


## Article

# Influence of Climate Change on Carbon Sequestration in Pine Forests of Central Spain

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**Abstract:** Climate change influences carbon sequestration by forests, either positively or negatively. In the Mediterranean region, this effect is predominantly negative, although it seems to be compensated by the elevation. This study aims to analyse the impact of climate change on carbon sequestration in five pine species—*Pinus halepensis*, *P. nigra*, *P. pinaster*, *P. pinea*, and *P. sylvestris*—growing across an altitudinal gradient from 573 to 1743 m a.s.l. in central Spain. Data from 300 forest inventory plots in ten forests were used to first calculate carbon sequestration in 2024. To estimate future carbon sequestration, the expected values of precipitation and temperature for 2100 were determined, based on regionalised climate scenarios for RCP4.5 and RCP8.5. Values from 13 meteorological stations located around the forests, at different elevations, were analysed, conducting a statistical analysis to determine whether variations were significant. A statistically significant variation was detected for temperature and precipitation changes only under the RCP8.5 scenario. Using temperature and precipitation data for 2024 and 2100, net potential productivity in both years was established, considering its variation ratio equivalent as equivalent to that of growth and carbon sequestration. An inflection point was detected in 2100 at 1646 m a.s.l., with a decrease in productivity below and an increase above that elevation. Results reflect a decline in carbon sequestration in all the species, ranging from 6% in *P. sylvestris* to 28% in *P. halepensis*, conditioned by the elevation. Regionally, the average decrease would be 16.4%. In temperate and boreal regions, forest growth is expected to increase due to climate change, but the Mediterranean region will experience a significant decrease, except in mountain areas. To maintain current levels of carbon sequestration, it would be necessary to increase the existing carbon sinks through new plantations and the restoration of degraded forests.

**Keywords:** forest inventory plots; modelling; pine species; Mediterranean region



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## 1. Introduction

Greenhouse gas (GHG) emissions associated with human activity result in global warming [1], with varying intensity across regions [2]. This warming, in turn, leads to alterations in the climate system, which can affect other climatic parameters such as precipitation. In the Mediterranean region, regionalised scenarios point to a significant increase in temperatures and a reduction in precipitation by 2100. An analysis of recent decades already shows a statistically significant increase in temperatures, although the change in precipitation is not yet statistically significant due to its irregularity [3].

Plants are capable of sequestering carbon from the atmosphere and fixing it in their tissues through photosynthesis. Sequestration by trees is particularly important due to their greater longevity, which allows for more permanent sequestration, even persisting in the wood after the trees are cut down [4]. Climate change has a direct influence on carbon sequestration by vegetation. The increase in the amount of CO<sub>2</sub> can enhance photosynthesis [5], although, at least in the Mediterranean region, the photosynthetic rate is strongly related to soil moisture [6]. Additionally, a rise in temperatures during cold months with water availability can promote vegetative activity, thereby enhancing

growth [7–12]. Conversely, an increase in temperatures and a reduction in precipitation during water-scarce months limit the vegetative period, reducing growth and, consequently, carbon sequestration [7,13–15].

It has been noted that tree growth declined with elevation due to a shortening of the growing season and a reduction in mean summer temperatures [16]. However, in Mediterranean mountains, the reduction in summer temperature is an advantage rather than a disadvantage, as it shifts the growing season, which starts later but extends into the summer, when lower areas experience vegetative dormancy. In fact, a significant altitudinal shift in forest stands is expected for the period from 2080 to 2100 [17].

Consequently, the influence of climate change on forest growth varies significantly by region. Globally, climate changes appear to have a positive effect on forest productivity when water is not a limiting factor [18]. Increased temperatures enhance carbon sequestration in cold and humid regions, but not elsewhere [19].

There are numerous studies evaluating the effects of climate change on forest growth, productivity, or carbon sequestration, with varying assumptions ranging from optimistic to pessimistic, leading to disparate results [20]. In the United States, applied models show a wide range of growth forecasts for forests, with positive outcomes in some areas and negative outcomes in others, depending on the water balance [21,22]. In Canada, results vary, with some suggesting an increase in productivity [23], while others indicate that the positive effect of extended growing seasons due to temperature increases is offset by rising summer temperatures [24]. In China, a possible increase in forest biomass as a consequence of climate change has been reported, as well as variable responses depending on different scenarios of temperature and precipitation variation [25,26]. In Europe, models project an annual increase in commercial volume under climate change until 2050 [27]. However, these projections encompass countries with diverse climates. In Finland, particularly in its northern region, a clear increase in forest growth is anticipated [28]. In France, a slight productivity increase is projected until 2030 to 2050, followed by a plateau and decline towards 2070 to 2100, with greater growth in the north compared to the south [29]. A more global prediction suggests maintaining growth rates in boreal and temperate zones, while foreseeing reduced carbon sequestration in the Mediterranean region [30].

In Mediterranean pine forests, changes in temperature and precipitation patterns associated with climate change are altering growth rates [31], with a response to climatic variables more sensitive in this region [32]. Various studies highlight the limiting nature of climate on the growth of Mediterranean pines [33,34], as the positive effects of warming do not compensate for growth reduction due to increased summer aridity [35]. A large-scale study in Spain detected predominantly negative effects in growth, especially in southern populations, and moderate positive effects in northern populations [36].

Therefore, the influence of climate change on forest growth in the Mediterranean is predominantly negative, more limiting the further south of the region the forests are located. However, elevation counteracts latitude, mitigating the severity of the summers. The aim of this paper is to analyse the influence of climate change on carbon sequestration in five pine species—*Pinus halepensis*, *P. nigra*, *P. pinaster*, *P. pinea*, and *P. sylvestris*—growing in central Spain, in the Mediterranean region, across a wide altitudinal range from 573 to 1743 m a.s.l.

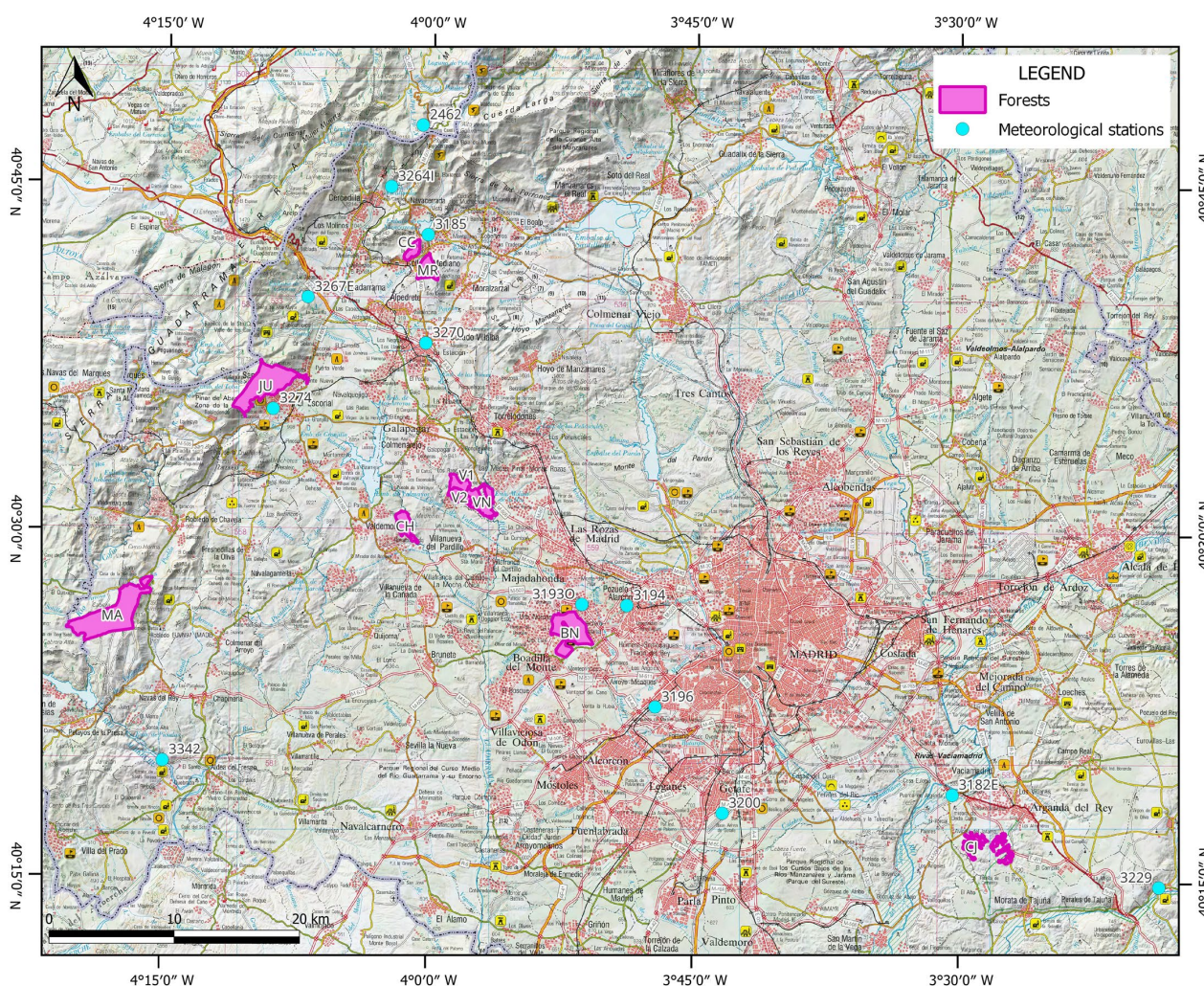
## 2. Materials and Methods

### 2.1. Research Hypothesis

The hypothesis examined in this study is that changes in climatic parameters, particularly temperature and precipitation, as a result of climate change, will affect the growth of forest stands and, consequently, the associated carbon sequestration, in a manner that could be either positive or negative, depending on the elevation.

## 2.2. Study Area

The study area is located in the province of Madrid, in central Spain. Madrid is a relatively small region (8000 km<sup>2</sup>) but with a significant altitudinal range, from 430 to 2430 m a.s.l. The western half of the province comprises mountains and their foothills, on siliceous substrates, hosting the majority of the regional forested areas, while the eastern half is dominated by carbonate terrains, where agricultural lands predominate. Ten pine forests have been studied (Figure 1, Table 1), mainly located in the western part of the province. The forests located in mountain areas are situated on granites and gneisses, while those in the foothills are on arkoses. Only one forest, Cerros Concejiles, is situated on limestone and gypsum, on the slopes of a large river valley. The average annual temperature is around 14 °C in most forests, decreasing in mountainous areas. Annual precipitation is around 500–600 mm, also higher in the mountainous zones.



**Figure 1.** Location of studied forests (Table 1) and meteorological stations (Table 4).

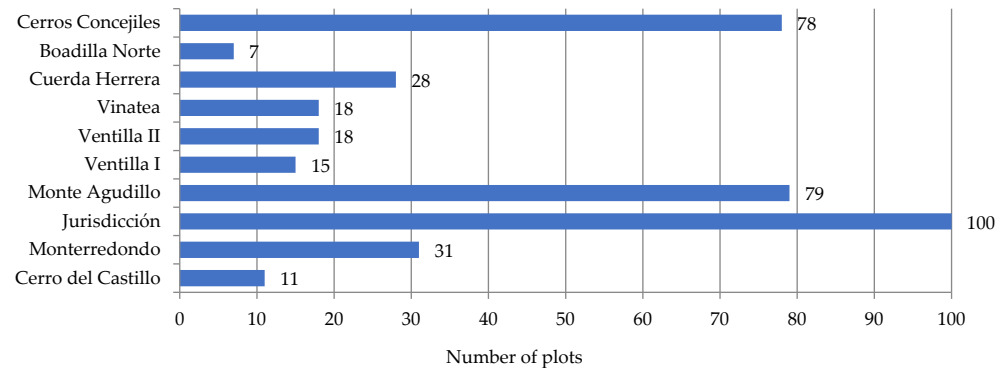
This altitudinal, lithological, and climatic range allows for the presence of diverse forest species, making it a highly representative region for study. This study focuses on plantations of five pine species, *Pinus halepensis*, *P. pinea*, *P. pinaster*, *P. nigra*, and *P. sylvestris*, planted at various altitudinal ranges and on different substrates.

**Table 1.** Studied forests.

Code	Forest Name	Area (ha)	Elevation (m a.s.l.)	Pine Species	Lithology	Rainfall (mm)	Temperature (°C)
BN	Boadilla Norte	503	670–730	<i>P. pinea</i>	Arkose	468–538	14.1–14.2
CC	Cerro del Castillo	103	1065–1235	<i>P. pinaster</i> , <i>P. sylvestris</i>	Granite	776–905	10.6–11.8
CH	Cuerda Herrera	207	630–827	<i>P. pinea</i>	Gneiss	422–650	13.8–14.4
CJ	Cerros Concejiles	255	565–715	<i>P. halepensis</i>	Limestone, gypsum	440–456	14.2–14.5
JU	Jurisdicción	848	950–1763	<i>P. nigra</i> , <i>P. pinaster</i> , <i>P. pinea</i> , <i>P. sylvestris</i>	Gneiss	842–1290	7.0–13.2
MA	Monte Agudillo	1212	590–1134	<i>P. pinaster</i> , <i>P. pinea</i>	Granite, schist	520–891	11.3–15.2
MR	Monterredondo	175	1020–1331	<i>P. nigra</i> , <i>P. pinaster</i> , <i>P. sylvestris</i>	Granite	742–977	10.0–12.1
V1	Ventilla I	141	685–855	<i>P. pinea</i>	Arkose	486–683	13.7–14.2
V2	Ventilla II	139	660–825	<i>P. pinea</i>	Arkose	457–648	13.8–14.3
VN	Vinatea	330	610–730	<i>P. pinea</i>	Arkose, gneiss, granite	399–538	14.1–14.4

**2.3. Basic Dendrometric Data**

To analyse the variation in carbon sequestration, data from 300 forest inventory plots across the ten forests were considered (Figure 2). The analysed plots are circular, each with a radius of 10 m, a size appropriate for the existing stand densities and commonly used for forest inventories at the stand level in Spanish pine forests. In each plot, data on location (coordinates and elevation) were collected, as well as the number of trees of each species. For each tree, its diameter at breast height, total height, and live crown height were measured, along with the total basal area and information on regeneration, as well as the shrub species present.



**Figure 2.** Analysed plots by forest.

**2.4. Determination of Current Carbon Sequestration**

To determine carbon sequestration, it is first necessary to calculate the volume and determine growth. For this purpose, the equations established for each pine species in the Spanish Forest Inventory, specifically for the province of Madrid, have been applied [37], where  $V_C$  is the commercial volume in  $dm^3$ ,  $I_{V_C}$  is the annual volume increment in  $dm^3$ ,  $d$  is the breast height diameter in mm, and  $h$  is the average height in m (Table 2).

**Table 2.** Volume and growth equations for the analysed species in the province of Madrid [37].

Species	Commercial Volume ( $V_C$ ) $m^3$	Annual Commercial Volume Increase ( $I_{V_C}$ ) $m^3/Year$
<i>Pinus halepensis</i>	$V_C = 29.18 + 0.0002253 \cdot d^2 \cdot h$	$I_{V_C} = 1.05 + 0.0481277 \cdot V_C - 0.0000277 \cdot V_C^2$
<i>Pinus nigra</i>	$V_C = 46.38 + 0.0003123 \cdot d^2 \cdot h$	$I_{V_C} = 5.84 + 0.0147345 \cdot V_C - 0.0000011 \cdot V_C^2$
<i>Pinus pinaster</i>	$V_C = 4.48 + 0.0002828 \cdot d^2 \cdot h$	$I_{V_C} = 4.5 + 0.0137175 \cdot V_C + 0.0000002 \cdot V_C^2$
<i>Pinus pinea</i>	$V_C = 67.09 + 0.0002340 \cdot d^2 \cdot h$	$I_{V_C} = 4.01 + 0.0079149 \cdot V_C + 0.0000024 \cdot V_C^2$
<i>Pinus sylvestris</i>	$V_C = 4.48 + 0.0002828 \cdot d^2 \cdot h$	$I_{V_C} = 3.50 + 0.0114846 \cdot V_C - 0.0000037 \cdot V_C^2$

Once the current growth is known, it must be converted into carbon sequestration. To achieve this, the relationship between commercial volume and total volume must first be considered. This involves accounting for the percentages of stem and branches in the aboveground part, as well as the ratio between aboveground and belowground parts, which are documented for these species in Spain [38].

Based on these values, a conversion ratio between commercial volume ( $V_C$ ) and total volume ( $V_T$ ) is calculated ( $BEF_{AR}$ ). It is assumed that this same relationship applies to volume increments. To determine carbon sequestration ( $C_{SQ}$ ), the increase in commercial volume is considered, along with the conversion ratio ( $BEF_{AR}$ ), wood density  $\delta$  ( $Mg/m^3$ ), percentage of carbon for each species  $c$ , and the ratio between  $CO_2$  and  $C$  molecules, which is  $44/12$  [39,40].

$$CSQ = IV_C \cdot BEF_{AR} \cdot \delta \cdot c \cdot (44/12) \quad (1)$$

Applying these values, a transformation function of  $IV_C$  into carbon sequestration ( $C_{SQ}$ ) is obtained for each species (Table 3).

**Table 3.** Carbon sequestration equations.

Species	$BEF_{AR}$ (Dimensionless)	$\delta$ $kg/m^3$	$c$ %	$C_{SQ}$ $Mg\ CO_2/Year$
<i>Pinus halepensis</i>	2.7043	600	0.499	$C_{SQ} = 2969\ IV_C$
<i>Pinus nigra</i>	1.9556	580	0.508	$C_{SQ} = 2114\ IV_C$
<i>Pinus pinaster</i>	1.6147	520	0.511	$C_{SQ} = 1573\ IV_C$
<i>Pinus pinea</i>	2.7458	590	0.508	$C_{SQ} = 3018\ IV_C$
<i>Pinus sylvestris</i>	1.7844	520	0.509	$C_{SQ} = 1732\ IV_C$

$BEF_{AR}$ —ratio between commercial and total volume, including aerial part and roots (dimensionless);  $\delta$ —wood density ( $kg/m^3$ );  $c$ —carbon percentage (%);  $C_{SQ}$ —carbon sequestration ( $Mg\ CO_2/year$ );  $IV_C$ —annual commercial volume increase ( $m^3/year$ ).

### 2.5. Basic Climatic Data

For the climate study, 13 meteorological stations located near the forests were considered, ensuring stations both below and above the forests' elevation ranges (Table 4).

**Table 4.** Meteorological stations.

Station Code	Station Name	Elevation m a.s.l.
3342	Villa del Prado Picadas	523
3182E	Arganda	530
3229	Tielmes	592
3200	Getafe	617
3196	Madrid Cuatro Vientos	687
3194A	Pozuelo de Alarcón	690
3193O	Majadahonda	725
3270	Villalba	917
3274	San Lorenzo de El Escorial	1028
3267E	Embalse La Jarosa	1060
3185	Embalse de Navacerrada	1140
3264I	Embalse de Navalmedio	1280
2462	Navacerrada Puerto	1860

### 2.6. Horizon Year, Climate Change Scenarios, and Regionalised Scenarios

The study objective requires making two preliminary decisions: the horizon year and the scenarios to be considered—both parameters conditioned by the information available in the regionalised scenarios.

Regionalised climate scenarios are qualitative and quantitative estimates of expected changes in climate in a specific region, which are continuously updated based on the

latest scientific knowledge. The Government of Spain produced regionalised scenarios for the Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5 with data at the municipal level for the whole country, last updated in June 2024 [41]. In these scenarios, the horizon year is 2100, a value adopted in this study.

RCPs are theoretical projections of the concentration pathways of GHGs in the atmosphere by 2100, which will result in an increase in total radiative forcing, relative to pre-industrial levels. Radiative forcing refers to the difference between incoming and outgoing radiation at the top of the atmosphere. RCP4.5 represents a radiative forcing of  $4.5 \text{ W/m}^2$  and an atmospheric  $\text{CO}_2$  concentration of 538.4 ppm in 2100, representing a medium emission increase scenario, while RCP8.5 assumes a radiative forcing  $> 8.5 \text{ W/m}^2$  and a  $\text{CO}_2$  concentration of 935.9 ppm in 2100, which correspond to a scenario of high increase in emissions, often referred to as ‘business as usual’ [42,43]. This study initially considers both RCP 4.5 and RCP 8.5, with detailed regionalised information available.

### 2.7. Statistical Analysis of Regionalised Climate Scenarios

To determine whether the variation in temperature and precipitation, obtained from the regionalised climate scenarios for RCP4.5 and RCP8.5, is significant, a linear regression analysis on the data series between 2024 and 2100 for each meteorological station was conducted, calculating the  $p$ -value and the  $R^2$  coefficient. Variations in temperature or precipitation were considered statistically significant if the  $p$ -value was lower than 0.05, corresponding to a 95% confidence interval. Statistical processes were performed using Statgraphics Centurion 19 software (® Statgraphics Technologies, Inc., The Plains, VA, USA).

### 2.8. Climatic Parameters in the Horizon Year

The basic climatic parameters considered were precipitation and temperature, whose variations for RCP4.5 and RCP8.5 were modelled in the regionalised climate scenarios. After statistically analysing the data series for these RCPs and establishing their significance, the estimated values of precipitation and temperature for each of the considered meteorological stations were determined.

### 2.9. Calculation of Growth and Sequestration Variations

To evaluate the hypothesis of this study, it is necessary to apply an indicator that quantifies changes in carbon sequestration associated with variations in temperature and precipitation due to climate change. The carbon sequestration of a tree is directly related to its growth, as the carbon absorbed from the atmosphere is fixed in its tissues, enabling growth [44]. Therefore, to determine the potential variation in carbon sequestration, the variation in growth must first be established.

The selected indicator is net primary productivity ( $NPP$ ), assuming that changes in tree growth will be proportional to changes in  $NPP$  under identical conditions. To calculate  $NPP$ , Rosenzweig’s formula [45], which is well suited to the conditions of the Iberian Peninsula, was applied:

$$\log NPP = 1.66 \cdot \log AE - 1.66 \quad (2)$$

$NPP$ —net primary productivity;  $AE$ —actual evapotranspiration.

The calculation of  $NPP$  is based on the actual evapotranspiration ( $AE$ ), which is determined using temperature and precipitation, the basic climatic parameters considered in this study.  $AE$  was calculated by generating water balance sheets for each meteorological station [46]. To do this, potential evapotranspiration ( $PE$ ) was first determined using the Thornthwaite method [47]:

$$PE = 1.6 \cdot [(10 \cdot t)/I]^a \quad (3)$$

where  $PE$  is the potential evapotranspiration (mm/month),  $t$  is the average monthly temperature,  $I$  is the annual heat index calculated from the average temperatures of the twelve months (Equation (3)), and  $a$  is a parameter dependent on  $I$  (Equation (4)).

$$I = \sum (t_i/5)^{1.514} \quad (4)$$

$$a = 0.000000675 \cdot I^3 + 0.0000771 \cdot I^2 + 0.0179 \cdot I + 0.49239 \quad (5)$$

$PE$  is a potential value, as not all of this evapotranspiration actually occurs.  $AE$ , on the other hand, represents the actual maximum evapotranspiration that can occur, based on  $PE$ , precipitation ( $P$ ), and soil water storage ( $R$ ), with the following premises:

$$\begin{aligned} P_{\text{month } x} > PE_{\text{month } x} &\rightarrow AE_{\text{month } x} = PE_{\text{month } x} \\ P_{\text{month } x} < PE_{\text{month } x} &\rightarrow AE_{\text{month } x} = P_{\text{month } x} + R_{\text{month } x-1} \end{aligned} \quad (6)$$

For the calculation of  $R$ , standard criteria for Spain were applied, assuming no soil water storage at the end of summer, a field capacity of 100 mm, and a monthly variation determined by the deficit or surplus, i.e., the difference between  $P$  and  $PE$  [48,49].

To calculate  $AE$  in 2100, monthly data are necessary. For temperatures, the monthly variation was modelled using the two most recent complete climate series (1961–1990 and 1991–2020). A regression was established for each month, enabling the calculation of temperature variation by month and station based on the elevation and the temperature variation between 2024 and 2100. For precipitation, the irregularity of the Mediterranean climate means that monthly variations are not statistically significant. Thus, monthly precipitation was set by applying the same proportional distribution as in 2024. Using these monthly values for 2100, the water balance sheets were recalculated, to obtain  $AE$ , which was then used to calculate  $NPP$ .

Consequently,  $NPP$  in 2024 and 2100 was calculated, along with the variation ratio over this period. This resulted in a series of 13 values for this ratio, one for each meteorological station. The series underwent polynomial regression, where the dependent variable is the variation ratio and the independent variable is the elevation, followed by statistical analysis for validation. The resulting equation allows for determining the variation ratio of  $NPP$  in all the studied plots. Based on the assumption that changes in tree growth will be proportional to changes in  $NPP$ , this ratio also enables the determination of growth variation, and subsequently, carbon sequestration.

### 2.10. Results per Species and Regional Extrapolation

For each plot and species, carbon sequestration data for 2024 and 2100 were obtained per tree. Results per species were weighted based on stand density. The Fourth Forest Inventory of Madrid [50] provides figures on the total number of mature trees and total volume for all forest species in the region. The volume of the average tree for each species was divided by the average volume obtained in our sample to obtain a correction factor, which allows for extrapolation of the sample results to regional values. While this extrapolation may introduce some uncertainty into the global results, it also provides a useful regional approach for managers and policymakers.

## 3. Results

### 3.1. Statistical Analysis of Regionalised Climate Scenarios

Statistical analysis of the expected temperature and precipitation variations between 2024 and 2100 in RCP4.5 and RCP8.5, according to the regionalised scenarios, was conducted for each meteorological station considered (Table 5). Across all stations, the reduction in precipitation under the RCP4.5 scenario was not statistically significant, whereas it was under the RCP8.5 scenario, with a moderate  $R^2$  value (40–55%). The reduction averaged around 24–25%, slightly more pronounced at higher elevations. Temperature increase was statistically significant in both scenarios, with a higher  $R^2$  value under the RCP8.5

scenario (98%) compared to RCP4.5 (75%). Temperature rise was more pronounced in mountainous areas, particularly under RCP8.5, where it exceeded lower altitude increases by 10%. Based on these results, only the RCP8.5 scenario was considered significant for this study, while the RCP4.5 scenario was disregarded.

**Table 5.** Statistical analysis of temperature and precipitation changes from 2024 to 2100.

Station Code	Scenario	Temperature Variation			Precipitation Variation		
		<i>p</i>	<i>R2</i>	Variation	<i>p</i>	<i>R2</i>	Variation
3342	RCP4.5	0.0000	75.2600	+11.35%	0.5576	0.4605	Not significant
	RCP8.5	0.0000	98.2258	+33.49%	0.0000	41.3634	−24.44%
3182E	RCP4.5	0.0000	75.2882	+11.55%	0.6282	0.3143	Not significant
	RCP8.5	0.0000	98.1940	+35.37%	0.0000	44.8696	−23.97%
3229	RCP4.5	0.0000	74.1796	+12.15%	0.5357	0.5135	Not significant
	RCP8.5	0.0000	98.0888	+36.45%	0.0000	46.9643	−24.54%
3200	RCP4.5	0.0000	75.1024	+11.72%	0.7072	0.1893	Not significant
	RCP8.5	0.0000	98.1780	+34.95%	0.0000	42.7091	−23.72%
3196	RCP4.5	0.0000	76.8640	+11.79%	0.7715	0.1132	Not significant
	RCP8.5	0.0000	98.1541	+35.28%	0.0000	38.8869	−22.94%
3194A	RCP4.5	0.0000	74.8852	+11.80%	0.7685	0.1163	Not significant
	RCP8.5	0.0000	98.1524	+35.29%	0.0000	38.8807	−22.94%
3193O	RCP4.5	0.0000	75.0060	+11.78%	0.7536	0.1321	Not significant
	RCP8.5	0.0000	98.1551	+35.30%	0.0000	39.1061	−23.04%
3270	RCP4.5	0.0000	74.9609	+11.80%	0.7417	0.1457	Not significant
	RCP8.5	0.0000	98.1575	+35.37%	0.0000	39.4802	−23.14%
3274	RCP4.5	0.0000	75.0642	+13.93%	0.6415	0.2906	Not significant
	RCP8.5	0.0000	98.0792	+42.65%	0.0000	46.6700	−24.94%
3267E	RCP4.5	0.0000	75.6693	+14.77%	0.4726	0.6902	Not significant
	RCP8.5	0.0000	98.1351	+44.93%	0.0000	49.9905	−24.80%
3185	RCP4.5	0.0000	75.4338	+14.56%	0.5122	0.5750	Not significant
	RCP8.5	0.0000	98.1231	+44.37%	0.0000	48.1213	−25.05%
3264I	RCP4.5	0.0000	73.9981	+19.70%	0.3073	1.3894	Not significant
	RCP8.5	0.0000	97.9474	+60.82%	0.0000	55.2596	−25.60%
2462	RCP4.5	0.0000	74.9716	+18.28%	0.3888	0.9920	Not significant
	RCP8.5	0.0000	98.0251	+55.95%	0.0000	52.5145	−25.54%

### 3.2. Variation in NPP, Growth and Carbon Sequestration

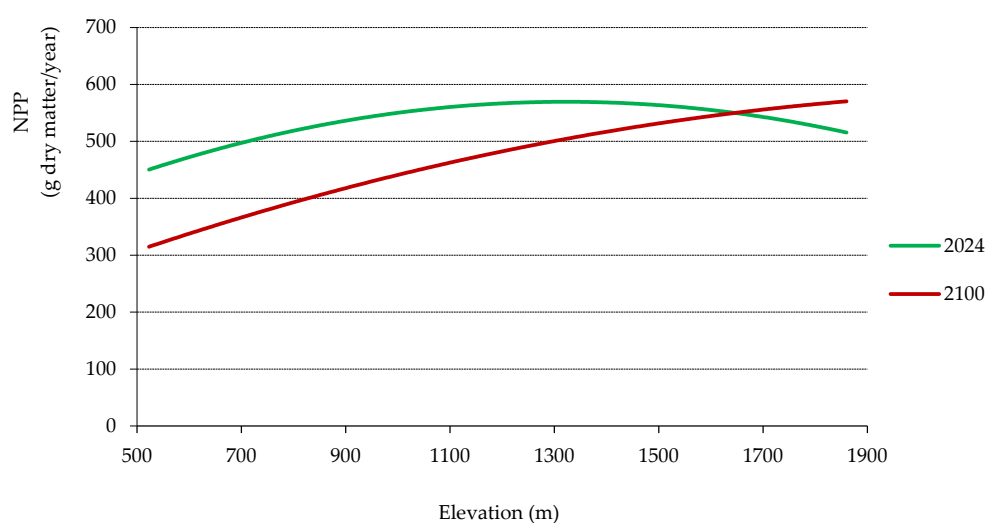
For the set of meteorological stations studied, NPP was calculated for 2024 and 2100, along with the variation ratio (*r*):

$$r = \text{NPP}_{2100} / \text{NPP}_{2024} \quad (7)$$

The series of values for the variation ratio obtained underwent polynomial regression, with the variation ratio ( $r$ ) as the dependent variable and elevation ( $e$ ) as the independent variable. The regression yielded a  $p$ -value of 0.0000 and an  $R^2$  value of 88.54%. The resulting equation to determine the variation ratio in the plots is as follows:

$$r = 0.654535 + 0.0000294159 \cdot e + 0.000000114375 \cdot e^2 \tag{8}$$

$NPP$  in 2024 and 2100 (Figure 3) intersect at a point, for  $e = 1646$ . This threshold represents the elevation at which  $NPP$  is equal in 2024 and 2100. Below this threshold,  $NPP$  is lower in 2100 than in 2024, and above this threshold,  $NPP$  is higher in 2100 than in 2024. This phenomenon occurs because above 1646 m a.s.l., the productivity loss due to drier and hotter summers is compensated by increased productivity from milder winters. This same ratio is applied to carbon sequestration, which consequently decreases below 1646 m a.s.l. while increasing above that elevation.



**Figure 3.** Change in net potential productivity (NPP) with elevation in 2024 and 2100.

### 3.3. Results per Species

Carbon sequestration values in 2024 and 2100 per species were weighted according to the stand density of each plot, obtaining overall values for the average tree in the sample (Table 6). Across all species, a reduction in carbon sequestration is observed in 2100 under the RCP8.5 scenario. The sequestration reduction is less pronounced at higher elevations (Figure 4). Thus, the most affected species would be *Pinus halepensis*, which grows at lower elevations, experiencing a 28% reduction, while the least affected would be *P. sylvestris*, a mountain pine in this area, with a reduction of 6%.

**Table 6.** Change in carbon sequestration for the average tree in the sample between 2024 and 2100.

Species	Elevation Range m a.s.l.	C <sub>SQ</sub> 2024 kg CO <sub>2</sub> /Year	C <sub>SQ</sub> 2100 kg CO <sub>2</sub> /Year	Variation %
<i>Pinus halepensis</i>	573–675	8.64	6.20	−28.27%
<i>Pinus pinea</i>	610–964	17.81	13.21	−25.85%
<i>Pinus pinaster</i>	810–1530	19.22	16.38	−14.77%
<i>Pinus nigra</i>	1087–1605	25.79	22.69	−11.30%
<i>Pinus sylvestris</i>	970–1743	12.10	11.37	−5.99%

C<sub>SQ</sub> 2024—carbon sequestration in 2024 per tree; C<sub>SQ</sub> 2100—carbon sequestration in 2100 per tree.

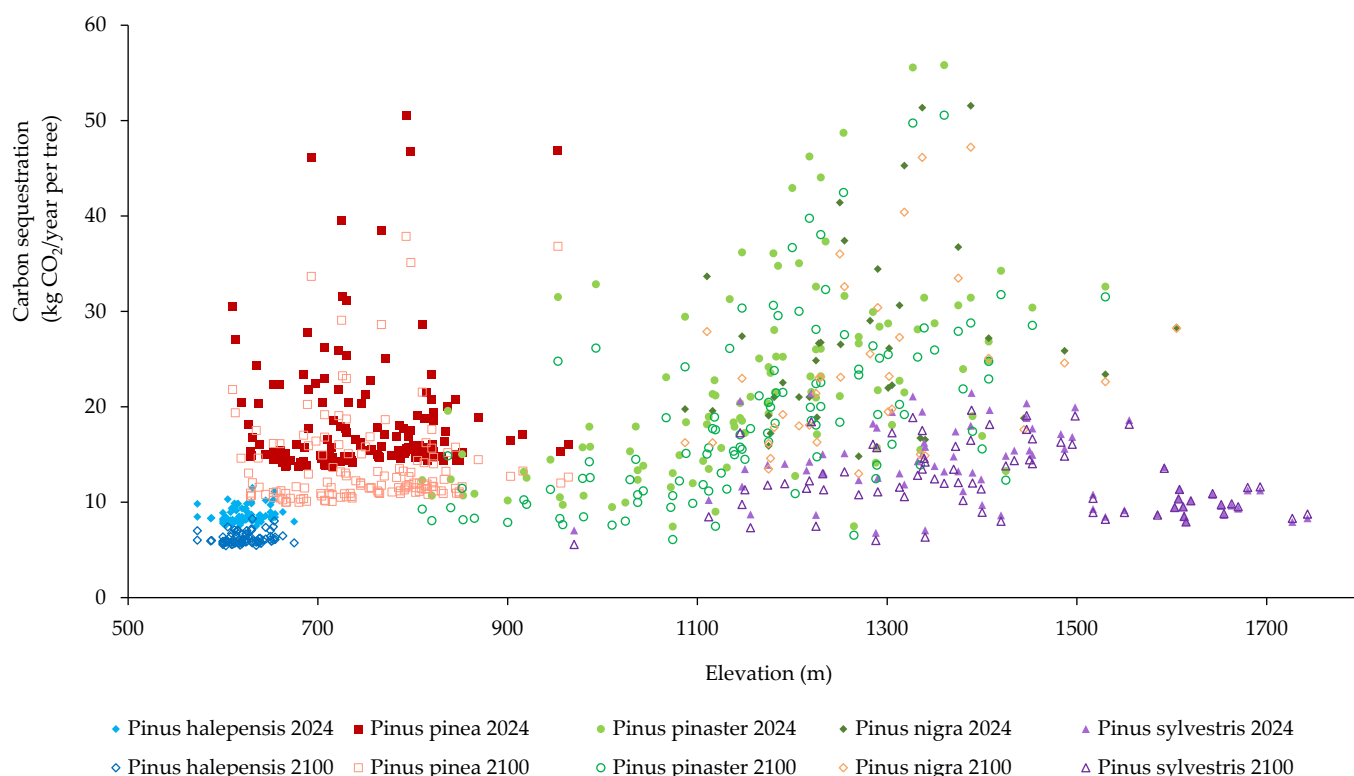


Figure 4. Carbon sequestration per plot and species in 2024 and 2100 (kg CO<sub>2</sub>/year per tree).

### 3.4. Regional Extrapolation

According to the forest inventory of Madrid [49], the main pine species is *P. sylvestris*, accounting for 58% in number of trees and 63% in volume. Following closely is *P. pinaster*, comprising 15% in number of trees and 19% in volume. *Pinus halepensis* ranks third in number of trees (15%), but fourth in volume (6%), due to a predominance of younger trees. *Pinus pinea* is the fourth species, representing 9% in number of trees and volume, and *P. nigra* is the least common, with 3% of trees and 2% of volume.

To extrapolate the sample results to the entire region, a conversion factor (*f*) was established, which is the ratio between the average tree volume in the sample and the average tree volume in the region. The sample contains younger trees of *P. halepensis* and *P. pinea*, and older trees above the regional average for the rest of the species. The regionalised variation in carbon sequestration for the year 2100 under the RCP 8.5 scenario is −71.119 Mg CO<sub>2</sub>/year, representing an overall reduction of 16.4% in carbon sequestration compared to 2024 (Table 7).

Table 7. Extrapolated results for carbon sequestration in 2024 and 2100 the Madrid province.

Species	Tree Number	f Adimensional	C <sub>SQ 2024</sub> Mg CO <sub>2</sub> /Year	C <sub>SQ 2100</sub> Mg CO <sub>2</sub> /Year	Variation Mg CO <sub>2</sub> /Year
<i>Pinus halepensis</i>	4,328,198	3.116	116,513.64	83,609.33	−32,904.32
<i>Pinus pinea</i>	2,648,146	1.453	68,536.34	50,834.65	−17,701.69
<i>Pinus pinaster</i>	4,139,720	0.728	57,896.28	49,341.37	−8554.91
<i>Pinus nigra</i>	772,477	0.510	10,155.53	8934.82	−1220.71
<i>Pinus sylvestris</i>	16,532,226	0.893	178,705.25 433,831.05	167,923.86 362,744.02	−10,781.39 −71,163.02

*f*—conversion factor between the regional average volume per tree and species and the sample volume; C<sub>SQ 2024</sub>—global carbon sequestration in 2024; C<sub>SQ 2100</sub>—global carbon sequestration in 2100.

#### 4. Discussion

Global warming appears to have a positive effect globally on forest productivity, when water is not a limiting factor [18], due to an extension of the vegetative period. In Europe, an increase in forest growth is expected [27], but only in boreal and temperate forests, while in the Mediterranean, a reduction is foreseeable [30]. The Mediterranean climate experiences the warmest and driest period coinciding in summer, leading to a disruption to the vegetative period, not observed in temperate and boreal climates. As a result, in this region, trees undergo two periods of dormancy [51], in winter and summer.

Regionalised climate scenarios for the Mediterranean region point to an increase in temperatures, greater irregularity in precipitation, and even a reduction in RCP8.5. The potential advantage of extending the vegetative period due to warmer winters is far outweighed by a significant reduction due to extended dry and hot summers. Drought is determinant for pine growth, with a critical effect if spring rainfall is reduced [7,10,13,14,52–54].

A reduction in radial growth in many Mediterranean forest species is already being detected, as well as an increase in mortality in areas with low elevation [55–57]. In the Eastern Mediterranean, a reduction in forest productivity of 16–31% for projected increases in temperature of 1–2 °C, respectively, has been predicted [58]. Our results showed an average reduction in carbon sequestration by 16.4% in Madrid, but with strong influence of elevation, which counterbalances latitude. Carbon uptake reduction is mitigated in mountainous areas, as milder winters partially offset the extension of the summer period. This trade-off requires a certain elevation; in the study area, the tipping point is 1646 m a.s.l., with a reduction in sequestration below and an increase above. However, this tipping point will be higher the drier and warmer the climate, which may mean that in practice may not be reached due to a lack of elevation.

A greater reduction in carbon sequestration does not necessarily imply greater vulnerability of the species. Thus, the analysed species that grows at a lower altitude, *P. halepensis*, is the one that will suffer the greatest reduction in carbon sequestration (28%), but it has the capacity to adapt to new situations and to colonise land where it can compensate for variable climatic conditions [59]. Conversely, mountain pines such as *P. sylvestris* and *P. nigra*, with lower carbon uptake reductions and closer to the productivity inflection point, have very little room for displacement, due to the scarcity of high mountain areas [60]. In these cases, there could be a change in the species present [61,62]. Consequently, pine plantations in semi-arid Mediterranean mountains are especially vulnerable to warming [63]. Additionally, beyond the growth reduction, there is significant concern over the decline in natural forest regeneration [3,64].

The reduction in carbon sequestration will lead to a change in national emission balances. The LULUCF sector (land use, land use change and forestry) is the only one considered a net sink, because its balance between carbon storage and emission is positive. In Spain, in 2023, this sector accounted for a reduction of –17.3% in total national GHG emissions [65]. A progressive reduction in sequestration, as a consequence of climate change, will generate an increasingly smaller reduction in the LULUCF sector, and consequently a larger net emissions balance.

Additionally, although the Mediterranean region is not a major timber producer due to its climatic limitations, a progressive reduction in tree growth rates would further diminish production, increasing pressure on other regions to meet timber demands.

#### 5. Conclusions

The Mediterranean region has limitations to tree growth due to its hot and dry summers, which generate two dormancy periods, in winter and summer, dividing the growing season. This region is especially sensitive to climate change, with a significant increase in temperatures, which is already occurring, and greater irregularity in precipitation, with a significant reduction at least in the RCP 8.5 scenario.

Although in the temperate and boreal regions of Europe, global warming will increase forest growth, due to the lack of water limitations, in the Mediterranean, its influence will

be mostly negative. The reduction in growth and carbon uptake will be more pronounced at lower elevations. In the studied area, there is a tipping point at 1646 m a.s.l., with increased sequestration above it and reduced sequestration below it, which justifies the lower impact on mountain pines. This tipping point will be higher towards the south of the region and lower in the north. As a consequence, the most significant sequestration decrease will occur in *Pinus halepensis* (28%), growing at lower elevation, and the least intense in *Pinus sylvestris* (6%), which is a mountain species. However, the former pine has better adaptation capability than mountain pines, like *P. sylvestris* and *P. nigra*, with limited space to migrate upward.

By 2100, carbon sequestration in the Madrid region is expected to decline by 16.4% under the RCP8.5 scenario. While the negative impact is moderated at higher elevations, the overall trend points to reduced forest growth due to longer, hotter summers that outweigh the benefits of milder winters. This reduction in carbon sequestration will influence national GHG inventories, particularly in the LULUCF sector, which is the only net carbon sink. A reduction in carbon sequestration can lead to a synergistic effect, further exacerbating climate change.

To maintain current levels of carbon sequestration, it would be necessary to increase the existing carbon sinks with new plantations or through the restoration of degraded forests. Additionally, it would be necessary to adapt forest to future climatic conditions so that they can maintain growth levels under the new conditions; this may require changes in the main species.

In conclusion, climate change is already leading to shifting conditions in Mediterranean forests, which are mostly negative and require increasingly intensive adaptation measures as temperature and precipitation changes become more severe.

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