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Effects of Climate Change on Forest Regeneration in Central Spain

Álvaro Enríquez-de-Salamanca [1,2]

[1] Department of Biodiversity, Ecology and Evolution, Faculty of Biological Sciences, Universidad Complutense de Madrid, 28040 Madrid, Spain; alvenriq@ucm.es
[2] Draba Ingeniería y Consultoría Medioambiental, 28200 San Lorenzo de El Escorial, Spain

Abstract: The Mediterranean climate has dry and hot summers, which is harsh for plants, especially seedlings. During the 1950s and 1960s, most reforestations carried out in Central Spain, a Mediterranean climate area, were successful, but in recent decades an increasing difficulty in forest regeneration has been observed, often attributed to increased summer drought. This study analyses changes in climatic parameters related to forest regeneration through statistical treatment of meteorological data series from the mid-twentieth century to the present. Simple and multiple regressions and ANOVAs were performed for five parameters, considering annual, summer and extended summer values. Rainfall reduction and prolongation of the summer drought period were not statistically significant. The change that better explains regeneration problems is the increase in temperature, especially in July and August, which was mostly significant between 2002 and 2021. Raising temperatures increase the vapor pressure deficit, exacerbating drought effects and plant mortality. Climate change scenarios point to an increase in temperatures until 2100; thus, the tipping point for natural regeneration of some species could be passed. The most affected species are those at their ecological limit. It is necessary to facilitate the adaptation of these forests to climate change, since their future will depend on the actions carried out today.

Keywords: climate change; forest regeneration; rising temperatures

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1. Introduction

Climate change is altering climatic parameters in an indisputable way, raising temperatures in the Mediterranean region. It has a more uncertain influence on precipitation, which is undoubtedly suffering greater irregularity, and probably, a reduction. This is one of the most significant threats for Mediterranean forests, which are suffering a decline due to the combined effect of warming and drought [1,2].

In recent decades, episodes of forest mortality related to droughts and heat waves have occurred [2–4]. In addition, since the last quarter of the 20th century, an increasing difficulty in the regeneration of Mediterranean forests has been observed [5], frequently associated with increased summer drought that hampers regeneration, causing seedling and even adult tree mortality [6–9]. Regeneration problems are especially important in the Mediterranean, but have also been identified in boreal areas [10,11].

The Mediterranean climate has two growing seasons, one in spring and the other in autumn, separated by a dry and hot summer period. Overcoming this summer period is harsh for plants, especially for young seedlings. Mediterranean plants have adapted their life cycles to the vegetative periods, which justify the abundance of therophytes and which are sometimes ephemeral. Perennial species must be able to survive the summer period, for which they have developed adaptations [12]; however, despite these adaptations, germination and early development of seedlings is a critical stage. One of the main climate-mediated bottlenecks that limits natural regeneration is initial seedling survival [13]. Seedlings must overcome the first summer period within a few months of life, depending on whether they were germinated in spring or autumn. This period results in drastic selection, with more than 90% of seedlings often dying [14]; many tree species are extremely dependent on summer moisture conditions [7]. There is evidence of tree regeneration failure of some species in the Iberian Peninsula forests, even after reforestation, and of transitions to shrublands [15–17]. Effects are more intense in species at their ecological limit, such as *Pinus sylvestris* L. [9], which are sometimes replaced by drought-tolerant species [18]. However, more dry-tolerant species such as *Pinus pinea* L. are suffering seed production reductions as a response to climate change [19], affecting regeneration.

Not only pines are affected: *Quercus* species are also suffering regeneration problems [20,21], causing increased concern about long-term persistence in Central Spain [22]. *Quercus* species, which form many Mediterranean forests, are resprouters, making regeneration problems less evident; even so, most young specimens are resprouts and not individuals born from acorns.

Recurrent droughts reduce forest resilience and the ability to regenerate [23]. Adult trees positively affected seedling survival; therefore, canopy decline affects regeneration, favoring permanent changes in forest composition and shrub transitions [24,25]. In addition, tree seeds of many Mediterranean species are big to guarantee reserves to the seedlings, limiting the regeneration of the crown influence area [26].

Drier conditions may cause adult mortality to not be compensated by seedling recruitment [27], producing differences between canopy and seedling layer composition [28]; both factors may result in future shifts in species composition.

During the 1950s and 1960s, numerous reforestations were carried out in Central Spain using different pine species, which proved to be successful; the climatic conditions allowed the small pines planted to take root and grow. However, the success rate of current reforestations is much lower, which suggests that changes in climatic parameters affecting forest regeneration have occurred over the last decades.

A major problem in analyzing variations over time in the Mediterranean climate is the enormous inter- and intra-annual variability, requiring a statistical treatment of long series of data to determine whether trends are significant. An example of this irregularity was observed in 2021, when there was heavy snowfall and frost in January in Central Spain at low altitudes, and record temperatures in August of 47.4 °C in Andalusia and 42.7 °C in Madrid [29]. In addition, annual climatic conditions do not necessarily fit with summer ones; a rainy year can be extremely dry in summer, and vice versa.

The aim of this study is to analyze significant changes in climatic and bioclimatic parameters that could be related to seedling survival and forest regeneration, particularly in summer conditions, through the statistical treatment of meteorological data series from the mid-twentieth century to the present.

2. Materials and Methods

To analyze climate variability, we considered five meteorological stations located in Central Spain (Figure 1, Table 1), a Mediterranean climate zone. We searched for complete weather stations with long data series that were located on the southern and northern slopes of the Spanish Central Range, from the foothills to the summits. The area is dominated by pine forests (*Pinus pinea* L., *P. pinaster* Aiton, *P. nigra* J.F. Arnold and *P. sylvestris* L.) and stands of *Quercus rotundifolia* Lam., *Q. faginea* Lam. and *Q. pyrenaica* Willd.

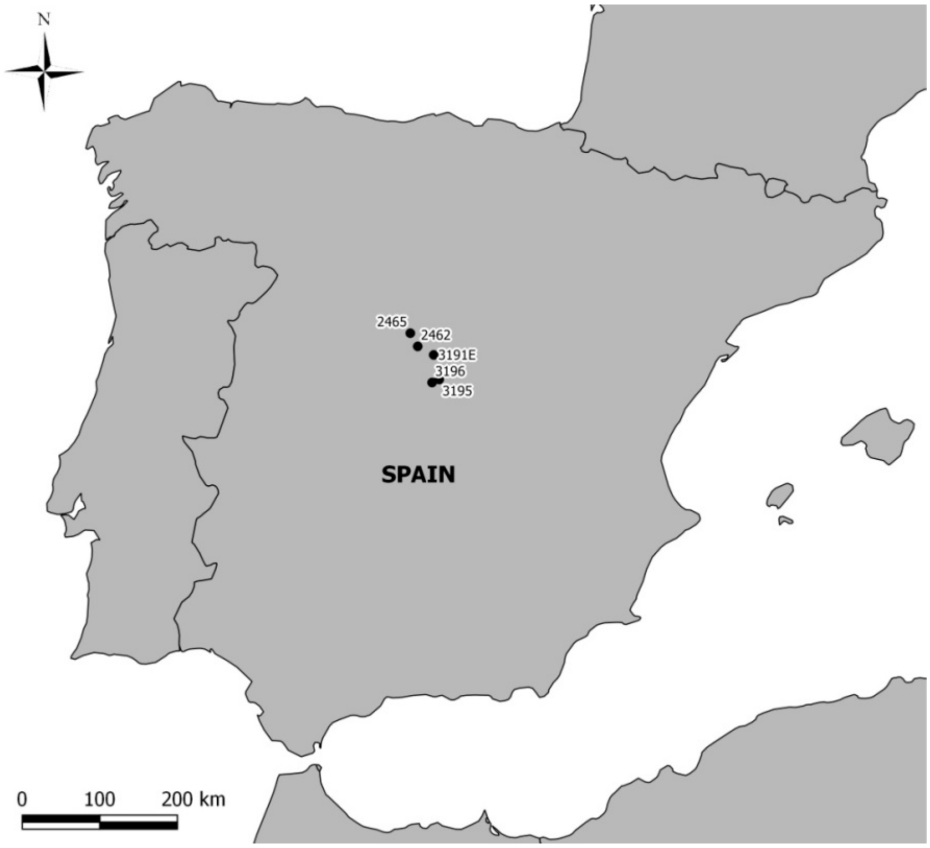

Figure 1. Location of the studied meteorological stations.

Table 1. Meteorological stations studied.

Code	Name	X	Y	Elevation	Period
3195	Madrid—Retiro	442470	4473702	667 m	1952–2021
3196	Madrid—Cuatro Vientos	433267	4469738	690 m	1952–2021
3191E	Colmenar Viejo-FAMET	435367	4505305	1004 m	1978–2021
2465	Segovia	405190	4533294	1005 m	1960–2021
2462	Puerto de Navacerrada	414745	4516276	1894 m	1952–2021

Coordinates EPSG: 25,830 (ETRS89/UTM zone 30N).

As pointed out in the introduction, regeneration problems are common throughout Mediterranean Spain, especially in continental areas. Numerous works highlight the regeneration problems of *Pinus* and *Quercus* stands in Central Spain [5,17,22,30–34], which sometimes go far back in time. Forest inventories prepared for management plans in this region frequently show an absence of regeneration, even of young trees, which confirms that it is a problem that has been present for decades. Local conditions may mitigate or exacerbate the climate impact on seedlings [15]; sunny exposures are much more unfavorable than shady ones, and even locally, medium shade areas increase seedling survival during dry summers [6]. Stands without regeneration problems are frequently located in shady and higher areas, but despite these exceptions associated with favorable local conditions, regeneration problems are a widespread problem in the region, and therefore can be correlated with the regional climate.

The World Meteorological Organization [35] states that at least 10 years of observations are needed to develop statistical benchmarks, and 30 years for precipitation, although climate trends indicate that such short periods may not be representative. For this study we sought to include at least two precipitation periods (60 years). Meteorological stations with such long time series are scarce, limiting selection possibilities. Firstly, three stations with complete data for 70 years (1952–2021) were selected, two in Madrid city and the other in the Central Range. In order to consider the northern slope, the Segovia station was included, with records for 62 years (1960–2021). Finally, the Colmenar Viejo station was considered with a shorter period of records of 44 years (1978–2021), but was seen as interesting because it is located at an average altitude between Madrid and the Central Range, and at the same elevation as Segovia on the opposite slope. The climatic data for these stations came from the Spanish State Meteorological Agency [36].

Monthly mean temperature and precipitation data were collected for each year, using them to calculate the water balance sheet [37,38] and the ombrothermic diagram [39]. Five study parameters were selected (Table 2): (i) mean temperature (T); (ii) rainfall (R); (iii) potential evapotranspiration (PET), calculated [40] and included in the water balance sheet; (iv) physiological drought (PD), obtained from the water balance sheet; and (v) duration of summer drought (SD), obtained from the ombrothermic diagram.

Table 2. Studied parameters.

Parameter	Code	Period	Unit
Mean temperature	T_A	Annual	°C
	T_S	July–August	°C
	T_{SE}	June–September	°C
Rainfall	R_A	Annual	mm
	R_S	July–August	mm
	R_{SE}	June–September	mm
Potential evapotranspiration	PET_A	Annual	mm
	PET_S	July–August	mm
	PET_{SE}	June–September	mm
Physiological drought	PD_A	Annual	mm
	PD_S	July–August	mm
	PD_{SE}	June–September	mm
Summer drought	SD	Annual	days

Three study periods were considered: (i) annual, which is useful as a general reference, but not significant for understanding forest regeneration problems; (ii) summer (S), including the months of July and August, the hottest and driest in this region; (iii) extended summer (SE), which includes June to September, spanning the whole summer but also the end of spring and the beginning of autumn. The summer drought duration had only one period, summer, which, depending on the year, may also extend into spring, autumn or both.

Firstly, simple regressions and ANOVAs were performed for each parameter studied, period and meteorological station, determining whether the results were statistically significant at a confidence level of 95% ($p < 0.05$); the Pearson correlation coefficient and the R2 value were also obtained. Two multiple regressions were performed for each meteorological station, one using summer parameters and the other with extended summer parameters; the duration of the summer drought was incorporated in both regressions. In the regressions a stepwise approach was used, eliminating at each step the variable that was not statistically significant and had a higher *p*-value. The process was repeated until a result was obtained in which all the variables considered were statistically significant.

In order to determine variations over the studied period, analysis was carried out by dividing the series into three sub-periods of two decades each: 1962–1981 (excluding station 3191E with no data in that period), 1982–2011 and 2012–2021. In each sub-period, simple regressions for all parameters were conducted to determine whether their variation is statistically significant.

Calculations were performed using Statgraphics Centurion 19 software (®Statgraphics Technologies, Inc., The Plains, VA, USA).

3. Results

To evaluate the results, it is necessary to be aware of the time differences in the data series: 70 years in three stations, 62 in one and 44 in another; comparison of results should be taken with caution when considering the global period of time, although this does not apply to the analysis by sub-periods, which was equal in all the meteorological stations.

There seems to be a slight increase in the duration of summer drought, but the ANOVAs performed for the simple regressions (Table 3) indicate that it is not statistically significant in any case. For precipitation, in most cases the annual, summer and expanded summer precipitation have negative correlation coefficients, which would point to a reduction, but in 87% of the cases the result is not statistically significant. Conversely, the increase in temperatures is statistically representative in almost all cases (93%), with R2 values between 12 and 65%; only the annual temperature variation at station 3191E, with a shorter data series, is not significant. PET is statistically significant for all stations and periods, with R2 values between 9 and 65%. PD is statistically significant in the three stations with the longest study period, with R2 values between 11 and 30%; at station 2465 it is only significant in summer and at station 3191E there is no period of statistical significance for this parameter.

Table 3. Simple regressions and ANOVAs for the meteorological stations and parameters analyzed.

Par	3195			3196			3191E			2465			2462		
	p	r	R2	*p*	r	R2	*p*	r	R2	*p*	Corr	r	*p*	r	R2
SD	0.4830	0.0852	0.7264	0.3520	0.1129	1.2750	0.6480	0.0708	0.5001	0.1552	0.1717	2.9482	0.4709	0.0933	0.8697
T_A	0.0000	0.7921	62.7371	0.0000	0.8033	64.5347	0.0875	0.2606	6.7937	0.0000	0.7163	51.3114	0.0000	0.6194	38.3613
T_S	0.0000	0.7527	56.6554	0.0000	0.7526	56.6352	0.0177	0.3561	12.6823	0.0032	0.3473	12.0624	0.0008	0.4140	17.1413
T_{SE}	0.0000	0.7806	60.9265	0.0000	0.7705	59.3644	0.0110	0.3798	14.4259	0.0000	0.6699	44.8790	0.0002	0.4620	21.3438
R_A	0.2638	−0.1354	1.8325	0.0480	−0.2372	5.6745	0.7948	0.0403	0.1628	0.1982	−0.1557	2.4228	0.7554	−0.0404	0.1630
R_S	0.6845	−0.0494	0.2443	0.5273	−0.0768	0.5903	0.7365	−0.0522	0.2723	0.9836	0.0025	0.0006	0.4111	0.1063	1.1292
R_{SE}	0.1914	−0.1580	2.4967	0.0696	−0.2182	4.7613	0.3916	−0.1324	1.7525	0.0099	−0.3063	9.3802	0.2463	−0.1495	2.2341
PET_A	0.0000	0.7908	62.5410	0.0000	0.8029	64.4627	0.0000	0.5859	34.3324	0.0000	0.6123	37.4948	0.0000	0.5802	33.6659
PET_S	0.0000	0.7417	55.0156	0.0000	0.7401	54.7804	0.0445	0.3045	9.2696	0.0000	0.4703	22.1158	0.0083	0.0332	11.0506
PET_{SE}	0.0000	0.7735	59.8260	0.0000	0.7611	57.9236	0.0363	0.3165	10.0180	0.0000	0.6181	38.2090	0.0020	0.3850	14.8222
PD_A	0.0005	0.4027	16.2135	0.0002	0.4258	18.1314	0.5348	0.0961	0.9242	0.0025	0.3556	12.6419	0.1916	0.1681	2.8252
PD_S	0.0000	0.5510	30.3551	0.0000	0.5320	28.3032	0.1396	0.2263	5.1233	0.0046	0.3351	11.2291	0.0000	0.5647	31.8839
PD_{SE}	0.0000	0.4755	22.6131	0.0000	0.5333	28.4355	0.0953	0.2547	6.4845	0.0021	0.3610	13.0348	0.1002	0.2107	4.4411

Meteorological stations in Table 1; parameter abbreviations (Par) in Table 2; r—Pearson correlation coefficient; *p*—grey cells are statistically non-significant ($p > 0.05$); R2 values in %.

Multiple regressions (Figure 2, Table 4) show a low relationship between variables, which are progressively excluded at each new stage of the regression because they are not statistically significant. The last variable that remains is, in all cases, the temperature. In the summer period, the two northernmost stations (2462 and 2465) also have PET_S as a statistically significant variable. In the expanded summer period, only station 2462 also has PET_{SE} as a statistically significant variable.

To assess the variability of the temporal series, simple regressions were performed for all parameters and for all stations in three sub-periods of two decades each (Table 5): 1962–1981 (excluding station 3191E with no data in that period), 1982–2011 and 2012–2021. In the first period (1952–1981), only station 2465 shows a statistically significant variation in T_A, PET_A and PET_S. In the second period (1982–2011), three stations have no significant changes, and two show some significant values in T_A, PET_A and PD_S (3196) and in R_A and PD_A (2465). In the third period (2012–2021), the only station without significant changes is 2465; in the rest, the increase in annual and summer temperatures is significant, and in three cases, PET_S is significant. Only in one case is the variation in summer precipitation significant, but it is an increase, not a reduction.

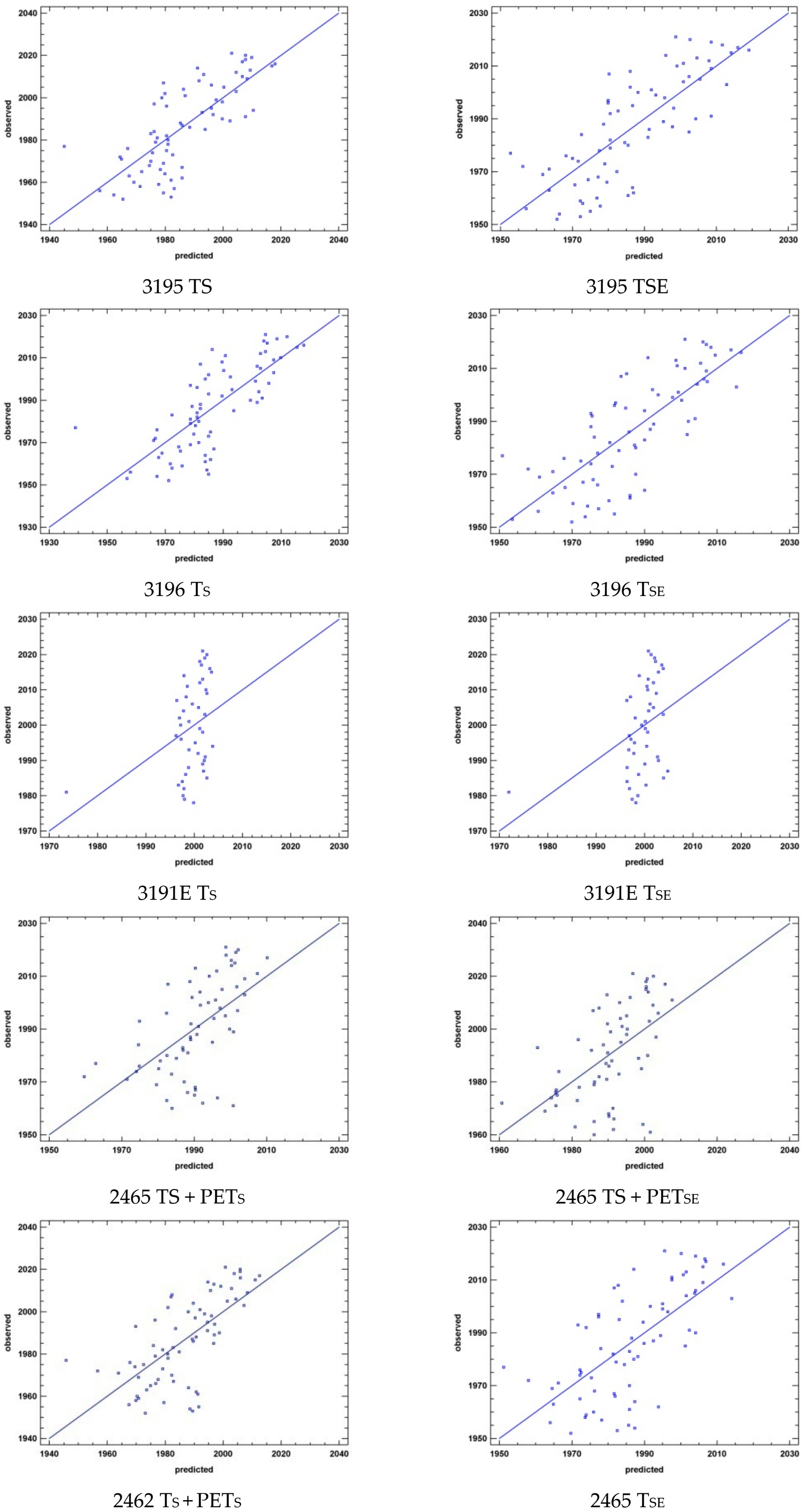

Figure 2. Multiple regression results. Meteorological station codes in Table 1; studied parameter abbreviations in Table 2.

Table 4. Multiple regressions and ANOVAs for summer and extended summer periods.

Period	Est	1st Regression			2nd Regression			3rd Regression			4rd Regression			Remain
		p	R2adj	Out	p	R2adj	Out	p	R2adj	Out	p	R2adj	Out	
Summer SD + $\sum X_S$	3195	0.0000	54.9726	SD	0.0000	55.6536	PD_S	0.0000	56.2178	R_S	0.0000	56.1576	PET_S	T_S
	3196	0.0000	54.2578	SD	0.0000	54.9487	PD_S	0.0000	55.6154	R_S	0.0000	56.0413	PET_S	T_S
	3191E	0.2872	3.2982	R_S	0.1795	5.7636	SD	0.0967	8.0560	PET_S	0.0444	9.9092	PD_S	T_S
	2465	0.0001	31.0426	SD	0.0000	32.0316	RS	0.0000	32.6101	PD_S	0.0000	30.3015	-	T_S + PET_S
	2462	0.0000	43.8003	SD	0.0000	44.6218	PD_S	0.0000	43.6710	R_S	0.0000	43.2437	-	T_S + PET_S
Expanded summer SD + $\sum X_{SE}$	3195	0.0000	57.4294	PD_{SE}	0.0000	58.0825	PET_{SE}	0.0000	58.6507	R_{SE}	0.0000	59.1684	SD	T_{SE}
	3196	0.0000	60.0179	PET_{SE}	0.0000	60.5997	RS_E	0.0000	61.1009	PD_{SE}	0.0000	61.3526	SD	T_{SE}
	3191E	0.1071	10.0407	PD_{SE}	0.0587	12.1870	PET_{SE}	0.0388	12.6003	SD	0.0217	12.9929	R_{SE}	T_{SE}
	2465	0.0002	29.0314	SD	0.0001	30.2764	R_{SE}	0.0001	27.3419	PD_{SE}	0.0000	26.9267	-	T_{SE} + PET_{SE}
	2462	0.0000	42.6008	RS_E	0.0000	43.4835	PD_{SE}	0.0000	43.7984	SD	0.0000	44.1704	PET_{SE}	T_{SE}

Meteorological stations (Est) in Table 1; parameter abbreviations in Table 2; *p*—grey cells are statistically non-significant ($p > 0.05$); R2adj—R2 adjusted; Out—statistically non-significant variable removed; Remain—statistically significant variables.

Table 5. Simple regressions for the stations and parameters analyzed for 20-year periods.

Par	1962–1981				1982–2001					2002–2021				
	3195	3196	2465	2462	3195	3196	3191E	2465	2462	3195	3196	3191E	2465	2462
SD	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T_A	-	-	-	-	-	0.0154	-	-	-	0.0256	0.0235	0.0200	-	0.0142
T_S	-	-	0.0353	-	-	-	-	-	-	0.0042	0.0251	0.0165	-	0.0500
T_{SE}	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R_A	-	-	-	-	-	-	-	0.029	-	-	-	-	-	-
R_S	-	-	-	-	-	-	-	-	-	-	0.0307	-	-	-
R_{SE}	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PET_A	-	-	0.0266	-	-	0.0098	-	-	-	-	-	-	-	-
PET_S	-	-	0.0421	-	-	-	-	-	-	0.0048	0.0284	0.0271	-	-
PET_{SE}	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PD_A	-	-	-	-	-	-	-	0.0196	-	-	-	-	-	-
PD_S	-	-	-	-	-	0.0195	-	-	-	-	-	-	-	-
PD_{SE}	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Only *p*-values of statistically significant results are shown.

In conclusion, the reduction in rainfall and the prolongation of the summer drought period were discarded as determining factors in the regeneration problems of the forest stands, as they were not statistically significant. The parameter that better explained these problems was the increase in temperature in all the periods studied, but especially in July and August. This variation was generally non-significant between 1952 and 2001, but became mostly significant between 2002 and 2021. Although variations in the extended summer temperature were significant over the whole period studied, they were not significant in the two-decadal sub-period analysis.

4. Discussion

Progressive regeneration problems in Mediterranean forest stands, especially in pine forests, are often attributed to increased summer drought [6–9,20]. However, our results show that there was not a significant increase in summer drought in the studied period, at least in the strict sense of the term "drought". Neither reduction in precipitation nor increases in the length of the summer drought period were statistically significant, as a rule. The increase in summer physiological drought was statistically significant for the whole period, but much less so when analyzing two-decadal sub-periods.

The increase in summer temperatures was statistically significant in all cases, and induced an increase in PET during this period; temperature increments may have had a positive effect on Northern Europe forest growth, but a negative effect on Mediterranean forests due to the increase in evapotranspiration and drought stress [41]. Raising temperatures increased the vapor pressure deficit (VPD), as a 3 °C increase raised the VPD by 45%, which affects water use by plants, exacerbating drought effects [42]. The VPD reflects the potential for the atmosphere to extract water from terrestrial ecosystems [43], and has been established as a major contributor in drought-induced plant mortality [44]. Elevated temperatures may also exacerbate carbon starvation and hydraulic failure [45]. A recent study showed that the impacts of VPD-induced atmospheric dryness on ecosystem production are at least equally, if not more important, than soil moisture [46]. There is evidence on the negative relationship between seedling survival and August average maximum temperature [34].

As a consequence, the problem does not seem to lie in reduced rainfall or length of the dry period as compared to the 1950s or 1960s, but in increased physiological stress induced by rising temperatures, a process that is widespread worldwide [1].

This result is worrying for Mediterranean forest stands, since the regionalized climate change scenarios for Spain [47] point to an increase in maximum temperatures and PET until 2100 (Table 6), with values for the latter parameter in the study area ranging between 8–10% for the RCP 4.5 scenario and 20–34% for the RCP 8.5 scenario. With this variation, the tipping point for the natural regeneration of some species could be passed, something that may already have happened in some locations. Projections in the US show that if the VPD continues to increase as projected by climate models, forest drought stress in the 2050s will exceed that of the most severe droughts in the last 1000 years [48].

Table 6. Expected PET values for different climate change scenarios.

Meteorological Station	Municipality	PET (mm/Month)			
		Scenario RCP 4.5		Scenario RCP 8.5	
		2021	2100	2021	2100
3195, 3196	Madrid	66.98	72.37	68.56	92.03
3191E	Colmenar Viejo	57.47	62.60	58.70	70.17
2465	Segovia	63.41	69.99	64.67	78.79
2462	San Ildefonso	63.88	70.03	65.26	79.54

Data obtained from [47].

The species most affected by this increase in summer temperatures are those located at their ecological limit [9,30]. Among them, two significant species are *Pinus sylvestris* and *Quercus pyrenaica*. The former has wide altitudinal range, between 1100 to 2200 m, allowing for greater adaptive capacity; in the future the lower stands will probably decline due to a lack of regeneration, and the species will take refuge at higher altitudes, where the increase in summer temperatures is less critical. However, populations of this species without altitudinal shift possibilities may suffer increased drought-induced mortality [49] or even disappear progressively or abruptly in the most unfavorable situations [50]. The second species has a narrow ecological range; the expected dramatic reductions in the extension of sub-Mediterranean environments [51] where this species grows and its limited ability to move to higher or lower elevations makes it likely to disappear or become rare in the medium or long term. Higher altitude stands have improved resistance and resilience [52], a result consistent with our findings, as altitude reduced temperature, and with it, the VPD. Other pine species, such as *P. nigra* and *P. pinaster*, which occupy mid-mountain areas between 800 and 1200 m, are also suffering regeneration problems, and will also have to move up the mountains to compensate for the increase in temperatures; in mixed stands of *P. pinea* and *P. pinaster* in Central Spain, a lack of regeneration of the second species has been observed [17,34]. Altitudinal shifts are already occurring; for example, with *Fagus sylvatica* L. in Northwest Spain [53]. Changes in climate will lead to a progressive dominance of Mediterranean species and a rarefaction of boreo-alpine species located at their southern limit of distribution [54], such as *P. sylvestris* in the studied area.

The increase in temperatures observed since the 1950s, which has been particularly significant in the last 20 years, will continue to increase with an intensity that will depend on human efforts to mitigate climate change. Consequently, the problems of regeneration of Mediterranean forests will increase in the future, reaching tipping points in many places (probably already reached in some sites), where regeneration of the currently existing main species will be impossible. If no action is taken, the stands will age without regeneration until they will eventually disappear as the trees die of old age.

It is important to identify these tipping points in order to facilitate the adaptation of forests to climate change. Some options include: assisted regeneration, modifying the main species if necessary; use of plants from drought-resistant provenance regions; inclusion of resprouter species; adaptation of nursery plants to water stress; use of containers according to the species root growth; use of water-retainer hydrogels in plantations; microcatchments for runoff harvesting; treeshelters; deeper planting holes; organic amendments; and biotic interactions to facilitate establishment [17,55–58].

Change processes in forests are often slow, but may be inexorable. Therefore, the future of these forests will depend on the actions undertaken at present.

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