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Impact of Forest Management on Wood Production under Climate Change in the Bonis Catchment

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Abstract: The concept of integrated forest management offers a framework for understanding how forest ecosystem services interact with efforts to conserve natural resources. Forests face various disturbances stemming from human activities, management approaches, and shifts in climate patterns. This study aims to explore how forested watersheds respond to diverse silvicultural practices amidst changing climate conditions. The research is centered in the Bonis catchment, situated in the mountainous region of Sila Greca (latitude 39°25′15″ N, longitude 16°12′38″ W) within Southern Italy's Calabria region. Nearly 93% of the catchment area is cloaked in a forest dominated by approximately 50-year-old *Pinus laricio* Poiret stands. To model the catchment's response to various climate and management scenarios, the FEST-FOREST eco-hydrological model, which is distributed and based on physical principles, has been employed. This model accounts for the dynamic interactions between vegetation and the watershed's hydrological processes. The monitoring of the basin has been ongoing since 1986, with runoff measurements collected at the catchment outlet using dedicated gauging structures. These data have been utilized to calibrate and validate the model, ensuring its accuracy in simulating future scenarios. These simulation results offer stakeholders some qualitative and scientifically based recommendations for the sustainable management of the catchment. In fact, thinning intensity affects hydrological processes, with a 50% stand density reduction identified as a threshold for significant impact on processes like rainfall partitioning and evapotranspiration. Under heavy thinning scenarios, runoff can change by over 60%, and the impact decreases with larger thinning intervals. Furthermore, different climate scenarios influence stem yield levels, with higher production under RCP 4.5 and RCP 8.5 compared to the base climate scenario. In particular, the RCP 8.5 scenario produces the highest yield due to better forest growth under different climate scenarios. This implies the idea that in regions with a Mediterranean climate and coniferous forests, amidst climate change, meticulous forest management involving precisely calibrated thinning schedules and intensities, tailored to unique biotic and abiotic factors, could potentially enhance carbon sequestration while positively influencing runoff rates.

Keywords: forest management; climate chance; FEST-FOREST; Bonis catchment

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1. Introduction

Forest ecosystems are sensitive to the changing environment (climate, soil conditions, pollution., etc.), which affects tree dynamics, for example [1]. Climate change is a challenge for the forest since it has a direct impact on this ecosystem [2]. The projected climatic change trends showed to have both negative and positive impacts on forests [3] that are considered a key solution to mitigate climate change effects [4]. Adapting forest management to cope with climate change requires a better understanding of the interactions between climate projections and forest management options. The United Nations promoted the sustainable forest management concept, which mainly gained importance in the last century [5,6]. Today, several management options have been set, allowing for better and more sustainable forest growth, and have been adopted by forest managers targeting the optimization of wood yield [7]. Meanwhile, forest management options should account for several criteria and different conflicts of interest among stakeholders [8]. Forest managers tend to prioritize timber production when managing forests while risking the alteration of the trees' production due to climate change [9]. In this context, the selection of management options needs to consider climate change impacts while preserving the ecosystem's services [10]. In particular, forest management must achieve both economic and environmental aims focused mainly on biodiversity conservation and, at the same time, emphasize the ecological, economic, and social functions at both a local and global scale. Thinning proved its positive impact on forest growth since it decreases tree densities, thus reducing leaf area and competition among trees [11,12]. In addition, forest management through thinning takes into account not only the regulation of C-stocks and C-uptake capacity, but at the same time raises drought stress resistance with the reduction in water competition, and slows down the aging effects of Mediterranean forests as opposed to no forest management [13,14]. Commonly, various forest management options are carried out taking into account several usual densities and intervals according to the local and regional forest regulations and policies. Meanwhile, sometimes these decisions do not adjust to changing environmental and climatic conditions [15]. In the context of climate change and limited water resources, integrated water resource management has been proposed as a concept for watershed management [16]. In the latter, vegetation is considered one of the main components, especially in forested watersheds. In effect, to assist stakeholders in selecting the forest management options to be implemented, two kinds of support tools are available: long-term observations and simulation models [17]. Over the decades, several eco-hydrological models have been developed. These models take into consideration the interplay between the ecological and hydrological cycles [18]. In addition, these models made it possible to forecast the effect of the different forest management options on forest growth and the hydrological response of forest watersheds. These models are used for forecasting the impact of forest management scenarios combined with the effect of climate change scenarios.

The aim of the present study is to assess the impact of forest management on wood production in the Bonis River basin in Southern Italy, and its implications on hydrology, under the effects of climatic change. For this purpose, the FEST-FOREST model was employed, a spatially distributed hydrological model integrated with a forest growth simulation module presented in [19].

2. Methodology

2.1. Study Site

The Bonis River basin is located in the central-western sector of the Calabria region in Southern Italy (39°25′15″ N, 16°12′38″ W). It is one of the small basins typical of the Sila Plateau (1500 km^2), the primarily mountainous area of the region. It has a perimeter of about 5.7 km and an area of 1.39 km^2 within which a wide hydrographical network flows, with a drainage density of 7.43 km km^{-2}. The main river length is 2.2 km, and the average, minimum, and maximum altitudes of the basin are 1131, 994, and 1301 m a.s.l., respectively (Figure 1). About 93% of the total area of the basin is covered by rangeland and forest (80%), dominated by the Calabrian pine (*Pinus laricio* Poiret), largely artificial and planted in the past century between 1955 and 1970. In 1993, a targeted thinning operation was conducted, resulting in a reduction of approximately 55% in stand density (38% in low-density areas, 69% in high-density areas). Since 1986, continuous monitoring of the basin has been undertaken to establish a permanent laboratory for investigating basin-scale hydrological dynamics. This monitoring includes the measurement of rainfall and temperature at three distinct meteorological stations, as well as runoff assessments at the catchment outlet utilizing a dedicated gauging structure (see Figure 1). Furthermore, in 2003, a tower was erected at an elevation of 1100 m above sea level within a 54-year-old Laricio pine plantation to measure eddy fluxes [20]. The basin's climate mirrors that of the interior regions of Calabria, characterized by cold, occasionally snowy winters, and mild, intermittently rainy summers [21]. The annual average precipitation stands at 915 mm, with the mean temperature of the coldest month hovering around 0.1 °C and that of the warmest month reaching 18.3 °C [22].

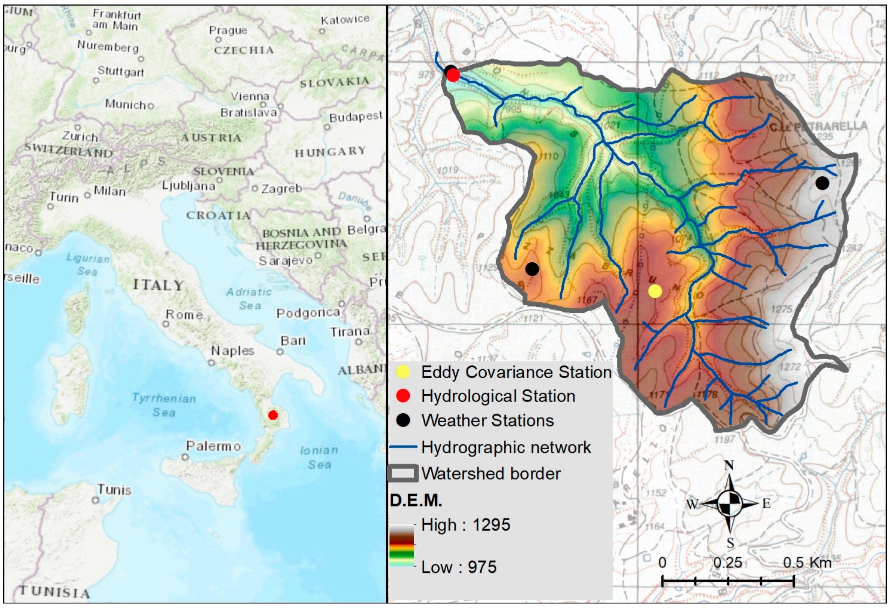

Figure 1. Location of the Bonis catchment area alongside the employed instrumentation for monitoring purposes.

2.2. Model Description

For simulations, the FEST-FOREST model [19] was used, which is an updated version of the FEST-WB model including the forest growth component. Figure 2 illustrates the main processes included in the FOREST module. The FEST-WB distributed hydrological model, developed at the Politecnico di Milano, is the acronym for Flash-flood Event-based Spatially distributed rainfall–runoff Transformation, including Water Balance [23].

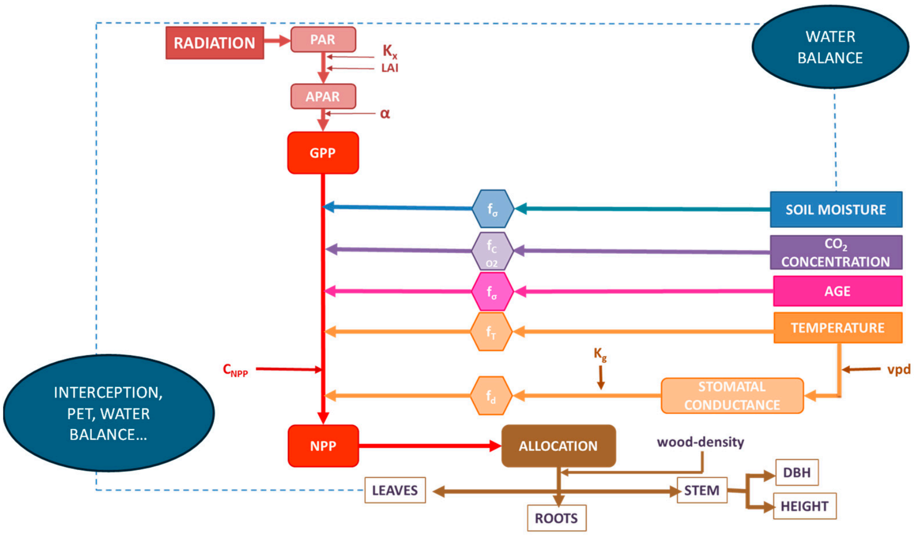

Figure 2. Flowchart depicting the FOREST module, as described in Feki et al. [19].

The FEST-FOREST model is a dynamic, process-based tool capable of simulating daily gross primary production (GPP) and net primary productivity (NPP), along with carbon allocation, for a uniform tree population (even-aged and pure stands). The model has been developed based on different equations from the literature, commonly used in eco-hydrological models such as 3PG [24], EcH$_2$O [25], and SWAT [26].

The amount of fixed carbon is determined through the amount of intercepted light calculated through the Beer–Lambert law as the absorbed photosynthetically active radiation (APAR). Carbon assimilation is influenced by various factors known as modifiers, including temperature, water content, vapor pressure deficit, and CO$_2$ concentration. Specifically, the CO$_2$ modifier is determined using the following formula [27]:

$$f_{CO_2} = \frac{f_{C\alpha x} \cdot CO_2}{350 \cdot (f_{C\alpha x} - 1) + CO_2} \tag{1}$$

where $f_{C\alpha x}$ is a dimensionless parameter used to calculate the modifier, and CO_2 represents the current atmospheric carbon dioxide concentration in parts per million (ppm).

The model allows for the simulation of carbon allocation to the roots, stem, and foliage. This feature makes it possible to follow the forest change in subsequent years according to the value of net primary production NPP, previously computed based on gross primary production GPP and conversion factor CNPP. Afterwards, trees foliage, roots, and stem parameters are updated together with the total biomass. The FEST-FOREST includes three factors for simulating tree mortality: self-thinning, age-dependent mortality, and the "crowding competition function" (this mortality mechanism guarantees that the pixel's vegetation cover percentage remains below 95%). The required inputs for forest growth simulations are reported in Table 1.

Table 1. Model parameters used for the simulation of forest growth.

Parameter	Description
Fprn	Parameter to compute allocation factors
Sprn	Parameter to compute allocation factors
GPP-NPP	GPP/NPP ratio
Alpha	Parameter to compute allocation factors
wood-density	Wood density
Agemax	Maximum age of the plant
hdmin:	H/D ratio in carbon partitioning for low
phi-theta	Density
K	Empirical coefficient of the soil moisture efficiency
Albedo	Function for canopy resistance
Fpra	H/D ratio in carbon partitioning for low
Spra	Density
Sla	Plant albedo
phi-ea	Parameter to compute allocation factors
Canopymax	Parameter to compute allocation factors
laimax	Specific leaf area
hdmax	Empirical coefficient of the vapor pressure efficiency
tcold-leaf	Function for canopy resistance
dbhdcmax	Maximum canopy storage capacity
dbhdcmin	Maximum leaf area index used
denmax	Precipitation interception
denmin	H/D ratio in low carbon partitioning

The details of the FEST-FOREST model are presented in Feki et al. [19]. The application of the model has been tested by following several steps. In the first step, after soil properties were determined through field and laboratory measurements as a first guess, model parameters related to runoff simulations were calibrated against the observed discharge time series. To this end, short simulation periods were taken into account in order to consider the vegetation as static. A coefficient of determination equal to 0.88 was achieved. In the second step, forest-related model parameters were calibrated using measured data of tree height and diameter at breast height (DBH). Coefficients of determination equal to 0.98 and 0.96 were achieved, respectively, for DBH and tree height simulation. Simulation results proved the ability of the FEST-FOREST model to simulate hydrological and forest growth processes and their mutual interconnection, and to reproduce an accurate response of the catchment to eco-hydrological dynamics.

2.3. Management Scenarios

In the model, a module allowing for the simulation of different management scenarios was incorporated, as reported in Figure 3. In this study, for the management options, thinning with different intensities in terms of percentages (10, 15, 20, 30, and 40) and different thinning intervals (20, 25, and 30 years) were considered. These scenarios have been chosen in agreement with the Sila National Park (https://parcosila.it/ (accessed on 12 December 2023), in charge of the scheduling and control of the forest cutting. Simulations were carried out considering the different/no-management options in combination with two climate change scenarios, RCP 4.5 and RCP 8.5. In addition, a simulation was carried out with a no-management scenario where a base climatic scenario was considered.

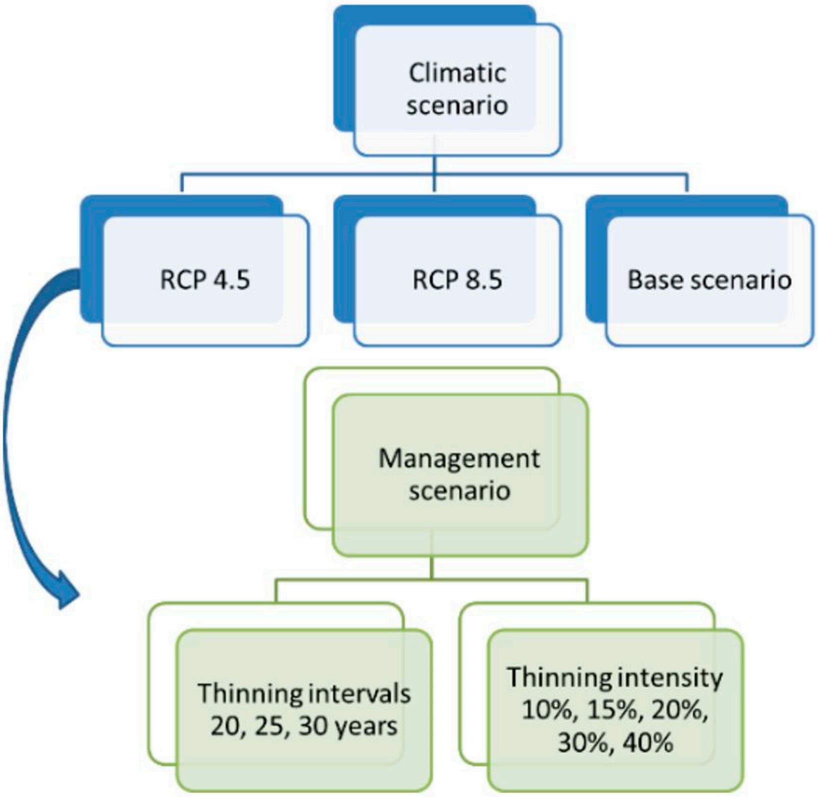

Figure 3. Different simulations of combined management options and climatic scenarios.

Simulations were performed at hourly time steps. The model was initialized with measured vegetation parameters: age, density, diameter at breast height (DBH), height (H), leaf area index (LAI), roots biomass, foliage biomass, and stem biomass.

2.4. Climate Scenarios

For the simulations, available measured climatic data from the meteorological stations located in the Bonis catchment were used for the period of 1976–2018. Future climate change projections were provided by the "Fondazione Centro Euro Mediterraneo sui Cambiamenti Climatici" (CMCC). Original climate projections come from COSMO-CLM simulations performed under the project GEMINA (Project Italian MIUR/MATTM n. 232/2011), at ca.

0.0715° grid resolution and for the period of 1971–2100. COSMO-CLM was forced by the global model CMCC-CM [28].

As mentioned before, the climate scenarios used in this project were RCP 4.5 and RCP 8.5. To evaluate the impact of future climate change, both scenarios were compared to past climate data (1976–2006). This comparison is reported in Figures 4–6. Temperatures are expected to increase for both climate scenarios, whereby the highest increment will be observed in the period of 2066–2096. RCP 8.5 presents the worst scenario in terms of temperature increase (Figure 4). Future climatic projections also predict a decrease in precipitation for both RCP 4.5 and RCP 8.5 (Figure 5).

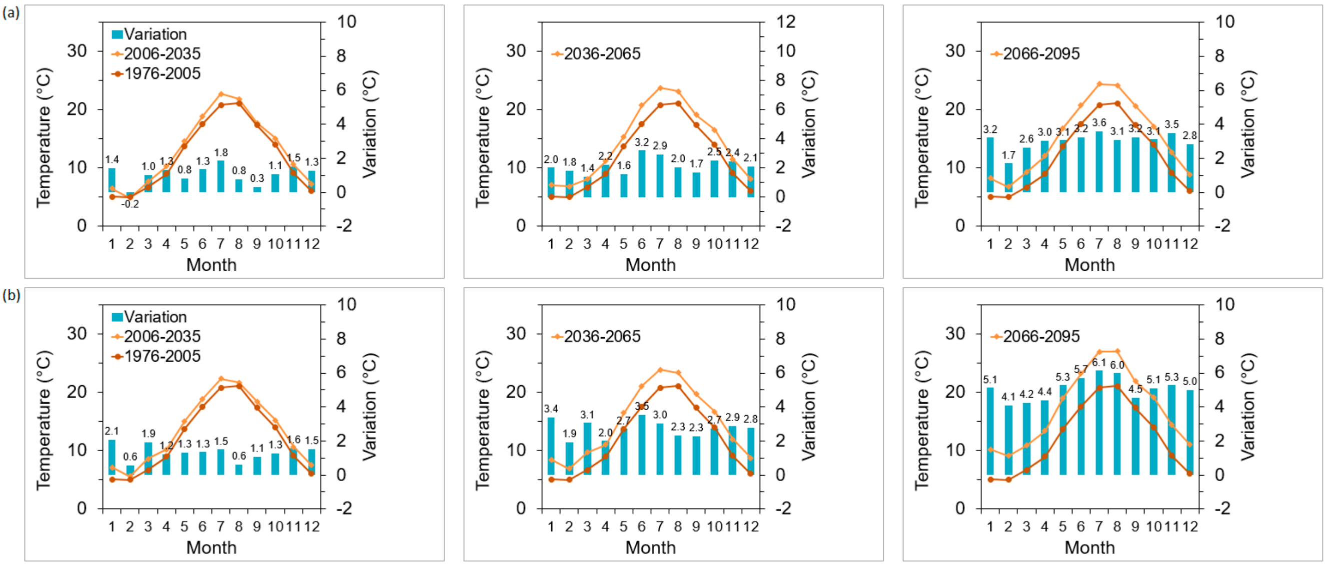

Figure 4. Trends of monthly variation in the temperature (T) in °C for both climate change projections RCP 4.5 (**a**) and RCP 8.5 (**b**). Brown lines show values for the reference (light) and future (dark) period, blue bars show the variation between future and reference period.

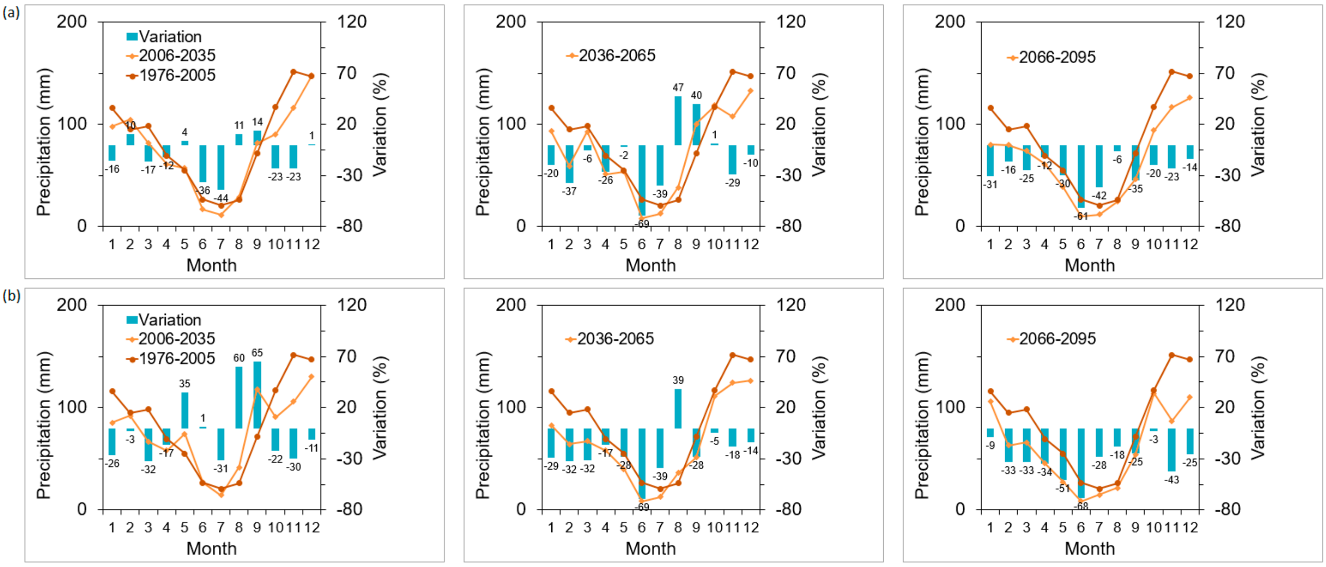

Figure 5. Trends of monthly variation in the precipitation (P) in mm for both climate change projections RCP 4.5 (**a**) and RCP 8.5 (**b**). Brown lines show values for the reference (light) and future (dark) period, blue bars show the variation between future and reference period.

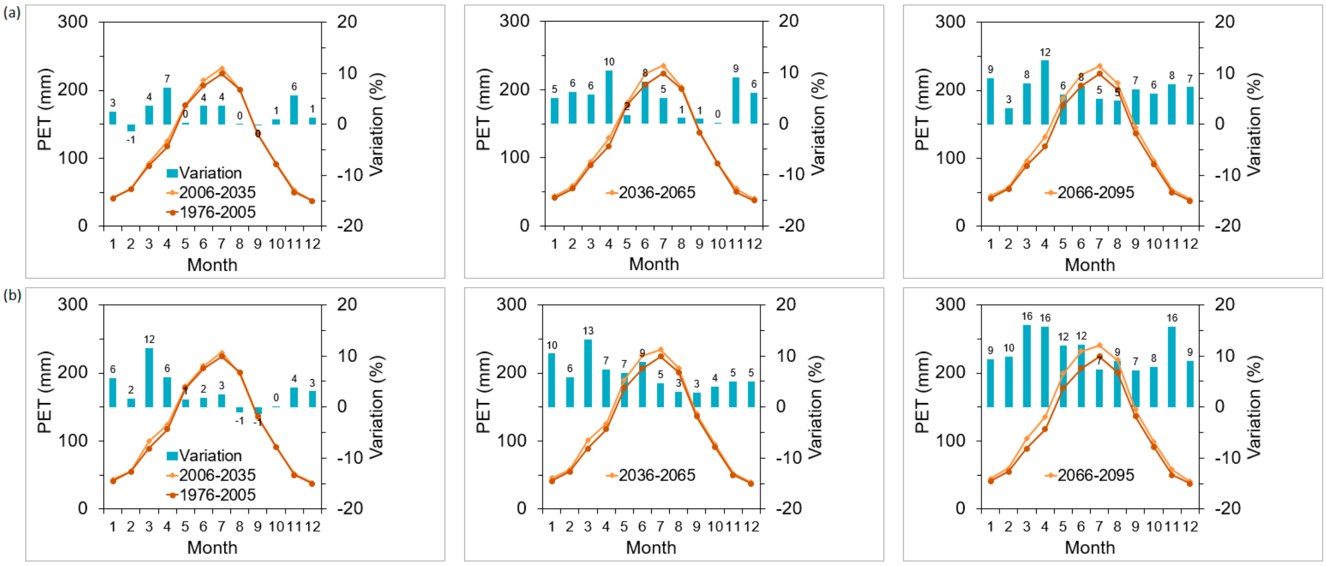

Figure 6. Trends of monthly variation in the potential evapotranspiration (PET) in mm for both climate change projections RCP 4.5 (**a**) and RCP 8.5 (**b**). Brown lines show values for the reference (light) and future (dark) period, blue bars show the variation between future and reference period.

In the initial 40-year period at the Bonis site under the RCP 4.5 scenario, there is a general uptick in both maximum and minimum air temperatures of approximately 1 °C, alongside a decrease in annual precipitation of roughly 14 mm. Subsequently, from 2066 to 2095, the simulated maximum and minimum temperatures experience further increases of about +2 °C and +1.8 °C, respectively, accompanied by an additional decline in annual precipitation of approximately 124 mm. Conversely, the RCP 8.5 scenario presents more drastic alterations at the Bonis site, with temperatures rising by about 1.5 °C in the initial thirty-year period and annual precipitation decreasing by around 99 mm. For the last thirty years, the average increases in daily temperatures have been about 3.5 °C, and precipitation has been reduced by about 185 mm.

A small increase in the potential evapotranspiration (PET) during the summer season was observed as compared to historical data for both RCP 4.5 and RCP 8.5 for the period of 2006–2036 (Figure 6).

For the periods of 2036–2066 and 2066–2096, PET reaches the highest values during the summer months. Higher differences, as compared to the historical data, can be observed for the climate scenario RCP 8.5, considering the notable increase in the temperature for this scenario. The CO_2 emissions for RCP 4.5 reach a peak around the year 2040 and then start declining. For the scenario RCP 8.5, CO_2 emissions are more alarming and always continue to increase until the end of the projected period (2096).

3. Results and Discussion

The results found in this study should be interpreted with a lot of caution, since, in this particular case, the spontaneous growth of new trees was not included in the model. Thus, the number of trees was always decreasing due to thinning. The latter causes a reduction in the competition between the trees. In addition, diseases and pests were not considered.

3.1. No-Management Option with Climate Scenario Simulations

The first simulation was carried out in order to evaluate the impact of climate change on forest growth. Therefore, only the RCP 4.5, RCP 8.5, and base climatic scenarios were considered, while forest management options were not included. The simulation results of DBH and H are reported in Figure 7. The simulations were performed starting from historical data and then including future climate projections. The thinning carried out in 1993 was also included in these simulations.

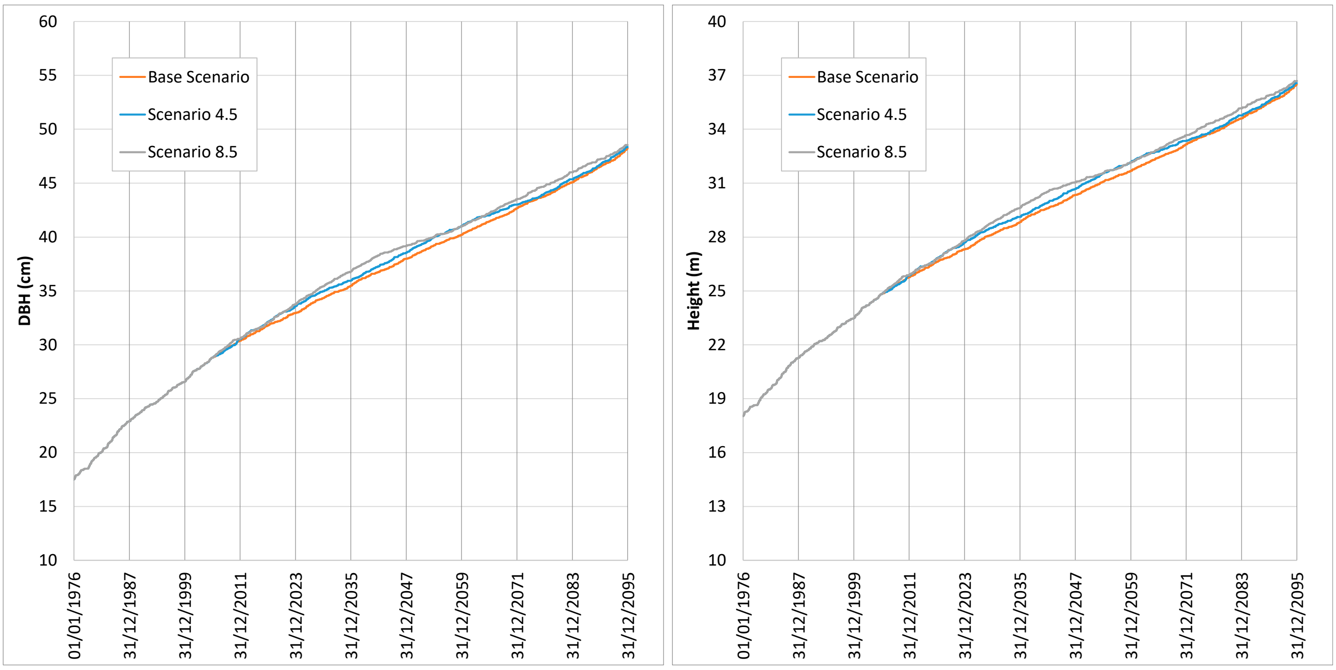

Figure 7. Result of forest growth simulations of DBH and height considering base climatic scenario, RCP 4.5, and RCP 8.5.

The results proved that better forest growth would be achieved under climate change conditions as compared to the base climate scenario, especially under the RCP 8.5 scenario, although the difference between the different climate scenarios was not so pronounced. The increase in CO_2 concentration provided by climatic scenarios stimulates plant growth. Moreover, the increase in temperature lengthens the growth period, which is not limited by the small decrease in precipitation amount. At the end of the simulation period, the DBH and H reach comparable values for all the considered climatic scenarios. According to this result, the climatic conditions were not constraining the forest growth in this watershed, allowing for the maximum possible growth at the end of the simulation period. It should be mentioned that pine is considered one of the most abundant trees in European forests, and has proven its resistance and survival under some climate change scenarios in a study carried out by Buras and Menzel [29]. The simulation results found in the present study seem to confirm this. In addition, similar growth trends were found by Pellicone [30] for the same study site using a 3D-CMCC forest ecosystem model [31]. His study proved that the model showed the highest growth variables for the extreme RCP 8.5 scenario with respect to RCP 4.5 and the base climate scenario.

The runoff simulations were also evaluated by considering the different climate change scenarios as compared to the historic trend of runoff generation between 1976 and 2006. The predicted runoff under future climatic scenarios resulted in a similar trend to past runoff data. For the analysis of these results, simulations were subdivided into three 30-year periods as reported in Figure 8. The monthly patterns show an increase in the runoff due to summer precipitation concentrated in a shorter period. These peaks tended to increase in the last 30 years of simulations lasting between 2066 and 2096. Runoff peaks were more relevant for the RCP 8.5 scenario for the whole simulation period. Meanwhile, for the period lasting from April to August, no remarkable changes were detected, in line with the precipitation regime of this watershed.

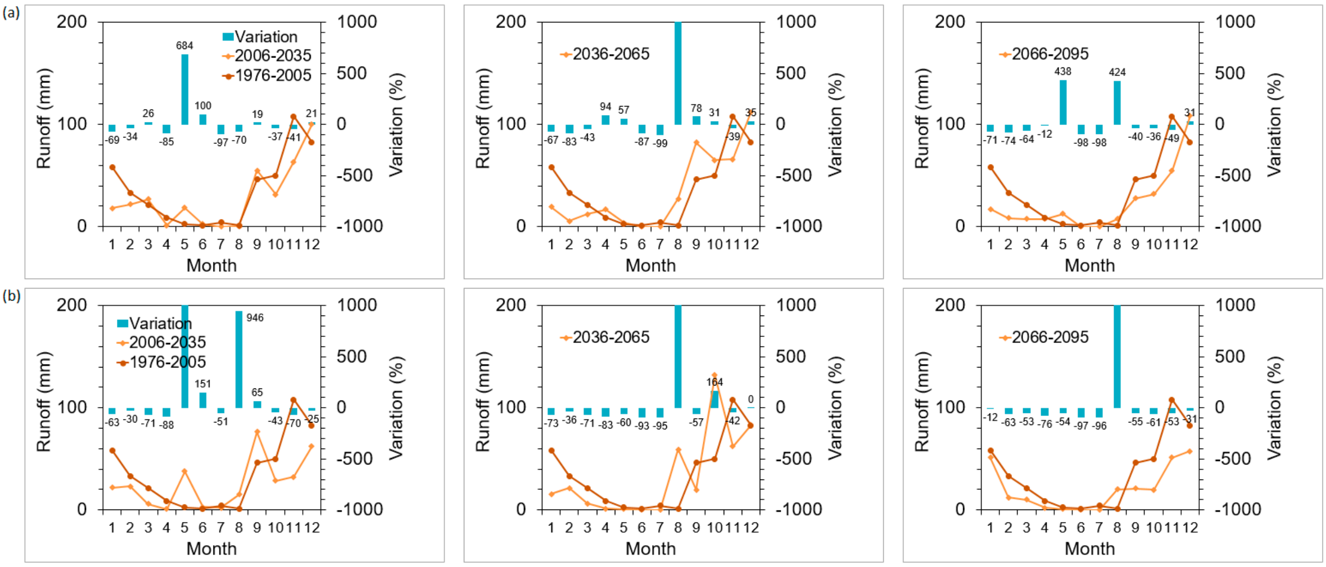

Figure 8. Trends of monthly variation in surface runoff in (mm), for both climate change projections (**a**) RCP 4.5 and (**b**) RCP 8.5. Brown lines show values for the reference (light) and future (dark) period, blue bars show the variation between future and reference period.

3.2. Management Options and Climate Change Scenario Simulations

As reported in several works [32–34], the thinning practice makes it possible to reduce the forest canopy; enhancing the light penetration and water availability for the surviving trees promotes a decrease in the natural mortality rate. This explains why reducing the tree density through thinning leads to an increase in the DBH, which was assessed as an indicator of forest growth in this case (Figure 9). The latter is due to an increase in the thinning intensity, in terms of percentage, of the trees to be cut, or also a decrease in the thinning intervals. For heavy thinning scenarios, in particular, the variance in the growth was obvious with respect to other treatments.

Figure 10 shows the behavior of the basal area in relation to different thinning intensities and time intervals. In particular, there is a significantly higher increase in the basal area in forest management options that involve thinning with low intensity and frequent cuts compared to longer time intervals. Furthermore, there is a noticeable decrease in the basal area in forest management options characterized by high intensities and very long time intervals, especially with the increase in the age of the forest stand, for both of the climate scenarios.

With regard to the hydrological response of the watershed to different thinning intervals and intensities, we compared the variation in the surface runoff with respect to the base scenario simulations in terms of percentages of variation. The increase in the thinning intensity produced a higher variation in surface runoff with a possible impact on floods and soil erosion.

In a review paper, Del Campo et al. [35] synthesized the results of several works analyzing the impact of thinning on key hydrological dynamics, particularly focusing on rainfall distribution, soil moisture levels, and evapotranspiration processes. As a result, a thinning intensity of about 50% (between 40% and 60% for a confidence interval equal to 95%) of the stand density has been identified as the threshold at, or over, which the hydrological processes are affected. These processes include rainfall partitioning, soil water redistribution, transpiration, evapotranspiration, etc. [36]. This effect strongly depends on three classes of factors considered: ecological, treatment intensity, and research timeframe [35]. Del Campo et al. [35] observed that thinning had a pronounced effect on hydrological processes, particularly evident in densely populated juvenile pine stands. In such cases, alterations in soil moisture, stand transpiration, and sap flow were notably significant. This outcome can be attributed to variances in anatomical features (such as sapwood proportion and higher sap flow per unit of sapwood) and physiological characteristics (like faster growth rates) between young conifers and mature forests [37].

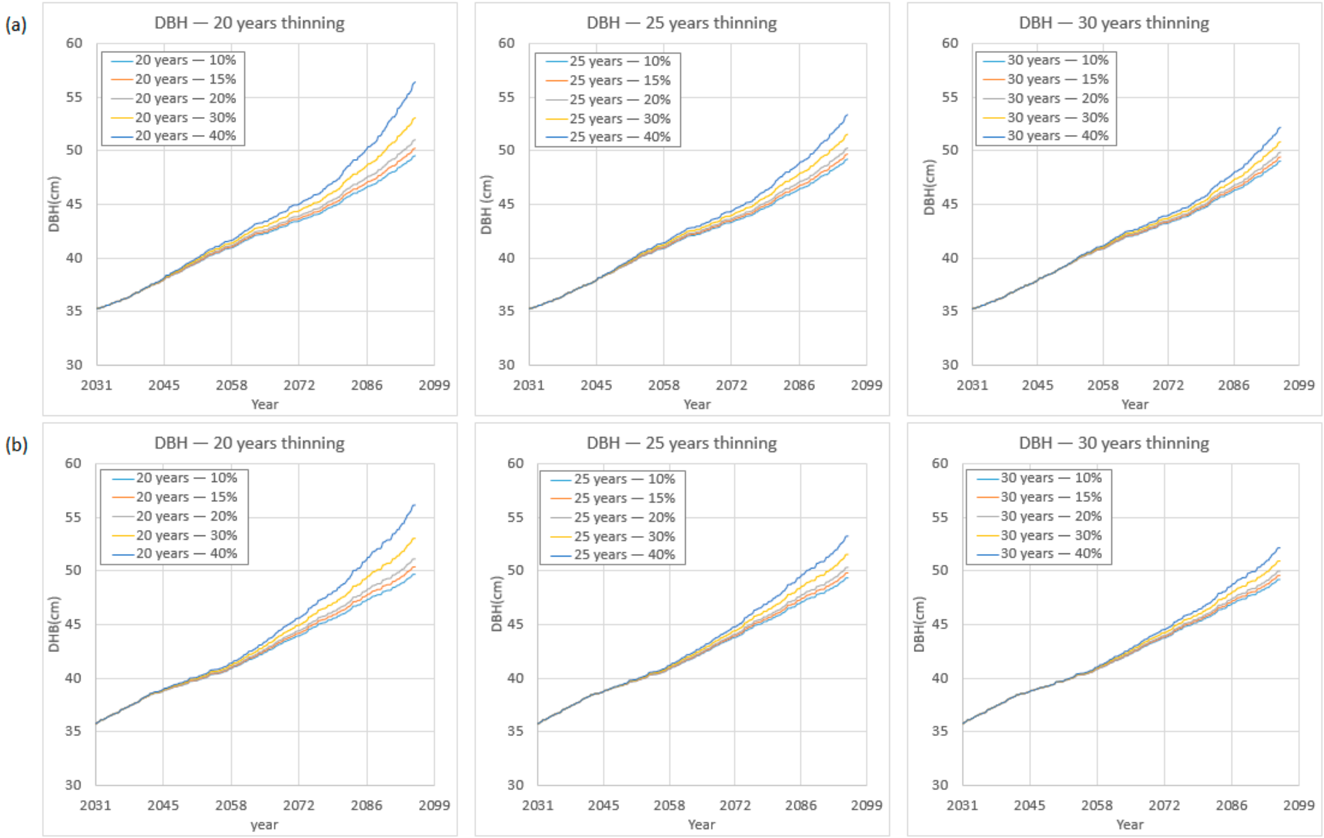

Figure 9. Response of DBH to the different thinning intervals of 20, 25, and 30 years, and intensities (10, 15, 20, 30, and 40%) for both climate change projections (**a**) RCP 4.5 and (**b**) RCP 8.5.

For this study, the runoff under heavy thinning scenarios reached 60% greater change with respect to the no-management scenario. In addition, a remarkable decrease of this magnitude with larger thinning intervals was also observed. Thinning decreased the number of trees, thus reducing the canopy interception of the precipitation. Moreover, thinning also means lower basal area/sapwood and LAI area and, thus, lower transpiration even if individual tree transpiration increased. As a result, more water will be able to reach the floor, yielding an increase in the generated runoff. Some researchers suggested such intervention as an important management strategy to enhance runoff and groundwater discharge, and increase water use efficiency [38]. Accordingly, considering the different consequences of thinning intervals and intensities, decisions should be taken in line with regional strategies, and the peculiarities of each site. Increasing the thinning percentage will boost the stem yield but, at the same time, it will intensify the surface runoff. Stakeholders should find a compromise between the wood yield target and the sustainable management of the Bonis basin. Based on these results, the increase in the runoff was more influenced by the thinning than by climate change as compared to the base scenario.

In this case, selective thinning was not considered, since all the trees were supposed to have the same conditions and the same characteristics. The considered thinning intensities could be regarded as moderate for the intensities 10, 15, and 20% and heavy for the intensities 30 and 40%. Clearly, the heavy thinning allowed us to obtain more wood yield but, at the same time, the latter induced a drastic decrease in the tree density.

Thus, an increase in the thinning intensities or a decrease in the thinning intervals caused a reduction in the density of the pine trees. The cut trees constitute the yield, considered one of the major forest ecosystem services. The yield augmented as a consequence of the increase in the intensity of the thinning. As shown in Figure 11, a higher yield will be achieved by decreasing the thinning interval.

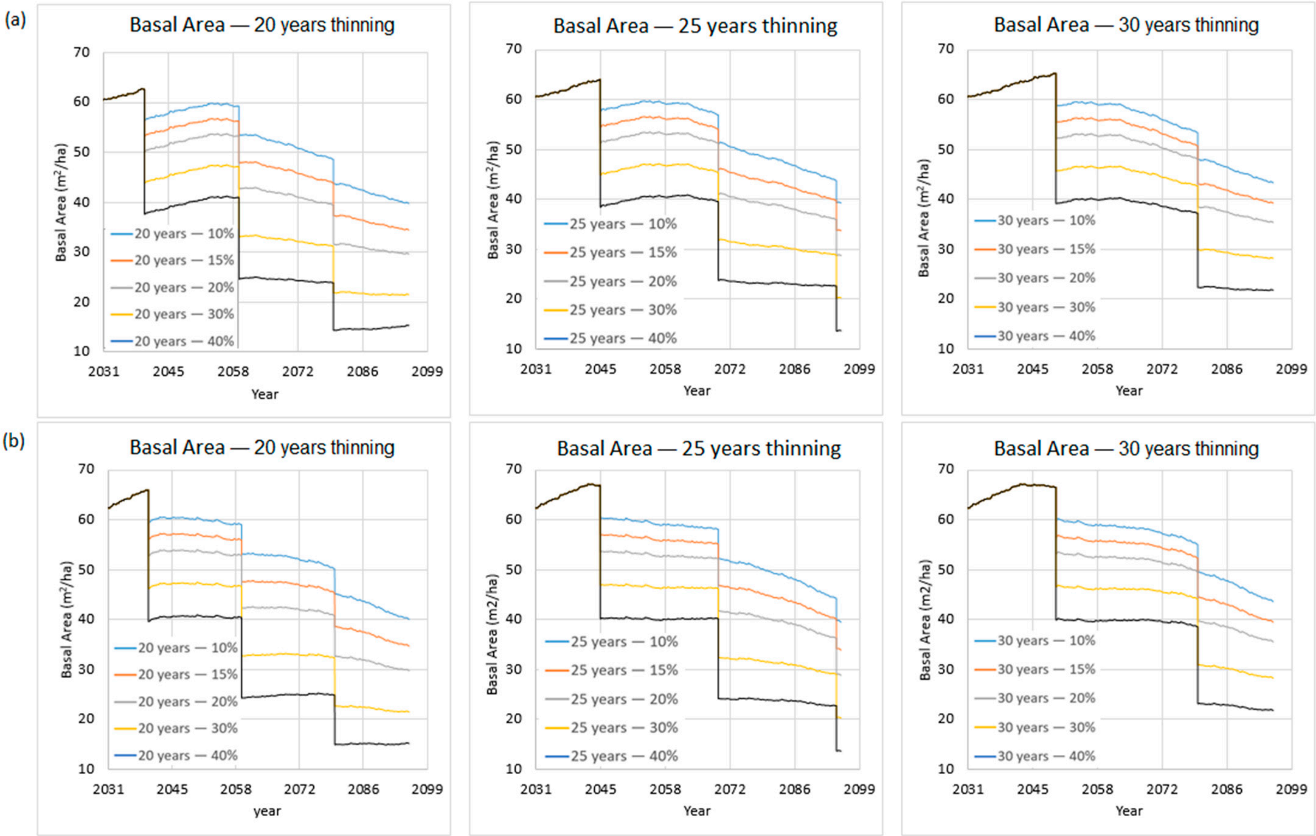

Figure 10. Response of the basal area to the different thinning intervals of 20, 25, and 30 years, and intensities (10, 15, 20, 30, and 40%) for both climate change projections (**a**) RCP 4.5 and (**b**) RCP 8.5.

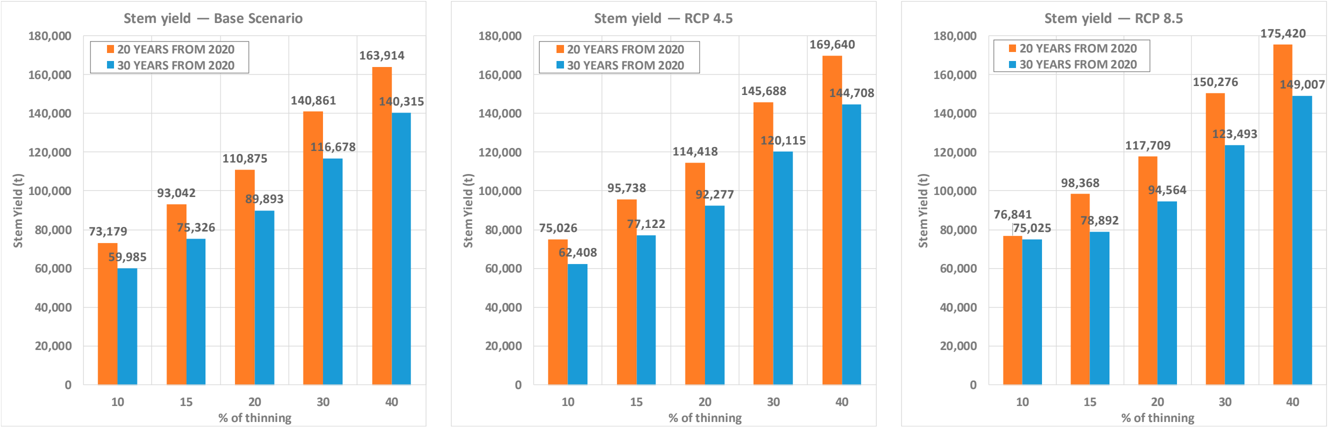

Figure 11. Results of thinning with different intervals and intensities on the stem yield (t).

In addition, the different climate scenarios showed a direct influence on stem yield levels. In fact, higher production will be reached under RCP 4.5 and RCP 8.5 as compared to the base climate scenario. The highest yield, which is a consequence of the highest forest growth rate, was achieved with the RCP 8.5 scenario. These results rely on simulation outcomes previously reported regarding forest growth under different climate scenarios. In effect, better forest growth will produce higher yields.

4. Conclusions

The climate of the Bonis catchment is expected to change in the future (thirty-year period of 2066–2095) toward a rise in temperature (about 2 °C for RCP 4.5 and 3.5 °C for RCP 8.5) and a reduction in annual precipitation (124 mm for RCP 4.5 and 185 mm for RCP 8.5). This will lead to an increase in PET to a maximum monthly percentage of 12% and 16% for RCP 4.5 and RCP 8.5, respectively. Precipitation reduction will lead to a general decrease in monthly runoff as well but with a relevant increase in summer (>100%) likely due to a rise in the frequency of short high-intensity periods of convective events. Concerning vegetation response, an augmentation in forest growth was evident irrespective of forest management practices. Particularly, significantly higher values were observed across all forest growth parameters under the more extreme RCP 8.5 scenario, in comparison to both the RCP 4.5 and baseline scenarios. This leads to the conclusion for this particular study site that the rises in temperature and CO_2 concentration are beneficial for forest growth and wood yield in the future. For this reason, the impact of climate change should be studied case by case since the results of future impacts differ from one case to another. Conversely, thinning enables the reduction in the forest canopy, thereby enhancing light availability for the remaining trees and consequently leading to a decline in the natural mortality rate. The increase in the thinning percentage will boost the stem yield but at the same time, may induce a rise in the surface runoff. Stakeholders should find a compromise between the wood yield target and the sustainable management of the Bonis basin.

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Data Availability Statement: Data will be sent if anyone requests.

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