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Carbon versus Timber Economy in Mediterranean Forests

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Abstract: Forests produce goods and services, but the forest economy is based on goods, with market price, more than on services. Under Mediterranean climate conditions forests have low timber production, being frequently financially loss-making, despite the environmental services provided, such as carbon sequestration. Timber production and carbon sequestration are compatible, and a proper valuation of both can allow for a more balanced management. The aim of this paper is to assess financially a scenario based on maximizing carbon sequestration versus another based on maximizing timber harvesting in a Mediterranean forest. To do that, timber stock, growth and harvesting, and carbon sequestration have been calculated. Applying market prices for timber and CO_2 both scenarios have been assessed, carrying out a sensitivity analysis. Maximising carbon sequestration was more profitable in the vast majority of combinations; timber harvesting was only more profitable if CO_2 prices fell below 30% and timber price increases more than 20%; timber price rise is possible, but a collapse in CO_2 price is not probable. The real barrier is that while timber is as a commodity with market price, carbon sequestration is not. The challenge for the future is to pay for carbon sequestration, mobilising resources from polluting sectors to forests.

Keywords: carbon sequestration; environmental services; sustainable forestry

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1. Introduction

Forests produce goods, such as timber, firewood, fruits or mushrooms, and services, such as landscape, biodiversity, water or soil protection, carbon sequestration or recreation [1–4]. However, the forest economy is frequently based on the production of goods, with a market value, and does not usually consider services [5]. In addition, even benefits from forest products have declined over the last decades [6]. As a result, forests with low timber productivity often operate at a financial loss, despite the important environmental services provided. Landowners often lose money, and these negative financial results discourage forestry [7].

The Mediterranean climate is characterized by a cold winter period and a warm and dry summer. This seasonality gives rise to two short growing seasons, in spring and autumn, separated by two interruptions, due to cold in winter and drought in summer [8]. This short growing seasons limits vegetation growth. As a consequence, timber production under Mediterranean climate is low, unlike, for example, Atlantic, Central European or Scandinavian forests. This does not mean that Mediterranean forests lack value, as they host, for example, a high number of rare and locally endemic taxa [9].

Ecosystem services may be complementary or opposed; for example, recreational use and wildlife conservation may conflict. Similarly, timber extraction and carbon sequestration may conflict with each other. For example, the rotation length varies according to whether the aim is to maximise timber production or carbon sequestration, being longer in the second scenario [10–12].

Timber is a renewable resource that allows carbon to be stored, so increasing its use, especially in construction, is highly desirable from an environmental point of view [13], but at the same time, carbon sequestration is an increasingly important goal in forest management [14]. Managed forests, are usually younger, and have 50% lower C stocks than unmanaged ones [15]. However, the effects of unmanaged timber exploitation, which can lead to forest disappearance, are well known. Several authors have pointed out the risks to biodiversity that maximising carbon sequestration can have [16–21]. In addition, climate change impacts, especially intense in the Mediterranean, may reduce timber production and carbon sequestration, while increasing the risk of forest fires [19].

Both timber production and carbon sequestration are environmental services provided by forests, and are compatible with each other and with other services. A proper valuation of both can allow for a more balanced forest management and greater income [10,18]; the objective should be to find win-win strategies, increasing both carbon stocks and timber harvest [22].

Forest fires, a recurrent occurrence in the Mediterranean region, are a key factor that produce timber losses, and with it a loss of accumulated carbon stock, abruptly released into the atmosphere. It is therefore a factor to be taken into account when assessing the forest carbon balance, as there is a probability of carbon (and timber) stock losses. Fire frequency depends on the risk of the area but also on the extinction means. The risk is very variable from year to year, since not only the fuel load, its structure and flammability influence, but also the humidity, which is very variable depending on the annual distribution of rainfall, and above all on the existence or not of late-spring and summer rainfall. Spain has extensive and efficient means of fire extinction, given the frequency of wildfires, so that although the number of fire outbreaks increases, they do not usually spread. Even so, periodically there is a conjunction of unfavourable conditions, often combined with negligent or criminal behaviours, which despite the efforts of prevention and extinction can lead to a fire.

There are previous works that analyze the influence of forest management on carbon sequestration [10–12,23], some of them focused on the Mediterranean region, but they do not include an assessment of scenarios based on specific growth and harvest data. The aim of this paper is to assess financially a scenario based on maximizing carbon sequestration versus another based on maximizing timber harvesting in a Mediterranean forest, considering in both cases the risk of forest fires. In both scenarios the two factors, sequestration and harvesting, were combined. In the first scenario timber extraction was limited to forest management and conservation requirements, with sequestration as a priority. In the second scenario harvesting was maximized, in a sustainable manner, with carbon sequestration being secondary. A sensitivity analysis was conducted discussing the profitability of both scenarios.

2. Materials and Methods

2.1. Study Area, Species and Period

The study area (Figure 1) was a forest located in the province of Madrid (Central Spain), at an average altitude of 1400 m (range 950–1763 m). The total area of the property was 847 ha, 653 ha forested and the rest rocky, scrub or pasture areas. The area was deforested at the end of the 19th century, being reforested later in two periods, the first in 1892–1914 and the second in 1952–1954. The main tree species are *Pinus sylvestris* L. (49% of the stock), *P. pinaster* Aiton (47%) and *P. nigra* J.F. Arnold (3%); other less abundant species are *Fraxinus angustifolia* Vahl, *Pinus pinea* L., *Acer pseudoplatanus* L., *Cedrus atlantica* (Endl.) Manetti ex Carrière and *Abies pinsapo* Boiss. The climate of the area is Mediterranean, with an annual rainfall of 884 mm and an average temperature of 13.1 °C, with a marked summer drought period. The dominant lithology is gneiss, on which inceptisol soils develop, with a high rockiness.

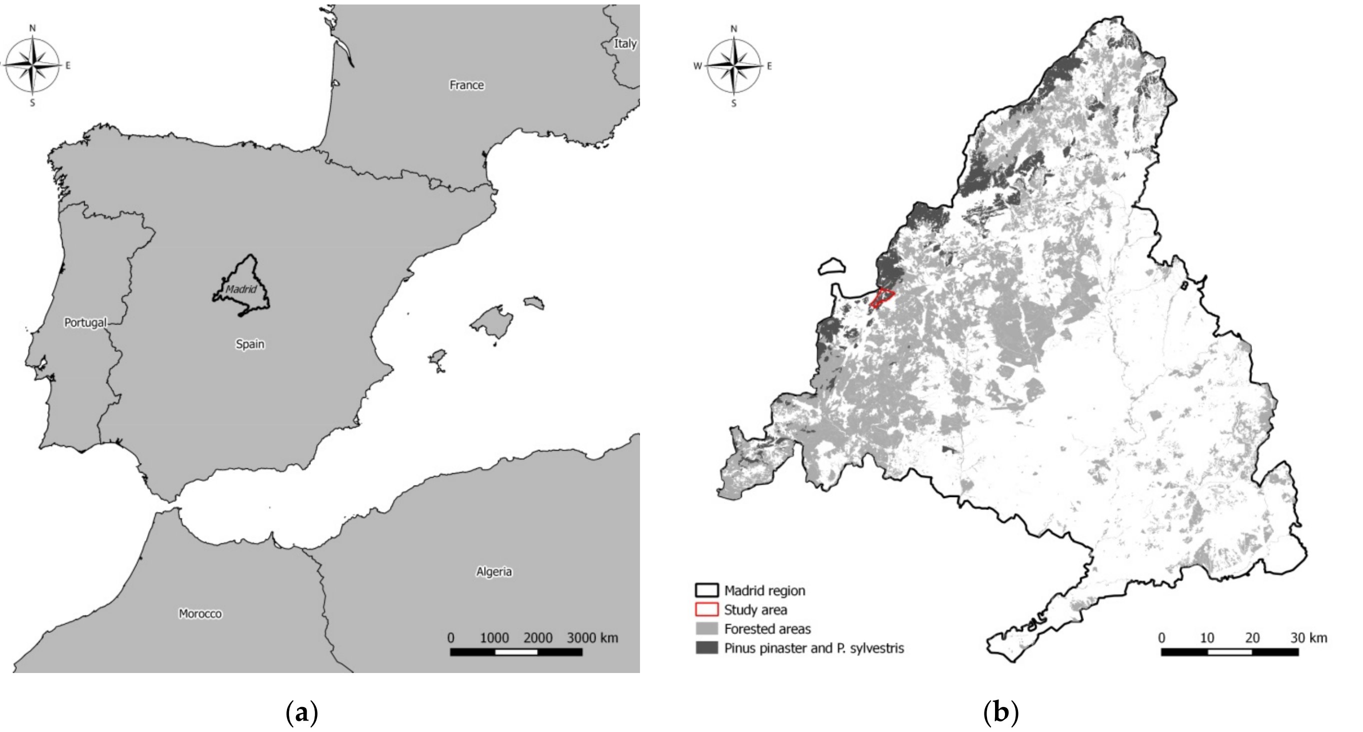


Figure 1. Study area. (**a**) Situation of Madrid Region in the Western Mediterranean; (**b**) Forested areas of Madrid Region, *Pinus pinaster* and *P. sylvestris* stands, and study area.

This study considered the two main tree species, *Pinus sylvestris* and *P. pinaster*, which accounted for 91% of the forest timber stock [24]. The two species generally form pure stands, the former dominating in the higher zones, between 1300 and 1760 m, and the latter in the lower zones, between 950 and 1300 m; only occasionally are both species mixed, in contact areas.

The study period was 1999 to 2020 for the historical analysis of forest fires, and 2005 to 2024 for the analysis of timber harvesting and carbon sequestration.

The forested area of Madrid accounts for 264,658 ha, 82.4% dense forests and 17.6% agroforestry systems, with sparse trees. Dense forests are dominated in 58.4% by hardwoods (mainly *Quercus rotundifolia* Lam.) and in 41.6% by conifers. Stands dominated by *Pinus sylvestris* and *P. pinaster*, with an ecology and management similar to those analysed in this study, account for 44% of conifer stands and 18.6% of total dense forests [25]. Nationally, these two species account for 33% of all conifers and 8% of forests [26].

In terms of timber volume, *P. sylvestris* and *P. pinaster* represent 49% of the total timber volume in Madrid, and 34% for the whole of Spain; both species occupy the first place in terms of timber stocks in Spain, with around 153 million m^3 [25,26]. The volume of timber harvested in Spain in 2018 [26] was 19.7 million m^3, 53.9% of which was conifers and 46.1% hardwoods (overwhelmingly *Eucalyptus*). The volume of *Pinus pinaster* was 3,184,441 m^3 and that of *P. sylvestris* was 1,275,061 m^3; both species accounted for 22.6% of the total annual of timber harvesting, and 41.9% of conifers total.

The total timber yield of these two species in Spain was 80.2 million € [26]. The total value at basic prices of forestry and logging products in Spain in 2019 was €960.5 million, 0.1% of the national total [27]; timber from these two pines accounted for 8.35% of the value of forestry products.

Consequently, the stands of *P. sylvestris* and *P. pinaster*, similar to those analysed in this work, are very representative in Spain, both superficially and in terms of their timber existences and annual harvesting volume.

2.2. Studied Scenarios

Two scenarios have been analysed:

- Scenario A. Current situation. The forest has conservation objectives, without commercial harvesting (only for forest maintenance); economic return is secondary. Timber extraction is scarce, but carbon sequestration is maximised.
- Scenario B. Maximum sustainable timber production. The objective would be to maximize timber harvesting, in a sustainable form, with guarantees of forest preservation. Timber extraction would be maximised, but carbon sequestration would be reduced.

In both cases it is intended to obtain the cost-effectiveness of the model, in order to determine differences. In order to make the calculations comparable with those of other regions, we have always used relative values per hectare, considering the forested area.

2.3. Timber Stock, Growth and Harvesting

Forest inventories carried out in 2005 and 2014 [24,28] calculated timber volume (commercial fraction). In the two scenarios studied there was forest growth and harvesting, associated with management or timber production. Net timber volume growth (G_{TV}), in m^3/ha, is timber volume growth (I_{TV}) minus timber volume harvesting (H_{TV}). Annual timber volume increase (I_{TV}) was calculated using the equations for *Pinus pinaster* and *P. sylvestris* established for Madrid region in the National Forest Inventory [29].

In scenario A harvesting between 2005 and 2014 focused on dead trees, especially *Pinus pinaster* affected by bark beetles. From 2015 to 2024 the management plan [24] established an annual logging calendar, focused on reducing excessive density in some areas, mainly covered by *P. sylvestris*. In scenario B the maximum possible timber harvesting (H_{TV}), in m^3/yr, was calculated using Gehrhardt equation [30], recommended for decades for *Pinus sylvestris* forests in this region [31], and currently of obligatory use in the Madrid region for irregular forests with stand management [32], as well as in most Spanish regions. In this equation p is the period established (in this case the forest rotation, 120 years) and I_{TV} the annual increase of the volume (m^3):

$$H_{TV\ (Scenario\ B)} = V_T/p + I_{TV}/2 \quad (1)$$

2.4. GHG Sequestration

Forest inventories, growth equations and harvesting use timber volume (m^3), but for carbon sequestration calculations it is necessary to use biomass values (Mg). Consequently, whenever a biomass value had to be used, it was obtained by multiplying the timber volume (V_T) in m^3, by timber density (δ_T) in Mg/m^3. The average density for Mediterranean conifers is 0.507 Mg/m^3 [33].

Carbon sequestration is the amount of CO_2 removed from the atmosphere by vegetation and fixed in plant tissues. For its calculation it is necessary to determine the net biomass growth of the forest (G_{NB}), in Mg/ha, not only for the commercial fraction (timber), but for the whole forest biomass. The forest biomass (T_B) in Mg/ha is [34]:

$$T_B = M + B + U + PL \quad (2)$$

where M is the commercial biomass (Mg/ha), B is the non-commercial aerial part (branches and leaves; the aerial part corresponds 79.5% to the stem and 20.5% to leaves and branches in *Pinus pinaster*, and 71.3% and 28.7% respectively in *P. sylvestris* [35]. Operating with these values we obtained $B_{P.\ pinaster} = 0.258 \cdot M$ y $B_{P.\ sylvestris} = 0.403 \cdot M$), U is the underground biomass (roots; the aerial part in *Pinus pinaster* is 77.9% and the root part 22.1%, and in *P. sylvestris* 78.6% and 21.4% respectively [35]. Operating we obtained $U_{P.\ pinaster} = 0.357 \cdot M$ y $U_{P.\ sylvestris} = 0.382 \cdot M$) and PL is the soil litter (Tthe mean value is 13.2 Mg/ha in *Pinus pinaster* and 48.2 Mg/ha in *P. sylvestris* [36]).

Biomass increase (I_B) due to tree growth affects to the aerial part and the roots (M + B + U), but tree extraction, harvesting (H_B), affects only to the aerial part but not to the roots

(M + B). Stumps and roots are not extracted after felling, remaining in the ground, where they decompose slowly, given the large amount of resin they contain. This allows a progressive incorporation of carbon into the soil, and a very slow release into the atmosphere, so for GHG balances its influence can be considered negligible. Therefore, their separate calculation is necessary to obtain the net biomass growth. Net biomass growth (G_{NB}) is biomass increase (I_B) minus biomass extraction (H_B):

$$\begin{aligned} G_{B\,(P.\ pinaster)} &= I_B - H_B = 1.615 \cdot I_V \cdot \delta_T - 1.258 \cdot H_V \cdot \delta_T = 0.819 \cdot I_V - 0.638 \cdot H_V \\ G_{B\,(P.\ sylvestris)} &= I_B - H_V = 1.785 \cdot I_V \cdot \delta_T - 1.403 \cdot H_V \cdot \delta_T = 0.905 \cdot I_V - 0.711 \cdot H_V \end{aligned} \quad (3)$$

Sequestration (SQ), in Mg $CO_{2\,eq}$/ha·yr, is the net biomass growth (G_{NB}) multiplied by the percentage of carbon ($C_{\%}$) and the equivalence factor between CO_2 and C (3.67). Carbon percentage in *P. pinaster* is 51.1% in *P. sylvestris* 50.9% [35]. Consequently:

$$\begin{aligned} SQ_{\,(P.\ pinaster)} &= G_B \cdot C_{\%} \cdot 3.67 = ((0.819 \cdot I_V - 0.638 \cdot H_V) \cdot 0.511) \cdot 3.67 = 1.538 \cdot I_V - 1.196 \cdot H_V \\ SQ_{\,(P.\ sylvestris)} &= G_B \cdot C_{\%} \cdot 3.67 = ((0.905 \cdot I_V - 0.711 \cdot H_V) \cdot 0.509) \cdot 3.67 = 1.692 \cdot I_V - 1.329 \cdot H_V \end{aligned} \quad (4)$$

2.5. GHG Emissions from Forest Fires

To obtain GHG emissions from forest fires we used IPCC equation [37]:

$$L_{FT} = A \cdot MB \cdot C_f \cdot G_{ef} \cdot 10^{-3} \quad (5)$$

where L_{FT}, total emission of GHGs by forest fires (Mg $CO_{2\,eq}$), including CO_2, CH_4 and N_2O. A, burnt area (ha), estimated as an average of historical forest fire data. Between 1999 and 2020 there was one major fire (1999), 15 years without fires and 6 years with small fires (Table 1), the average annual burnt area was 5015 ± 4959 ha.

Table 1. Forest fires in the studied area.

Year	Burnt Area	Year	Burnt Area
1999	109.16 ha	2010	0.00 ha
2000	0.00 ha	2011	0.14 ha
2001	0.03 ha	2012	0.00 ha
2002	0.00 ha	2013	0.01 ha
2003	0.00 ha	2014	0.00 ha
2004	0.00 ha	2015	0.41 ha
2005	0.32 ha	2016	0.00 ha
2006	0.00 ha	2017	0.00 ha
2007	0.00 ha	2018	0.00 ha
2008	0.00 ha	2019	0.26 ha
2009	0.00 ha	2020	0.00 ha

MB, mass of fuel available for combustion (Mg/ha), including the aerial part and the soil litter, but not the roots, so MB = M + B + PL. We considered the average forest timber volume (V_A), and weighted according to the area of each of the species:

$$MB = 1.333 \cdot M + 31.4 = 1.333 \cdot V_M \cdot 0.507 + 31.4 = 0.676\ V_M + 31.4 \quad (6)$$

where C_f is 0.48 (dimensionless) and G_{ef} 1.577.50 g $CO_{2\,eq}$/kg [38].

We have worked with average values per hectare, so the total annual emission from forest fires (L_{FT}) is divided by the forested area, obtaining the average emission (L_{FA}).

2.6. GHG Balance

Using annual sequestration (SQ) and emissions from forest (L_{FA}) the GHG balance (Mg $CO_{2\,eq}$/ha·yr) was obtained:

$$SQ = SQ_{\,(P.\ pinaster)} + SQ_{\,(P.\ sylvestris)} - L_{FA} \quad (7)$$

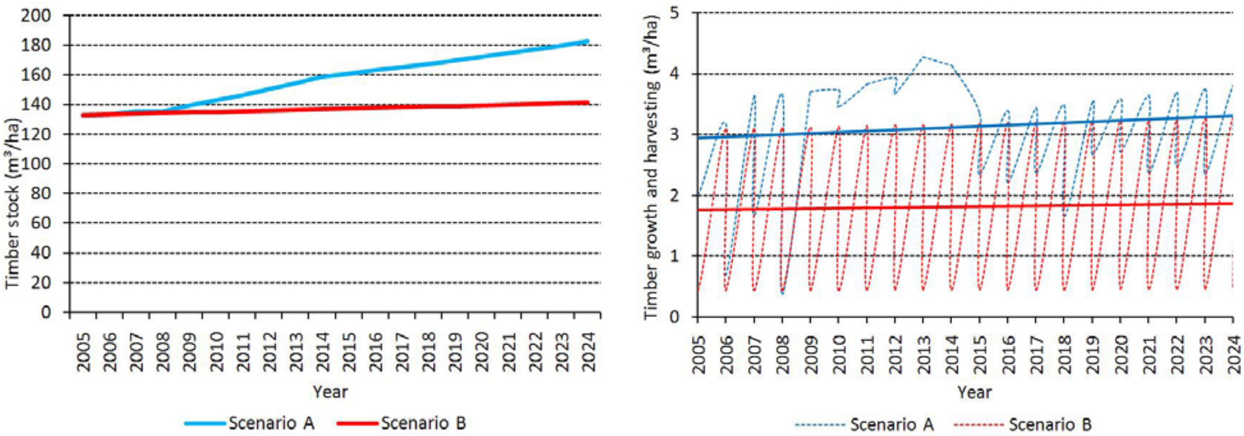
2.7. Financial Assessment of Scenarios

The average timber price in Spain according to the latest published forestry statistics (2018) was 16.49 €/m^3 for *P. pinaster* and 21.03 €/m^3 for *P. sylvestris*. However, in the public forests of Madrid the average price was lower, 5.79 €/m^3 between 2008 and 2012 [25], well below the market value. This low value is due to the fact that logging is not focused on production, but on the maintenance of the stand, and consequently the extracted timber is irregular in production, size and quality. This is the case in scenario 1, where a timber price 50% of the average market price is currently being applied. For the financial valuation of CO_2 sequestration, the average price of Emission Rights in the European Union in 2020 (24.75 €/Mg CO_2) has been used.

3. Results

3.1. Timber Stock, Growth and Harvesting

Figure 2 summarises the results of growth, timber harvesting and stock for the two analysed scenarios. In scenario A the average growth was 3.64 ± 0.06 m^3/ha·y, average harvesting 1.04 ± 0.20 m^3/ha·y and average stock 156.96 ± 3.75 m^3/ha, and in scenario B 3.17 ± 0.01 m^3/ha·y, 2.73 ± 0.10 m^3/ha·y and 137.07 ± 0.59 m^3/ha, respectively.



(**a**) (**b**)

Figure 2. Timber growth, harvesting and stock in the studied scenarios. (**a**) Change in timber stock (m^3/ha·y) in the studied scenarios; (**b**) Changes in timber growth (m^3/ha·y) and harvesting (m^3/ha·y) in the studied scenarios.

3.2. GHG Sequestration

Figure 3 summarises GHG sequestration for the two analysed scenarios. In scenario A, average sequestration was 4.60 ± 0.31 Mg $CO_{2\,eq}$/ha·y, and in scenario B 1.69 ± 0.01 Mg $CO_{2\,eq}$/ha·y.

3.3. GHG Emissions from Forest Fires

In scenario A the average timber volume (V_A) was 156.96 m^3/ha, resulting in an annual GHG emission from forest fires (L_{FT}) of 522.16 Mg $CO_{2\,eq}$/y and a relative emission (L_{FA}) for the forested area of 0.80 Mg $CO_{2\,eq}$/ha·y; in scenario B the value of V_A was 137.07 m^3/ha, L_{FT} 471.10 Mg $CO_{2\,eq}$/y and L_{FA} 0.72 Mg $CO_{2\,eq}$/ha·y.

3.4. GHG Balance

The net GHG balance, as indicated above, is the sequestration minus the emission from forest fires. For scenario A the average value was 3.80 Mg $CO_{2\,eq}$/ha·y., and in scenario B 0.97 Mg $CO_{2\,eq}$/ha·y.

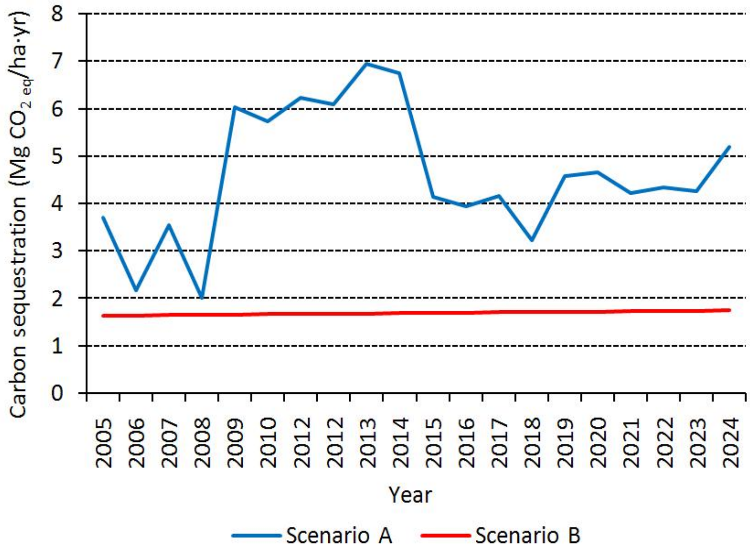


Figure 3. Carbon sequestration (Mg $CO_{2\ eq}$/ha·y) in the studied scenarios.

3.5. Financial Assessment of Scenarios

To assess the two scenarios considered, five possible prices for both timber and CO_2 have been considered: an average price (justified above); two low prices, 20 and 30% below the average; and two high prices, 20 and 30% above the average (Table 2).

Table 2. Financial valuation of studied scenarios. $\bar{x}$ means average price.

Scenario	Timber Harvesting							Carbon Sequestration				Global Balance €/ha
	Pinus Sylvestris			*Pinus Pinaster*			Total €/ha	Mg $CO_{2\ eq}$/ha·y	€/Mg $CO_{2\ eq}$		Total €/ha	
	m^3/ha·y	€/m^3		m^3/ha·y	€/m^3							
		−30%	7.36		−30%	5.78	6.81		−30%	17.33	65.84	72.65
		−20%	8.42		−20%	6.60	7.79		−20%	19.80	75.24	83.03
A	0.99	$\bar{x}$	10.52	1.09	$\bar{x}$	8.25	9.73	3.80	$\bar{x}$	24.75	94.05	103.78
		+20%	12.62		+20%	9.90	11.68		+20%	29.70	112.86	124.54
		+30%	13.68		+30%	10.73	12.65		+30%	32.18	122.27	134.92
		−30%	14.72		−30%	11.54	36.01		−30%	17.33	16.81	52.82
		−20%	16.82		−20%	13.19	41.15		−20%	19.80	19.21	60.36
B	2.75	$\bar{x}$	21.03	2.70	$\bar{x}$	16.49	51.44	0.97	$\bar{x}$	24.75	24.01	75.45
		+20%	25.24		+20%	19.79	61.73		+20%	29.70	28.81	90.54
		+30%	27.34		+30%	21.44	66.87		+30%	32.18	31.21	98.08

With these prices, a sensitivity analysis has been conducted for both scenarios, considering all possible price combinations (Table 3). Sensitivity analysis is a financial model that determines how target variables (in this study global income) are affected based on changes in other variables known as input variables (in this case timber and CO_2 income).

Analysing the 25 possible price combinations, carbon sequestration (scenario A) is more profitable in 92% of the cases (23 combinations), and timber production (scenario b) in 8% (2 combinations). The combinations that make timber production more profitable involve a CO_2 price 30% below average and a timber price 20–30% above average. However, the probability of occurrence of each combination is different. For example, it seems more likely that the price of timber and CO_2 will remain stable or increase than decrease, so options that combine stable prices or price increase scenarios would be more likely to occur than those with price decrease, but given the uncertainty it is not possible to establish their probability.

Table 3. Sensitivity analysis of scenarios. $\overline{x}$ means average price.

Prices (€/ha)		**CO_2**				
		−30%	**−20%**	**$\overline{x}$**	**+20%**	**+30%**
Timber	**−30%**	72.65 52.82	82.05 55.22	100.86 60.02	119.67 64.82	129.08 67.22
	−20%	73.63 57.96	83.03 60.36	101.84 65.16	120.65 69.96	130.06 73.26
	$\overline{x}$	75.57 68.25	84.97 70.65	103.78 75.45	122.59 80.25	132.00 82.65
	+20%	77.52 78.54	86.92 80.94	105.73 85.74	124.54 90.54	133.95 92.94
	+30%	78.49 83.68	87.89 86.08	106.70 90.88	125.51 95.68	134.92 98.08

Upper-left value: Scenario A. Lower-right value: Scenario B.

4. Discussion

Forest growth was calculated using the equations established for the Madrid region by the National Forestry Inventory [29]. Using two independent timber stock calculations from 2005 and 2014 [24,28], and quantifying timber removals in that period, it has been verified the adjustment of these equations to the studied forest with a 98.2% accuracy. Consequently, the calculated forest growth between 2005 and 2014 has been verified, and is in according to what is expected for the study region. Scenario A represents a typical practice in protective forests in Mediterranean Spain, with low timber extraction. Scenario B represents the maximum sustainable timber harvest, which could not be exceeded without forest decline. These are, therefore, reasonable scenarios.

Current timber production in the forest (scenario A) is marginal, limited to logging for forest maintenance. In addition, the price of timber is low, as production is irregular and of poor quality, as noted above. As a result, an average income of 9.73 €/ha·y is barely reached, and potential price fluctuations do not have much effect (6.81–12.65 €/ha·y). The maximum sustainable timber production would yield on average 51.44 €/ha·y, with a range depending on price fluctuations of 36.01–66.87 €/ha·y.

Considering the volume of timber harvested in 2018 in Spain, the area occupied by *P. pinaster* and *P. sylvestris*, and the average timber prices for these species [26], national average production of *P. pinaster* was 3.01 m^3/ha·y with a yield of 49.63 €/ha·y and that of *P. sylvestris* was 1.24 m^3/ha·y with a yield of 26.08 €/ha·y. In *P. pinaster* the production and yield were higher due to the existence of very productive stands in the north of Spain, in rainier areas; the value in *P. sylvestris* was more representative for pine forests similar to those studied. However, as noted above, timber prices in public forests of Madrid were below market values, and consequently below these yields.

For *P. sylvestris*, a more stable reference for the forests studied, the average yield was higher than that currently obtained in this forest (scenario A), although it is almost half the value that could be obtained by dedicating the forest to timber production (scenario B). These results are therefore consistent with national values.

The CO_2 sequestration rate for Spanish pine forests reported in the literature ranges from 3.66 Mg $CO_{2\,eq}$/ha·y [35] to 5.10 Mg $CO_{2\,eq}$/ha·y [39]. Our results were 3.80 Mg $CO_{2\,eq}$/ha·y in scenario A, consistent with these values; in scenario B, timber extraction greatly reduces the sequestration rate to 0.97 Mg $CO_{2\,eq}$/ha·y. Based on the price of emission rights in the EU, as noted above, an average sequestration value of 94.05 €/ha·y in scenario A and 24.01 €/ha·y in scenario B was obtained. Values reported in the literature for carbon sequestration in Southern Europe vary widely, ranging from 9 €/ha·y [40] to 895 €/ha·y [41]. In boreal forest it has been estimated that a 5% reduction in timber harvest revenues can produce a 15–23% increase in carbon sequestration [42].

It is important considering the incidence of forest fires in the sequestration rate, as it implies a loss of sequestration and a release of GHGs; in scenario A, for example, the sequestration rate without considering forest fires would be 4.60 Mg CO_2 eq/ha-y, dropping to 3.80 Mg CO_2 eq/ha-y if fire risk is taken into account. Although between 2007 and 2015, fire-related emissions in Spain decreased by 53% compared to 1998–2006 [38], predictions point to a fire risk increase in the Mediterranean as a consequence of climate change [43,44], so it is reasonable to incorporate this variable into the calculations. As noted above, in both scenarios, preventive fire prevention forestry is applied, removing dead fuel. In addition, the region has ample fire-fighting means, so there is no significant variation in fire risk between the two scenarios. More influential is the meteorology of each year, especially the distribution of rainfall in late spring, summer and early autumn, which determine the length of the high fire-risk period. Negligence and criminal acts are also important. It has therefore been chosen to use historical risk as an indicator, which already incorporates these uncertainties.

Calculations were based on reliable data and realistic assumptions. The sensitivity analysis demonstrated that forest protection, maximising carbon sequestration, was more profitable in 92% of price combinations. Timber harvesting was only more profitable if CO_2 prices fell below 30% of their current value coupled with an increase in timber prices greater than 20%. A sharp rise in timber price cannot be ruled out, but it is unlikely to be associated with a collapse in the price of CO_2, as concern about climate change is growing, and GHG emission reduction targets are intense and pressing, so everything points to a future increase in the price of emission rights, rather than a collapse.

Consequently, dedicating Mediterranean forests to carbon sequestration, without timber harvesting, is an economically viable and environmentally interesting option, due to its beneficial effects on climate change mitigation. However, valuing carbon sequestration does not mean abandoning timber harvesting. Both timber production and carbon sequestration are compatible forest environmental services, and maximising both at the same time is a win-win strategy [22]. A proper valuation of both, and not only of timber, can allow for a more balanced forest management, acting in each forest in a differentiated way according to its environmental potential and value.

The real barrier at present is that while timber is as a commodity with a market price, carbon sequestration is not. There is a valuation of the tonne of CO_2, but it is not a real market good, being associated with emission trading in regulated sectors (in the European Union the Emissions Trading System). Consequently, those who emit GHGs into the atmosphere must pay for it (at least in regulated sectors), but those who sequester carbon, such as forests, are not remunerated for it. The result is that forests, essential carbon sinks for mitigating climate change, are, at least in much of the Mediterranean region, financially loss-making and even a burden for their owners.

5. Conclusions

Carbon sequestration and timber extraction in properly managed forests are sustainable activities which may be compatible. An appropriate forest management ensures the persistence of the forest and avoids risks of damage biodiversity. Moreover, as management is based on reliable and objective information, it is possible to translate the carbon sequestration achieved into potentially tradable carbon credits [45].

The lack of adequate accounting and valuation of carbon sequestration, as happens with many other ecosystem services, leads to a forest economy based on timber, which in areas with a Mediterranean climate produce usually negative financial results due to the low timber productivity. It would be better to consider and value all these ecosystem services, but just by adequately valuing carbon sequestration the financial balance of the forests changes radically; timber production ceases to be a necessity and becomes just another option, together with carbon sequestration.

The challenge for the future is to make carbon sequestration a market good and not a free environmental service, and thus mobilise resources from polluting sectors (polluter-pays principle) to forests, which would lead to greater financial sustainability of the forest sector, and to an added improvement of the landscape, biodiversity and rural employment.

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Abbreviations and Unities

A	Burnt area in forest fires (ha)
B	Non-commercial aerial biomass (Mg/ha)
$C_{\%}$	Carbon percentage of the biomass (%)
GHG	Greenhouse gases
G_{NB}	Net biomass growth (Mg/ha)
G_{TV}	Net timber volume growth (m^3/ha)
I_B	Forest biomass increase (Mg/ha)
I_{TV}	Annual timber volume increase (m^3/ha)
H_B	Harvesting biomass (Mg/ha)
H_{TV}	Timber volume harvesting (m^3/ha)
L_{FA}	Average emission of GHG by forest fires (Mg $CO_{2\,eq}$/ha·y)
L_{FT}	Total emission of GHG by forest fires (Mg $CO_{2\,eq}$/y)
M	Commercial forest biomass (Mg/ha)
PL	Soil litter (Mg/ha)
SQ	Carbon sequestration (Mg $CO_{2\,eq}$/ha·y)
ST_V	Timber volume stock (m^3/ha)
T_B	Total forest biomass (Mg/ha)
U	Underground forest biomass (Mg/ha)
V_T	Timber volume (m^3/ha)
δ_T	Timber density (Mg/m^3)

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