might become carbon sources in the second half of the 21st century [15].

6. Adapting Umbrella Pines Stand Management to Climate Change

In order to adapt forest stands to climate change, the main objectives of the Silvicultural System (SS) used should be: (i) to reduce forests vulnerability to the impact of new climatic conditions, such as fire spread or lack of water; and (ii) to enhance their resilience and adaptability, ensuring that forest management objectives are achieved under these new scenarios [15,66,67]. Taking these ideas as the basis, the silviculture adaptation of umbrella pine stands to climate change can be synthesized in several principles considering the tree, stand and landscape scales (part of this section was adapted from [68] and [69] as proposed by [15]):

6.1. Tree Scale

6.1.1. Photosynthetic Efficiency and Individual Resistance to Biotic and Abiotic Agents Increase

An analogy can be drawn between each umbrella pine branch, its leaves and the respective stem xylem system and a well with the engine to draw water from it. Branches and the respective trunk xylem system are the well; leaves are the engine to take water from the well. The deeper the well, the higher is the energy that has to be spent to take water from it. The larger the well, the higher is the quantity of water that can pass through its sectional area at each time unit. The stronger the engine, the higher is the water quantity that can be pumped up at each unit of time.

With the reduction of water in the soil, more energy is needed to take water from the ground. With the reduction of water content in the soil due to climate change, it becomes more difficult to get water from the ground, thus making it important to have lower trees per hectare with the aim of counterbalancing the energy increase per unit of pumped water. This can be reached with lower and thicker trunks in trees with healthy crowns.

Umbrella pine is a species with low apical dominance [1,70–73], whose crown development and carbon allocation (and biomass production) may be susceptible to light availability, tending to steer the tree in its direction [74], favoring growth in height when in competition [1,75].

Taller trees are subject to higher stresses, and air bubbles are more prone to form in the xylem water column (cavitation) [76]. To avoid cavitation and temporary loss in the water-conduction system, the leaf stomata in trees with higher resistance (taller trees) close earlier in the day and/or earlier in a dry cycle. This closure reduces stomatal conductance and photosynthesis, reducing available carbon for timber growth [77–80], for cones growth at the last stage of development and for cones survival in the first two years. Genus *Pinus* species are more prone to cavitation phenomena than other conifers [80]. Cavitation has an increasing importance with the shortage of water availability induced by climate change [81,82]. Thus, there is an increasing importance to obtain trees with a smaller ratio between height and diameter, trees that are less susceptible to cavitation due to the lower effort to transport water from the soil to the leaves, trees capable maintaining their stomata open for a longer period of time and, thus increase the available carbon for growth and cone production.

Once the site resources, particularly light and moisture, are limited, any increase in competition will lead to a direct reduction in individual tree canopy size and/or efficiency. As a result, the amount of sugars produced by the leaves and fed down the branches and trunk for cambium growth (and cone survival and development) will be reduced [83]. This results in diameter at breast height growth reduction [83,84], which has a negative influence on the area available for water circulation in the xylem in trees trunk. The stem growth diameter of umbrella pines is positively related to rainfall [11,85] and temperature [85].

It is common to perform pruning when umbrella pines crowns get close rather than thinning. However, this practice does not prevent trees from competing for water and nutrients, resulting in growth in height rather than in diameter [86,87] (a fact that is observed in practice by forest owners), since the tree tends to recover their photosynthetic capacity eliminated by the removal of living branches [88]. Increasing tree height increases the ratio between height and diameter, making the trees more susceptible to water shortage. Excessive pruning also causes the elimination of male flowers, which are found in the lower part of the crown to avoid self-pollination, leading to a decrease in the available pollen.

Needle length is influenced by climatic conditions, competition and water availability. The needles are longer when there is greater water availability and low competition [89,90]. Longer needles have higher photosynthetic efficiency.

Cone quality is a parameter that has an increasing importance. Cone quality can be evaluated by the mean cone weight due to the relationship between kernel production and cone dimension. Trees subject to lower competition tend to produce heavier cones [29]. The larger the cone, the greater the number of seeds in shell it contains, and the greater the percentage of healthy kernel [40]. The number of seeds in shell within the cone is also highly correlated with the total number of cones [40].

In short, silvicultural treatments should be directed to obtain shorter trunks but with a bigger diameter, delaying pruning and shortening the rotations. These practices will cause changes in the root system, avoiding the dieback of species facing a drought episode [91].

6.1.2. Promote the Change of Structures or Species

The increase in water deficit caused by the increase in temperature and decrease in rainfall which lead to an increase in potential evapotranspiration and a decrease in primary net productivity, can decrease tree vigor, causing the phenomena of dieback and/or mass mortality associated with the interaction between drought and pathogens [92]. García-Güemes et al. [15] mentioned that this circumstance can be especially critical in areas whose vegetation is in its habitability range limit. From an adaptive point of view, structures and species substitution should be promoted in a proactive way, by species and varieties better adapted to a future range of conditions. If the arboreal vegetation stage is the last one before weeds, it is necessary to preserve the arboreal cover by introducing provenances and species more resistant to drought, eventually including exotic species.

In the southern boundary of the Portuguese umbrella pine range, if tree competition is not a limiting factor but cone production is systematically much lower, it may be interesting to try to diversify the tree flora by introducing species adapted to dryness, such as locust (*Ceratonia siliqua* L.), fig tree (*Ficus carica* L.), olive tree (*Olea europea* L.) or almond tree (*Prunus dulcis* L.), the last one especially interesting economically since the European Union is deeply deficient in almonds [93,94].

Other interesting species may be Christmas plum (*Carissa grandiflora* (Eckl.) A.DC.), jujube (*Ziziphus jujubas* or *Ziziphus zizyphus*), pomegranate (*Punica granatum* L.), umkokola (*Dovyalis caffra* Warb.), and among others for the production of fruit. The cork oaks in the region in question have a good vegetative vigor and good cork production so it may be interesting to expand the species in this area. KEFRI [95] considered a set of species that could be used in water limitation cases: Gum acacia (*Senegalia senegal*), acacia tortilis (*Vachellia tortilis* (Forssk.) Gallaso & Banfi), fever tree (*Vachellia xanthophloea* (Benth.) P.J.H.Hurter), neem tree (*Azadirachta indica* A. Juss.), zachum oil tree (*Balanites aegyptiaca* (L.) Del.), bularal (*Combretum aculeatum* Vent.), variable bushwillow (*Combretum collinum* Fresen.), velvet bushwillow (*Combretum molle* R.Br. ex G.Don), mgurure (*Combretum schumannii* Engl.), river red gum (*Eucalyptus camaldulensis* Dehnh.), Sydney blue gum (*Eucalyptus saligna* Sm.), apple-ring acacia (*Faidherbia albida* (Delile) A. Chev.), melia (*Melia volkensii* Guerke), siamese cassia (*Senna siamea* (Lam.) H.S.Irwin & Barneby), spectacular cassia (*Senna spectabilis* (DC.) H.S.Irwin & Barneby), and tamarind (*Tamarindus indica* L.).

6.2. Stand Scale

6.2.1. Managing Competition between Trees

Forestry aimed to promote adaptation to climate change is based on the implementation of practices that reduce vulnerability and increase the adaptative capacity of forest species in relation to the most limiting factor in the Mediterranean basin, which is water deficit in [15]. To reach this objective, each individual must achieve the highest possible vigor in order to be less susceptible to pathogens attacks and be more resistant to episodes of dryness [96].

This objective can be achieved by maintaining a reduced or non-existent competition between individuals, by decreasing the density at stand installation and by periodically reducing density to incrementally increase the growth surface potentially available to each individual [15], through a thinning regime implementation [6], allowing a convenient ratio tree height/diameter, competition for water resources and damage risk by extraordinary events or by disturbances such as fire reduction.

Competition determines the limitation or regulation of the access of a subject tree to limited resources—light, water, or nutrients—due to neighboring effects [6]. Thinning forest stands regulates intra-specific and interspecific competition [6], increase the availability of water and nutrients for each remaining tree, thus promoting diameter at breast height [36,88,97–107] and crown [88,106,108] growth. A higher diameter at breast height [36] or crown diameter [109] has a positive effect upon cone production. Thinning favors soil [110–113] and tree [114–116] water content, mitigating the effects of drought [117] on growth [15,117–119], promoting tree physiological responses such as photosynthetic rate, carbon assimilation and stomatal conductance increase [120,121], improving tree health [122], reducing the effect of pests and diseases [122,123], and/or creating an inhospitable environment barring their development or proliferation [124], promoting the stability of stands by reducing the trees height / diameter ratio of trees [15,125], which is being considered a mitigation measure against the effects of climatic changes [113]. Thinning also increases the cone production at the tree level [36,100,122,126–129]. This may be partly explained by the increase in available resources, such as water and nutrients, for each tree in less dense stands, allowing a greater amount of carbon to be allocated to the reproductive efforts [129] and cone turgescency increase at initial development stages which may allow higher resistance to the attacks of pathogens such as the *Leptoglossus occidentalis* bug. Thinning promotes productive potential concentration in a smaller number of trees that tend to be the ones of greater quality, increases dominant tree number and its average cone yield [27] and reduces the costs with cone picking, irrespective of the process being manual or mechanical, once the number of umbrella pines to be worked out is reduced [36].

In view of the above, it may be reasonable to conclude that the total effort expended by two or more trees in competition, with small crowns, for water and nutrients collection is higher than what is required by a single tree which has crown area equal to the sum of the previous ones, which grow without competition, tending to be lower and with thicker trunks than the previous trees due to lack of competition. The photosynthetic efficiency tends to be higher in the second case as well as the total cone production and average weight of a cone, increasing kernel quantity, quality and value.

The reduction of the available water under climatic change causes the competition for this resource to increase, which implies that the spacing between trees has to increase in order to reduce their effort in withdrawing water from the ground. This implicates the need for a stand density reduction.

6.2.2. Increasing Inter- and Intra-Specific Diversity

Interspecific diversity is achieved through the favoring (or even plantation) of stands with more than one species. In Portugal, umbrella pine occurs very often mixed with cork and holm oaks and/or maritime pine. The first two species are particularly appropriate for the mixture as their individuals have lower height than umbrella pines, having appreciable resistance to fire and survival rates reporting over 84% [130], especially when subject to adequate surface fuel management. It is beneficial to have cork oak trees with cork of different ages and to practice longer cycles of cork extraction, which increases fire resistance [131].

The coexistence of these species with umbrella pines allows a better use of the space, with a decrease of the fuel load to the surface by the shadowing provided by these complementary species, without this being reflected in the increased competition for the light by the pines, given cork and holm oaks are usually of smaller size. In several situations, an increase in cone production has been observed in umbrella pines vegetating in zones subject to the fall of cork oak leaves in comparison with others implemented in contiguous zones where this fall did not occur, which is corroborated by the findings of [132] on *Quercus* influence on soil fertility. In turn, cork oaks take advantage from the mixture by an increase in plant growth in the first stages due to the umbrella pine abundant mycorrhizae development, symbiosis formations which elicit cork oaks plants mycorrhization, suggesting that stone pine can potentially help in establishing cork oak seedlings, possibly facilitating nutrient uptake through mycorrhizae [133]. Furthermore, cork oaks partially vegetating under umbrella pines canopies present greater vegetative vigor and less defoliation. Cork and holm oaks have also the advantage of helping managing soil water content by promoting the upward and downward water circulation in the soil when, respectively, surface water content is reduced or abundant [134,135]. These species have the ability, in dry summers, of turning dominant groundwater uptake, representing 73.2% of tree transpiration [136], which reduces competition for superficial water.

This relationship between individuals of different species, occupying several ecological niches, and interacting with each other, allows complementary soil exploitation interactions in interspecific mixtures stands [133] that are also more resistant to disturbances, such as those caused by droughts and/or storms [137], recovering more easily from catastrophic episodes than monospecific stands [138].

García-Güemes et al. [15] reported that many forest pests and diseases have a high specialization degree in relation to the species they choose to attack, being monospecific stands more susceptible to pests and diseases than mixed stands. Intra-specific diversity, being based on a broad genetic base, allows mixed forests to have a greater adaptive capacity to climate change.

6.2.3. Irrigation

An adequate availability of water before primordia formation will guarantee a high differentiation of floral buds and, consequently, of the production of female flowers [3,4,139]. The same is true for the availability of water in a broad sense [109]. Cones with one or two years of development are very small [35] and very fragile to summer dehydration situations. In turn, Freire [9] concluded that there is a significant relationship between cone weight and rainfall between March and June one year before cone harvest.

Whenever water is available, for example stored from extreme rainfall phenomena, it can be used to irrigate umbrella pine stands, especially if planted.

Several studies focusing on the influence of irrigation on cone production have been carried out. The impact of irrigation will depend on soil characteristics and plantation types [33], providing flowering [139,140] and increasing the individual weight of cone [139], with greater influence on tree variables and cone production whenever the water deficit is higher [141].

Some studies focus on the application of irrigation without indicating the criteria used to define the amount of water to be applied. This is the case of [33] who concluded that irrigation promotes growth in bole diameter (by 85%), canopy (by 48%), and the number of cones (by 15 times).

Loewe et al. [142] reached, in an adult umbrella pine plantation, a cone production increase higher than 60% with a fertilized and irrigated treatment. The authors concluded that the use of horticultural techniques to umbrella pine stands had a positive influence on the quantity and quality of cones.

The optimization of irrigation in time and space requires scientific irrigation scheduling practices, which is a systematic procedure that estimates the future water requirements, considering relatively short periods, to meet all crop needs and avoid water over- or under-application. There are many variations, but these scheduling approaches generally use immediate past short-term climate data (e.g., last five days) to predict future short-term water use (e.g., next 10 days) to forecast the next irrigation event [143]. Bono et al. [139] calculated the water requirements in a trial established in a young, grafted umbrella pine plantation near Barcelona by subtracting rainfall (P) from evapotranspiration (ETc) at the previous week. The irrigation between April 1 and July 31, covering most of the three-year-old cones growth period, led to an increase of 100% in cone and kernel weight per hectare relative to the control and a 15% cone average weight increase, with the consequent increase in quality. Since in that year ETc was below P in a large period, including September, irrigation was not needed during that time period. The calculation of irrigation requirements by this method makes the replication of treatments feasible to other stands, allowing the prediction, with accuracy, of the impact of treatments on cone and kernel production.

When the available water is a limitation, such as in relatively arid areas with limited summer rainfall, regulated deficit irrigation (RDI) has become more and more common for tree and vine crops, but it has also been used on many annual crops [143], becoming a strategy for high-value perennial crops using conventional irrigation systems [143]. RDI consists of applying water in quantities below those necessary to satisfy ETc during certain crop cycle periods, namely when production and crop quality are hardly affected, applying all the water needed during the rest of the cycle, especially at critical cycle periods where yield and/or quality would be most affected by waterdeficit [144], the water stress being avoided or minimized (where water is limited) during rapid fruit growth [144–148]. Most studies have shown that mild water stress applied during a period of slow fruit growth controls excessive vegetative growth while maintaining or even increasing yields, leading to a more efficient use of water, largely due to transpiration reduction that appears attributable to partial stomatal closure. RDI usually requires adequate late season water allocations in order to maintain the quality and size at harvest. It is also required that the system be designed to, at least, consider crop water need peaks throughout the entire growing season. Automated micro -irrigation is often used for the maximum control of RDI [143].

Irrigation Systems

No work considering the irrigation systems for *Pinus pinea* stands has been found. Thus, the irrigation systems for fruit trees were analysed in order to evaluate which system might be more adequate to be considered to irrigate *Pinus pinea* plantations. From a wide range of irrigation systems, the use of sprinklers, micro-sprinklers, furrow, and drip were considered as the most adequate systems to irrigate medium-sized to large tree plantations. Therefore, these water systems applied to fruit trees orchards were analysed.

Fallahi et al. [149] concluded that water application through a drip system, calculated based on full ETc rate and adjusted for groundcover, results in major water saving and often improves yield and fruit quality when compared with full microjet sprinklers, achieving a water consumption reduction of about 1/3. Bryla et al. [150] concluded that the most effective irrigation methods for increasing peach production are surface and subsurface drips. Through three growing seasons, these two methods increased the average fruit size, reduced the number of nonmarketable fruits, and improved the marketable yield by 9% to 22% over more traditional furrow or microspray irrigation methods. On the other hand, Godin et al. [151] considered that, if managed properly, micro irrigation can increase yields and decrease water and fertilizer use and labor requirements when compared to gated pipe/furrow irrigation systems. An area with grass and 6000 pines extending just over 40 ha was irrigated with sprinklers. Since the water needs of grass and tree are different, the system installed had a negative impact on the health of both grass and trees. It was decided to install in each tree two in-line drip rings around its base. This procedure led to the conservation of water of about 27%, the reduction of the number of dead trees and the increase in vigor of the remaining trees in the first year of application [152].

From the review, it is patent that the drip systems offer many advantages over irrigation systems that use sprinklers, bubblers, and hose-end irrigation devices. The use of drip irrigation in orchards is increasing worldwide. Water shortage, ground water contamination prevention, efficiency increase and production improvement are the main reasons for this increase [153]. Micro irrigation has many advantages over sprinkler irrigation [154]:

- Water use can be reduced by 25 to 50% [155,156] because water is distributed to only the root zone of the target plants, reducing losses by percolation and evaporation from the wet soil;
- Plant foliage is not wetted, reducing the potential for foliar diseases, which have a particular importance in young stands;
- Since the area between rows is not irrigated, fewer weeds grow, which can reduce herbicide use;
- Water is distributed more uniformly, with typically 90% (or higher) uniformity;
- Energy costs reduction, since the system operates at lower pressure and less water is required;
- Water can be distributed on the soil surface (surface drip irrigation) or through lines in the plant root zone (subsurface drip irrigation), which will reduce damage to irrigation components by machinery and/or cattle;
- The drip irrigation system can be used to distribute water-soluble fertilizer. Fertirrigation allows fertilizer to be applied to the crop as needed during the growing season, reducing nutrient losses and leaching;
- Due to low water application rates, drip irrigation can be used on sloppy grounds without causing erosion or runoff;

There are also some drawbacks to drip irrigation [154]:

- The initial cost of the system can be highly relative to other types of irrigation systems, and there can be recurrent costs if the tubing is replaced periodically;
- Emitter openings are very small, so water must be filtered to prevent plugging;
- Depending on the source water quality, chlorination or acid rising can, eventually, be a problem.

With drip irrigation systems, the flow rate and spacing between emitters can be tailored to suit the soil type, in order that deep watering can be accomplished without runoff, even in heavy, dense clay soils [157]. In sandy soils, emitters will need to be closer because the water does not move as far horizontally. In coarse and fine sandy soils emitters must be respectively 15 till 46 cm and 30 till 91 cm apart. In clay soils, where the water moves farther sideways, the emitters may be 122 till 183 cm apart. In loam soil the distance between emitters must be 91 till 137 cm apart [154]. For their first 1–2 years in the ground, younger, newly planted containerized trees need to be irrigated more frequently on the root ball and out to the drip line. This is best accomplished by coiling the 12.7 mm drip line around the top of the root ball, in concentric circles, about 30.5 cm apart (space farther apart on clay soils). As the tree matures, the dripline can easily be moved away from the crown and extended to cover the growing root zone. Mature and established trees are best irrigated with 12.7 mm emitters line as well; however, the tubing should start well away from the crown of the tree. Established trees should be irrigated for longer and less frequent periods than trees that are newly planted, since they have a deeper and more extensive root system [157].

Pinus pinea L. plantations for fruit production are generally less dense than orchards from other kind of species. Thus, even with the drip line system (Figure 5a) (adapted from [158]), there may be a relatively large area with no crowns that would be irrigated, leading to some water and energy waste and weed growth. To avoid this problem, a drip ring system (Figure 5b) (adapted from [158]) may be considered in which the irrigation would be performed just where the roots are. In older trees, with large crowns, it could be necessary to consider more than one drip ring per tree. Since the drip ring will be away from the plantation line, it could bring some problems with the machinery movement. It is important to carefully plan the silvicultural treatments, such as weed control, in order to minimize those constrains. The drip ring system installation may be more expensive than the drip line but this one may have higher maintenance costs.

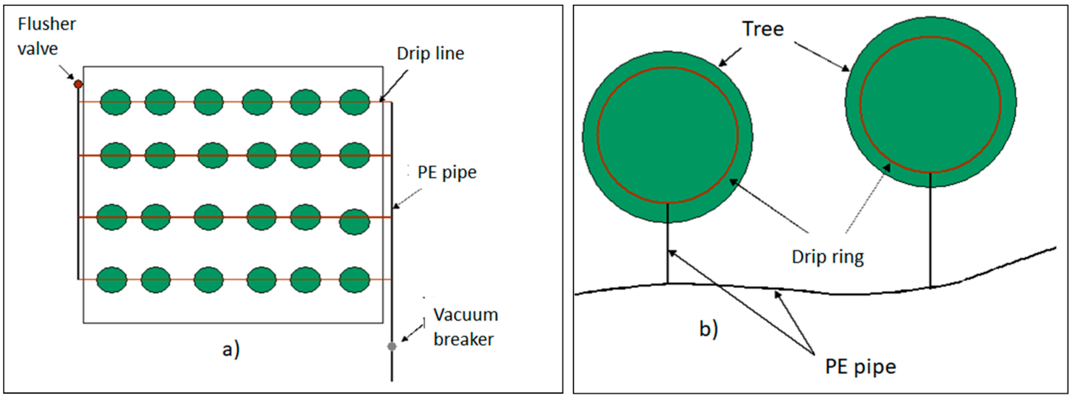

Figure 5. (**a**) Drip line; (**b**) drip ring (adapted from scheme [158]).

Information on which system (drip line or drip ring) has the lowest cost-benefit ratio is not available in the literature consulted, being necessary to undertake some field work in order to compare these systems.

It is difficult to irrigate umbrella pines on a large scale when there are periods of drought, especially when they are not aligned, so there is a need to manage forest stands in order to be more resilient to drought periods. This goes through water management relations in the tree, stand and landscape, passing through the management of the relationship between tree height and stem and crown diameters through stand density management. It is also important to frame the stand position at a landscape perspective.

6.2.4. Fertilization

Fertilization, often performed at the same time as irrigation, is one of the most important interventions to adjust soil nutrients, promoting tree growth, and improving yield and quality. Rational fertilization increases soil fertility, improves its organic matter, nitrogen and other nutrients content, and even promotes symbiotic bacteria and mycorrhizae fungi development. Likewise, by favoring a rapid expansion of the crowns, it reduces the number of years in which weed control is required [141]. Calama et al. [159] detected a linear relationship between dolomite amount and cone production per hectare increment in an adult plantation where several fertilization types and levels were tested. The best treatment led to a cone production increase of 1380 kg ha^{-1}. However, the authors concluded that fertilization was not economically viable. Of course, this conclusion depends on the price considered in the cost-benefit analysis (0.20 €/kg of cones, a value lower than what is practiced in some countries), and the number of years of the application of fertilizer (in this case, the three years of cone growth and maturation). The authors did not consider the influence of fertilization on cone production in the following two years. Thus, it is important to review the adult stands fertilization economic analysis, taking into account the reality of each target country and reviewing the way to consider fertilization costs. Nitrogen application, especially in early spring, benefits floral induction and increases the vigor of trees [141]. Boron is critical for growth and production in vascular plants [160].

6.3. Landscape Scale

García-Güemes et al. [15] proposed a vertical structure diversity of uneven-aged composition, with individuals belonging to different age groups vegetating in the same space. However, in the case of Portugal, where wildfires are becoming more frequent and severe, a vegetative continuum between soil and adult canopies increases the hypothesis that, in the event of a fire, crown fires, more difficult to control than low fires, emerge [161]. This fact may also lead to a continuum at the landscape level, which also makes it more difficult to fight forest fires. Uneven-aged stands allow a greater diversity at the stand level [162] but may create less diversity at the landscape level.

Forest Horizontal Compartmentalization (FHC) is proposed by considering medium even-aged forest patches. By definition, in a regular even-ages stands, the age difference between the youngest and oldest individual does not exceed 20% of the average rotation length, the rotation being the period of time between regeneration and stand harvest. FHC allows a stepped forest formation, raising the range of greater ecological niches and the consequent biodiversity conservation and making pests and diseases attack more difficult, mainly if specialized to a certain host age class. FHC also allows easier management of fuel load through the periodic application of prescribed fire in medium-aged and older stands, creating a multi-age fuel mosaic, providing better biodiversity conservation [163,164], reducing the potential for fire spread [165] and decreasing the probability that a surface fire turns into a crown fire. In this case, crowns will be less affected and survival chances increase for a greater number of trees in the stand by the existence of vertical or horizontal discontinuities [166]. FHC was considered to be the most appropriate way to limit the vulnerability of large forests, considering that this mosaic must have sufficient depth in order to allow the fire on entering to lose force [166]. The minimal size of a mosaic should be a function of topography and stand type. FHC allows the use of silvo-pastoralism without the need to use individual plant protectors to protect regeneration if it is chosen to seal the area(s) under regeneration. With similar-aged individuals vegetating in homogeneous low competition stands trees tend to have similar dimensions, usually needing similar space to develop, since they belong to the same age class and are subject to low competition, it becomes easier to plan and implement cultural interventions as well as to optimize silviculture by minimizing time for movement between trees, since at each time all stand is subject to the same cultural interventions.

Several authors report that in this system soil carbon loss occurs due to final cuts. However, such impact is substantially lower in umbrella pine stands for cone production, since stand densities and crown cover are low, the last often smaller than 50%. In order to reduce the impact on soil carbon by removing trees at the end of rotation, the next tree regeneration can be partly assured after the last thinning, using naturally regenerated trees as seedlings [6], so that the soil is never cleared of tree vegetation (a practice used for example at Leiria pine forest [167]). If needed, after the last thinning tree regeneration can be complemented with some planted trees. If grafting the regenerated trees will be an option, the remaining ones, due to the way grafted are usually pruned, ensure their pollination at a time when they have a small number of male flowers. If the slope is low, another technic to reduce erosion is by implementing a permanent grass land (pasture) [168,169] which has a high rainfall infiltration [170], having the second lowest soil rate loss from CORINE land cover classes [171]. Furthermore, several wildfire prevention programs in southern Europe are currently incorporating extensive livestock grazers in-fire prevention activities to reduce the high costs of mechanical clearance [172].

In Portugal, grazing has played a growing role in the management of umbrella pine stands for fruit production in a multiple-use perspective, as it reduces the risk of forest fire spreading and protects soil against erosion if the slope is not very pronounced. The highest Portuguese cone production per hectare always occurred in fertilized low-density stands subject to grazing.

7. Discussion and Conclusions

Climate change is not just expected to happen in the future, climate change is happening now, leading to decreased rainfall in all seasons but mainly in spring, when most cone growth occurs, being more severe in the most important regions for umbrella pine, the southern Portuguese basins. On its turn, the increase in temperature, mainly in summer, is leading to the death of cones with one or two years of maturation. This scenario, together with the increasing frequency and intensity of droughts, is leading to an increase of the Aridity Index, to the reduction of the available soil water, and the increase of fire risk and the respective spread rate. It is essential to consider this reality when programing Silvicultural Systems' forest cultural interventions, taking into account the tree, stand, and landscape levels.

7.1. Tree Level

At the tree level, it is important to have trees growing with little or even no competition, it being preferable to have at each age short trees with thick trunks and big crowns with long leaves, in order for the trees to use less energy to collect water and minerals from the soil, avoiding or decreasing cavitation and turning the photosynthetic process more efficient to produce the sugars needed for tree growth, health maintenance and cone production. The lower the competition, the higher will be the cone production in number and weight and the larger will be the individual cones. The larger the cones, the greater the number of seeds in the shell they will contain, and the greater the percentage of healthy kernels. Trees subject to low competition have a low height/diameter ratio, tending to be more resilient to storms.

Safeguarding that, in addition, management of cone production is dependent on site conditions, where soil and climate are included, that determine the potential growth for a given tree [6]. Regardless of the management type and of the age of the trees, in southeastern Portugal an average cone yield per tree of 15.26 kg was achieved [9], which contrast with the 0.308 kg considered by Calama and Montero [40] and the 2.472 and 4.575 kg tree^{-1} achieved at the Spanish Northern Plateau and Central Range, respectively [4]. In adult stands established in southeastern Portugal subjected to proper management, it was possible to achieve an average cone production of 195 kg tree^{-1}.

Pruning, usually done between 10 and 12 years of age and, if necessary, in the remaining trees after a thinning, is useful to eliminate dead, sick, and/or inclined branches or with few second ordered branches alive in order to concentrate the productive potential in sane branches and its cones. However, trees must not be pruned too much in order to avoid the promotion of subsequent height growth increase, since its strategy is to replace the living brunches that have been pruned.

7.2. Stand Level

At the stand level, the management of competition between trees takes primary importance. This can be achieved in two steps. First, by increasing the spacing between trees at stand installation, allowing to obtain, at the first thinning, woody material with commercial value, which is of particular relevance if trees are not grafted. Projections made with the PINEA.pt model (described in Freire [9]), suggested that the distance between non-grafted umbrella pines at stand installation should be between 9 and 10 m, depending on site quality [173]. Second, by thinning the application before the crowns touch each other, depending on its periodicity upon site quality, climate conditions, and canopy growth.

Data collected in the southeastern Portuguese region, the best-fitted Portuguese region for cone production, suggest that the umbrella pine basal area should be maintained between 8 and 14 m^2 ha^{-1}. Whenever the upper limit is reached, thinning should take place in order to achieve the lower limit, allowing the influence of fertility conditions and the incorporation of temperature and rainfall regimes on tree development and consequent planning of thinning. The Portuguese data also suggest that, in order to maximize cone production per hectare, stand density during the stand lifetime since installation until the rotation age should be much lower than the one prescribed in traditional management systems.

It is also important to increase interspecific diversity by increasing the number of species. In the umbrella pine implementation area, this could be achieved with cork and/or holm oaks, species with appreciable resistance to fire, and with individuals with lower height than umbrella pines, allowing a better use of the space, with a decrease of the fuel load to the surface by the shadowing provided by these species, without this being reflected in the increase of competition for light with the pines, creating a mixed multi-product and multi-objective stand. Cork oak also has the advantage of helping manage soil water content by promoting the upward and downward water circulation in the soil when, respectively, its surface content is reduced or abundant. Cork trees also promote soil fertility. Umbrella pines near cork oaks present higher cone production. Mixed species stands are less susceptible to pests and diseases than pure ones.

Fertilization can play a key role, namely in poor soils, by adjusting their nutrients, promoting tree growth, and improving yield and quality. Drip scientific and/or RDI may be very important principally during the third year of cone growth that occurs between March and June and by increasing the resilience of cones with one or two years of age to summer dehydration, increasing their probability of survival. Therefore, these techniques of irrigation may contribute to an increase of cone quantity, weight, and quality, in particular in planted grafted stands in which the root system development often cannot keep up with an increase in cone production, producing, principally in dry years, small sized cones which give less valuable kernels.

With the proposed stand management it was possible to achieve in southeastern Portugal an annual cone production of 6739 kg ha^{-1} year^{-1} at bumper crops in adult stands [52], which contrast with the 908 kg ha^{-1} year^{-1} reported by Mutke et al. [3] at a bumper crop. The contrasting annual cone production at tree and stand scale may be explained by the influence of several factors, namely site quality, silvicultural systems and management objectives.

Table 7 summarizes the comparison of different silvicultural systems corresponding to different stand densities (N) at the end of the stand. As an indicative exercise, discarding the influence of site quality and taking into consideration that no information about the silvicultural system influence on cone production in number and weight has been found, it has been chosen to consider each final stand density (N) from the bibliographic references, the maximum tree crown diameter (Mcw), which was considered equal to the mean distance between trees calculated from equation (1), the maximum tree cone number (Mnc) and production (Mwc) obtained from trees with cw until Mcw, which was taken from the data presented in Figure 2, and the average cone production per hectare $\left(\overline{\mathrm{Wc}}\right)$ for N that was taken from the data used in Figure 4. It can be seen that there is no linear relationship between the increase in crown diameter and cone production. That may be explained by the exponential relationship between these variables expressed in Figure 3, which is reflected upon cone production per hectare.

Table 7. Proposals for final stand density (N), maximum crown diameter (Mcw), cone number (Mnc), and weight (Mwc) per tree and average cone production per ha $\left(\overline{\mathrm{Wc}}\right)$.

N (Trees ha^{-1})	Reference	Mcw (m)	Mnc	Mwc (kg)	$\overline{\mathrm{Wc}}$ (kg ha^{-1})
28	[46]	18.9	2136	500.4	1124.3
75	[44]	11.6	1871	322.4	604.5
78	[174]	11.3	400	117.8	582.7
100	[17]	10.0	349	90.4	422.7
120	[49]	9.1	349	90.4	277.2
150	[175]	8.2	349	90.4	243.6
225	[48]	6.7	92	22.4	196.8

With climate change, the species habitability range tends to change, migrating from south to north and from the inland to the coast, being necessary, in certain situations, to promote structure and species substitutions, in a proactive way, by species and varieties better adapted to the future conditions.

7.3. Landscape Level

At the landscape level, fire is an increasing and unavoidable reality that is necessary to manage by controlling its spread and limiting its damage caused to trees. It can be achieved by FHC implementation with the consideration of medium size even-aged forest patches and the reduction of the fuel load.

The fuel load may be decreased by periodically applying prescribed fire in median age and older stands, creating a multi-age fuel mosaic, providing better biodiversity conservation, and reducing the potential for fire spread as well as lowering the probability that a surface fire turns into a crown fire. Therefore, crowns will be less affected, and the chances of survival will increase for a greater number of trees in the stands.

Agroforestry can be an important tool to reduce fire load, by selecting plants in pasture and decreasing bush occurrence. Pasture can reduce risk of erosion if the slope is not very pronounced in a multiple-use perspective. The existence of multiple products, business card of the agroforestry systems, allows a more effective response to various constraints such as difficulty in the flow of one or other product. In Portuguese agroforestry systems, it is possible to obtain from 1 to 6 Mg of cones per hectare in each year. The highest cone production per hectare was observed in extremely low dense mixed stands, constituted by adult umbrella pines with no traces of resin extraction and with reduced height /diameter ratio, seeming never to have been under competition, with cork oaks, in permanent fertilized pastures, subjected to extensive cattle agroforestry systems, with around 0.3 individuals per hectare.

In Portugal, the umbrella pine stands for cone production fix appreciable amounts of carbon in cones without seeds that can be incorporated in several products, such as MDF, allowing its withdrawal from the atmosphere to last longer.

7.4. Summarizing

Rainfall reduction and temperature increase are challenges to umbrella pine management for cone production in the Mediterranean climate region. It is necessary to adapt traditional silvicultural guidelines by reducing stand density during its lifetime, facing climate change consequences, in order to produce healthy and productive trees in healthy mixed even-aged stands.

The increase in forest fires frequency is a reality in the Mediterranean basin due to climate change. Facing this challenge involves reducing the fuel load and introducing a vertical discontinuity in the canopy to reduce fire intensity and avoid crown fires, which are more harmful for trees than surface fires. The reduction of fuel load may be achieved by the periodic application of prescribed fire in older stands, creating a multi-age fuel mosaic and/or by introducing pasture, which facilitates herbaceous and shrub vegetation management. The spread of fire may be controlled by introducing horizontal discontinuities, namely by FHC consideration.

The most productive Portuguese umbrella pine stands are mixed with cork oak, have few trees with low height/diameter ratio, with no evidence of ever been subject to competition or resin extraction, vegetating in permanent fertilized pastures subjected to cattle-extensive grazing in a multi-product and multi-objective perspective.

An important conclusion is the lack of knowledge regarding the selection of the irrigation system type and of the water level to be considered in each cone development phase, in particular in the RDI in umbrella pine plantations, namely grafted ones, as well as the soil fertility level and the density to be implemented in the development phase/age class of each stand in order to optimize cone and kernel production.

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