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Analyzing the Joint Effect of Forest Management and Wildfires on Living Biomass and Carbon Stocks in Spanish Forests

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Abstract: *Research Highlights*: This is the first study that has considered forest management and wildfires in the balance of living biomass and carbon stored in Mediterranean forests. *Background and Objectives*: The Kyoto Protocol and Paris Agreement request countries to estimate and report carbon emissions and removals from the forest in a transparent and reliable way. The aim of this study is to forecast the carbon stored in the living biomass of Spanish forests for the period 2000–2050 under two forest management alternatives and three forest wildfires scenarios. *Materials and Methods*: To produce these estimates, we rely on data from the Spanish National Forest Inventory (SNFI) and we use the European Forestry Dynamics Model (EFDM). SNFI plots were classified according to five static (forest type, known land-use restrictions, ownership, stand structure and bioclimatic region) and two dynamic factors (quadratic mean diameter and total volume). The results were validated using data from the latest SNFI cycle (20-year simulation). *Results*: The increase in wildfire occurrence will lead to a decrease in biomass/carbon between 2000 and 2050 of up to 22.7% in the medium–low greenhouse gas emissions scenario (B2 scenario) and of up to 32.8% in the medium–high greenhouse gas emissions scenario (A2 scenario). Schoolbook allocation management could buffer up to 3% of wildfire carbon loss. The most stable forest type under both wildfire scenarios are Dehesas. As regards bioregions, the Macaronesian area is the most affected and the Alpine region, the least affected. Our validation test revealed a total volume underestimation of 2.2% in 20 years. *Conclusions*: Forest wildfire scenarios provide more realistic simulations in Mediterranean forests. The results show the potential benefit of forest management, with slightly better results in schoolbook forest management compared to business-as-usual forest management. The EFDM harmonized approach simulates the capacity of forests to store carbon under different scenarios at national scale in Spain, providing important information for optimal decision-making on forest-related policies.

Keywords: European Forestry Dynamics Model; Spanish National Forest Inventory; wildfires and management scenarios; forest policy

1. Introduction

Forests store large amounts of carbon [1] and are a critical component of the global carbon cycle as they store over 80% of global terrestrial above-ground carbon [2]. According to the State of European Forests [3], in Europe, an average of 35.6% of carbon is stored in living biomass, comprised of above-ground biomass (28.5%) and below-ground biomass (7.1%) carbon pools. Thus, estimating carbon storage in trees as well as in harvested wood products is key to meeting the international information requirements related to the reduction of greenhouse gas (GHG) emissions [4]. Furthermore, under the Kyoto Protocol [5], the Paris Agreement [6], and Regulation 2018/841 of the European Union, countries are requested to estimate and report CO_2 emissions and removals from forests [7].

The long lifespan of trees does not allow them to adapt to rapid environmental changes, so forests are particularly sensitive to global change. The associated disturbances will increase stress and decay and will also have severe implications for forest ecosystem dynamics [8]. Global change is likely to affect disturbance regimes, with an expected increase in frequency, size and severity of fires [9] along with outbreaks of insects and disease. Furthermore, global change will lead to increased frequency of extreme weather events, such as prolonged drought, storms and floods [10].

European-wide forest planning and decision-making require policy makers to forecast the long-term development of European forests under alternative management regimes. Forest management is one of the potential means to mitigate global change [11]. Wood production, forest resources and biodiversity show high sensitivity to management intensity [12]. Regeneration methods and thinning treatments that maintain a large proportion of mature trees are better, in terms of maintaining carbon stores, than those associated with more intensive removals [13]. Both carbon storage and wood production will help to mitigate global change, the former by storing carbon in the forest, the latter by substituting fossil-based materials and storing the carbon in the unused fossils and the by-products [14].

In Mediterranean forests, wildfires are one of the greatest concerns [15]. Several studies have revealed that wildfires are natural in Mediterranean areas worldwide and that some species and communities are adapted to or are the result of this disturbance [16]. However, forest wildfires are considered a major cause of erosion and soil degradation [17]. Like other ecosystem disturbances, forest wildfires are highly sensitive to climate because their behavior responds immediately to fuel moisture, which is affected by precipitation, relative humidity, air temperature, and wind speed. An increment in temperature over the Mediterranean basin, which is projected under several climate scenarios [18], will increase fuel dryness and reduce relative humidity, this effect becoming more severe in those regions where rainfall decreases [19]. Accordingly, an increase in extreme climatic events, causing prolonged droughts and hot spells, is expected to have a substantial impact on fire risk, severity and burned area in Mediterranean zones [20]. Consequently, wildfires may become more important in terms of determining the carbon sink capacity of Mediterranean forests [21].

Flexible models not only allow comparable estimates to be made for forest-related policies and management, but also provide support for international negotiations on the role of forests in European commitments to reduce greenhouse gases. Several flexible models have been developed that can be applied at European scale: European Forest Information Scenario Model (EFISCEN) [22–24], Global Forest Model (G4M) [25], Global Biosphere Management Model (GLOBIOM) [26] and outside Europe, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) [27].

The European Forestry Dynamics Model (EFDM) [28] was developed to simulate the development of the above-ground forest stock and estimate the volume of harvested wood for any given forested area. This model is particularly appropriate for this study because it is based on data from the European NFIs and considers different ecological, technical, and socio-economic constraints. The EFDM has been parameterized for uneven-aged [29] and 'any-aged' forest management, combining multiple Markov chain models [30,31]. Further studies have shown the possibility of parameterizing the EFDM to produce carbon-related metrics under climate-induced uncertainties [32]. A study developed by Vauhkonen et al. [31] showed the feasibility of using EFDM to establish future projections of the above-ground carbon and that associated with fellings in 23 European countries.

The objective of this study is to use the EFDM to forecast the living biomass and carbon of Spanish forests for the period (2000–2050) under three forest wildfires scenarios [33] and two different forest management regimes (business-as-usual allocation and schoolbook allocation). To evaluate the results, a validation process was carried out using available data from the latest Spanish National Forest

Inventory (SNFI). We hypothesized that there will be a combined effect of, on the one hand, the increase in living biomass/carbon stored in the Spanish forests following the abandonment of traditional land uses and forest expansion, and on the other, the living biomass/carbon losses associated with both a more intensive management and an increase in forest wildfires based on future climatic scenarios. These forecasts provide key evidence for policy makers to disentangle the potential trade-offs between the effects of forest management and global change on Mediterranean forests. This is the first time that natural disturbances such as forest wildfires have been considered in the balance of living biomass and carbon stored in Mediterranean forests.

2. Materials and Methods

2.1. SNFI Data and Auxiliary Information

The SNFI is the primary source of forest data for national and large-area assessments because of the high number of monitored plots in the forests [34]. Since the Second SNFI, denoted SNFI2 (1986–1996), a continuous inventory has been conducted with permanent plots established in forested areas with an intensity of approximately of one plot per km^2. Each plot is re-measured approximately every 10 years. A total of 81,024 sample plots measured in the Third Spanish National Forest Inventory (SNFI3, 1997–2007), were used as the input data for the EFDM (Figure 1). For validation purposes, the 13,667 plots measured to date in the Fourth Spanish National Forest Inventory (SNFI4, 2008-to date) were used (Table 1).

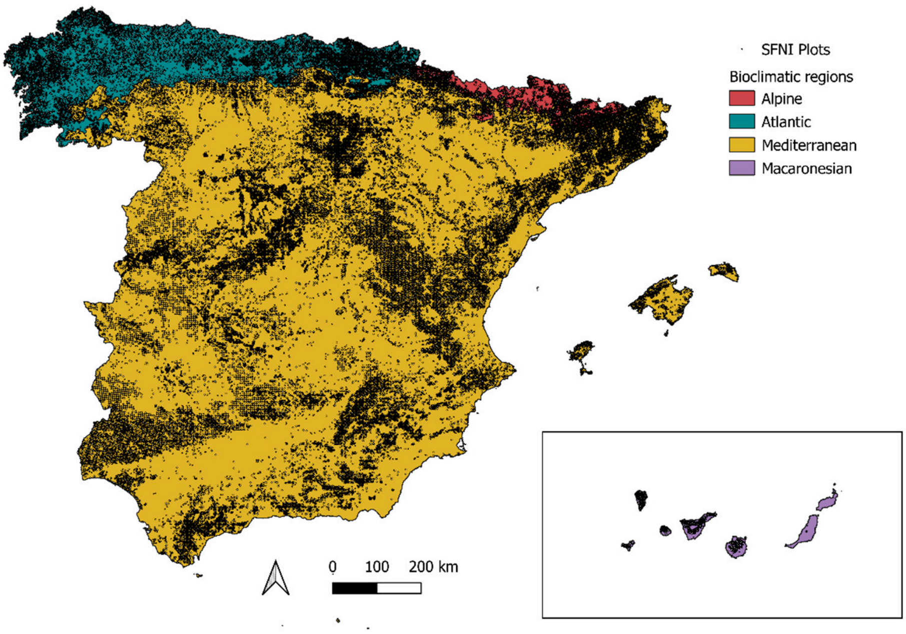

Figure 1. Distribution of bioclimatic regions and SNFI plots in Spain used in the study.

In each plot, trees are measured in four concentric circular subplots (5 m, 10 m, 15 m and 25 m radius) according to the diameter at breast height of the trees (dbh ≥ 7.5 cm, dbh ≥ 12.5 cm, dbh ≥ 22.5 cm and dbh > 42.5 cm, respectively). The following data are recorded in each plot: tree species, diameter at breast height, total height, and distance and azimuth from the plot center. SNFIs also record information on silvicultural practices, such as felled trees, soil preparation, pruning, and forest disturbances, such as forest fires or windthrows [35].

The EFDM is parameterized by matrices with dynamic and static dimensions or factors [36]. To analyze the dynamics of carbon storage in Spanish forests, SNFI plots were classified according to five static (forest type, known land-use restrictions, ownership, stand structure and bioclimatic region) and two dynamic factors (quadratic mean diameter and total volume) from SNFI field data recorded in each plot or using auxiliary cartographical information (Table 1).

Table 1. Area and sampled National Forest Inventory (NFI) plots used to simulate and validate the EFDM model per static factor.

	Simulation Plots	Simulation Area (1000 ha)	Validation Plots	Validation Area (1000 ha)
Forest type				
Broadleaf forests	28,992	6144.5	4874	1031.1
Conifer forests	28,092	4834.4	4664	757.8
Mixed forests	7013	1248.8	1323	334.5
Dehesas	4679	2014.3	777	246.3
Other Conifer forests	5116	876.7	615	104.1
Conifer plantations	3316	518.8	897	145.2
Broadleaf plantations	3816	658.1	517	96.0
Wood supply				
FAWS	73,306	15,147.1	12,211	2530.6
FNAWS	7718	1148.5	1456	184.3
Owner				
Private	49,560	10,570.6	9709	2047.6
Public	31,464	5725.1	3958	667.3
Stand structure				
Even-aged	22,604	4157.9	3768	703.9
Uneven-aged	58,420	12,137.8	9899	2011.0
Bioclimatic region				
Alpine	3103	501.0	618	98.4
Atlantic	13,539	2459.8	2946	546.4
Macaronesian	2414	141.5	791	43.9
Mediterranean	61,968	13,193.4	9312	2026.2
TOTAL	81,024	16,295.7	13,667	2714.9

One of the factors that most affects growth and management is forest species composition. The SNFI plots have been classified into seven different forest types: Broadleaf forests, Conifer forests, Mixed forests, Dehesas (open woodlands), Other Conifer forests, Conifer plantations, and Broadleaf plantations.

With regards to known land-use restrictions, forested areas can be subdivided into forest available for wood supply (FAWS) and forest not available for wood supply (FNAWS) [37]. The concept "Forests Available for Wood Supply" (FAWS) is defined as "forest where any legal, economic, or specific environmental restrictions do not have a significant impact on the supply of wood"; i.e., all forests except those with administrative restrictions. Therefore, "Forests Not Available for Wood Supply" (FNAWS) refers to "forest where legal, economic or specific environmental restrictions prevent any significant supply of wood" [38].

Ownership was classified as public or private according to data from the Spanish Nature Data Bank. Stand structure was classified as even or uneven-aged according to the Spanish Forest Inventory Service. The map of biogeographical regions of Europe was used as a reference for classification [39]. Spanish forests belong to four biogeographical regions: Alpine, Atlantic, Mediterranean and Macaronesian (Figure 1).

For forest wildfire scenarios, Vázquez de la Cueva et al. [33] developed estimates for future fire activity in peninsular Spain using regression models between monthly meteorological variables and the recorded fire activity in the period 1974–2005. With regards to results for the frequency of wildfires, a variable used in our modeling approach, the B2 scenario (characterized by medium–low greenhouse gas emissions, IPCC [40]) was found to cause a 2-fold increase and the A2 scenario (characterized by medium–high greenhouse gas emissions, IPCC [40]) a 2.5-fold increase in fire occurrence in peninsular Spain (see Vázquez de la Cueva et al. [33] for more detail).

2.2. EFDM Model

The EFDM [28] is a Markov chain and area-based matrix model, meaning that forest areas or strata (not trees or stands) are transiting between elements of a set of fixed states. The matrices represent forest areas classified according to ecological and socio-economic factors. The model simulates the development of the forest area distribution as a product of its initial state, proportions of areas expected to be managed according to different silvicultural practices, and the corresponding transition probabilities. The transition probabilities are conditioned by the activities, both of which can differ between factors. The parameterization of the Markov model is described in detail in Vauhkonen and Packalen [30].

Specific materials used in our simulations were:

- Spanish Forest Map 1:50,000 [41] providing the cartographic base to assign the equivalent area to each plot.
- The initial state (defined by the five static factors and two dynamics factors for each plot) was determined based on the SNFI3. The data processing involved the initial estimation and formatting of the data for the EFDM.
- The dynamics of any-aged forest management were simulated by using the forest area classified in the quadratic mean diameter and volume matrix as an input for the EFDM, plus the five static factors. Starting from the statements provided by experts [28] and then following by an iterative process, static factors were weighted selecting those that minimized the error. The selected weights were as follows: forest type (1), bioclimatic region (0.4), known land-use restrictions (0.2), ownership (0.2) and stand structure (0.2).
- Modeling the transitions due to natural processes was performed using pairwise observations from plots measured in both the SNFI2 and SNFI3 (51,676 plots out of 81,024 plots). These two data sets were also used to derive the transition probabilities matrix. Some plots, especially in the Atlantic bioregion, could not be included in the model because they were not re-measured in two consecutives inventories.
- The activities applied in our simulations were "No Management", "Thinning", "Final Felling", and "Wildfire".
- The activity probabilities were defined in two steps with two assumptions. First, the initial allocation of the harvests to the different types of forests was assumed to follow either the proportion of harvests carried out during the SNFI2–SNFI3 ten-year period ("business-as-usual allocation", ABAU) or the application of future harvests in accordance with the specific silvicultural recommendations ("schoolbook allocation", ASB) which are given in Serrada et al. [42] per species at national level. In a second step, the final values for the activity probabilities under both the allocations were obtained by iteratively adjusting the initial probabilities to produce the harvest levels in future, large-scale scenarios.

After running the EFDM, forest area for each time step in total volume, scaled-up to a hectare, is obtained for each stratum defined by the five static factors and two dynamic factors. From these results, standing volume, and fellings can be calculated.

Above- and below-ground biomass was calculated for all SNFI3 plots using species-specific allometric equations and diameter given by Montero et al. [43]. Biomass/volume ratios were then computed specifically for each stratum. Above- and below-ground biomass is calculated as follows:

$$W = R_1 \times V \quad (1)$$

where W: above- or below-ground tree biomass (dry weight, Mg), R_1: biomass/volume ratio Mg m^{-3}, and V: volume (m^3).

Above- and below-ground carbon were also estimated through a similar process, using a species-specific carbon conversion factor (given by Montero et al. [43]) for the biomass previously calculated through allometric equations. Having calculated carbon/volume ratios for each stratum, above- and below-ground carbon is obtained:

$$C = R_2 \times V \tag{2}$$

where C: carbon (Mg), R_2: carbon/volume ratio Mg m^{-3}, and V: volume (m^3).

Having derived projections for the future development of forests under both management allocations according to present scenario wildfire frequency, the simulations are then repeated, varying wildfire frequency proportions by 2 and 2.5 times the present frequency for B2 and A2 scenarios, respectively, given by Vázquez de la Cueva et al. [33]. It was assumed that wildfire severity was always severe, so the forests affected were forced to transition to the beginning of the rotation.

Therefore, a total of six combinations of management regimes and wildfire scenarios were considered in the study (Table 2).

Table 2. Combinations of management regimes and wildfire scenarios considered in the study.

Combinations	Management Regimes	Wildfire Scenarios
1	Business-as-usual allocation (ABAU)	Present
2	Business-as-usual allocation (ABAU)	B2
3	Business-as-usual allocation (ABAU)	A2
4	Schoolbook allocation (ASB)	Present
5	Schoolbook allocation (ASB)	B2
6	Schoolbook allocation (ASB)	A2

To determine the accuracy of the model predictions, the relative bias (*rBias*, %) of the model was calculated [44] using the statistics:

$$rBias(\%) = \frac{obs_i - est_i}{est_i} \times 100 \text{ with ideal value } = 0$$

where est_i: ith estimated value; obs_i: ith observed value.

3. Results

3.1. Business-as-Usual Allocation (ABAU) Management

A comparison of the changes in living biomass and carbon stock in Spanish forests as a result of the effects of wildfire is shown in Figure 2 and Table 3. If present climatic conditions (Combination 1) are considered, the simulation of total carbon stock reveals an increase from 629.0 M Mg in 2000 to 1115.4 M Mg in 2050 (+77%). In the same period, total biomass goes up from 1325.8 M Mg to 2366.7 M Mg (+78%), the growing stock increases from 962.0 M m^3 to 1844.0 M m^3 (+91%), and harvesting from around 75 to 183 M m^3 of roundwood over a ten-year period (+143%). Because biomass and carbon behavior are so similar, we limit the discussion below to the results for carbon.

Carbon sequestration varies significantly among static factors (Table 4) under the present scenario between 2000 and 2050. The greatest increases in carbon stock values (in percentages) are those for Other Conifer (+116%) and Conifer (+113%) forests, and the lowest values correspond to plantations (Broadleaf +44% and Conifer +41%) and Dehesas (+38%). We found similar carbon stock increments for FNAWS and FAWS (+78 and +77%), and ownership, with +79% for private forests and +75% for public forests. Even-aged forests (+97%) display a larger carbon stock increment than uneven-aged forests (+69%). Mediterranean areas present the highest increment, +95%, followed by Alpine areas (+59%). The increase in carbon stocks in Atlantic and Macaronesian areas is far lower, at +38% and +23% respectively.

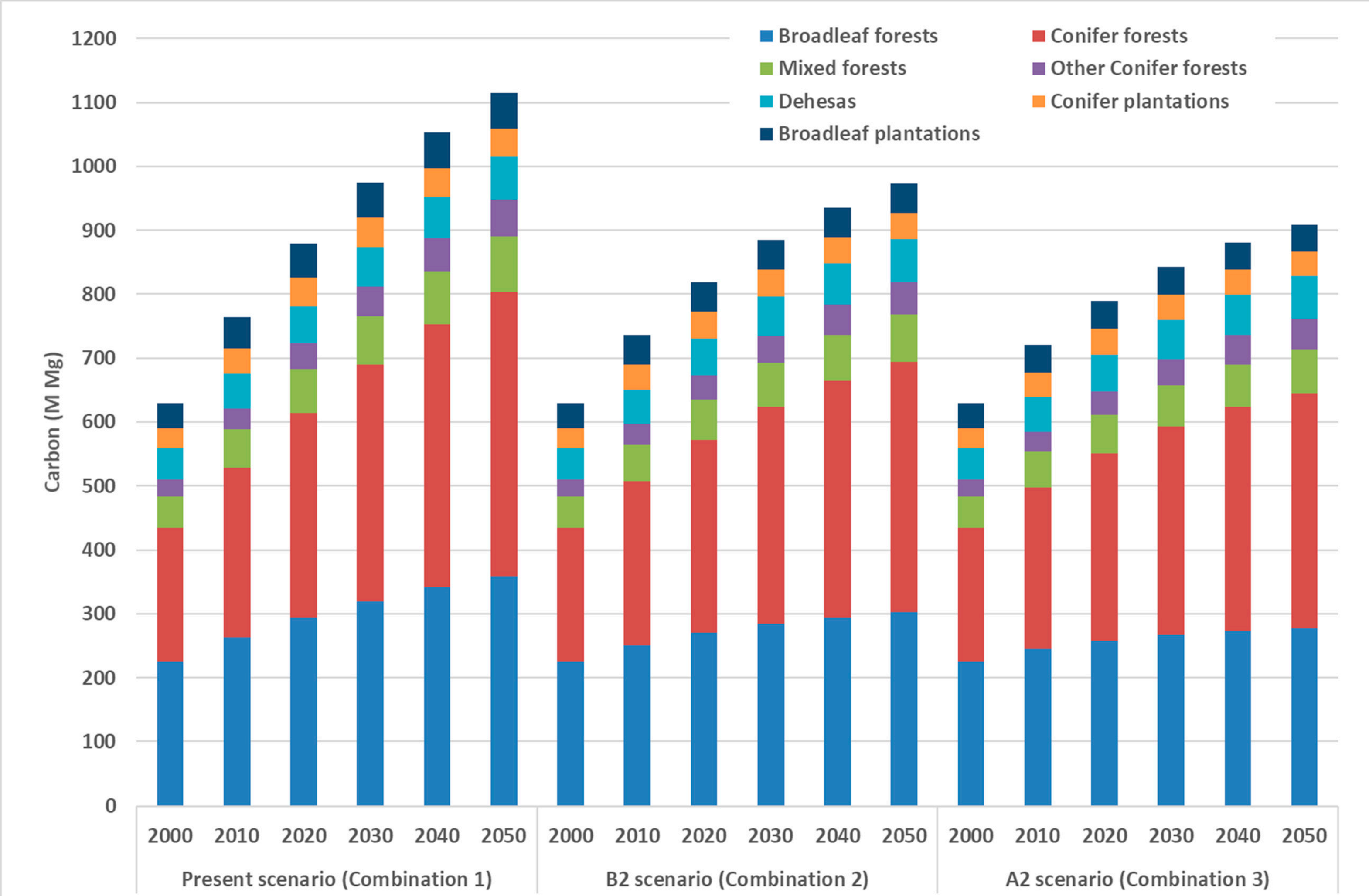

Figure 2. Projected carbon stock from 2000 to 2050 for all forests types under the three different wildfire scenarios and business-as-usual allocation (ABAU) in Spain.

Table 3. Projected volume, biomass and carbon stock from 2000 to 2050 for all forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

		Present Scenario (Combination 1)						**B2 Scenario (Combination 2)**						**A2 Scenario (Combination 3)**					
		2000	***2010***	***2020***	***2030***	***2040***	**2050**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Area	**1000 ha**	**16,295.7**						**16,295.7**						**16,295.7**					
Volume (Growing stock)	M m^3	962.0	1195.5	1400.0	1575.7	1723.4	1844.0	962.0	1154.3	1308.4	1432.0	1528.8	1601.9	962.0	1133.6	1264.2	1364.7	1440.0	1494.1
Volume (Fellings)	M m^3	75.1	105.7	130.8	151.4	168.6	182.9	75.1	101.6	121.0	135.5	146.8	155.6	75.1	99.6	116.3	128.1	136.9	143.5
Biomass (Aboveground)	M Mg	920.2	1121.4	1292.8	1439.6	1562.9	1663.6	920.2	1078.8	1205.1	1307.0	1387.3	1448.4	920.2	1057.5	1162.7	1244.7	1306.9	1352.2
Biomass (Underground)	M Mg	342.0	403.1	453.1	494.0	526.8	552.7	342.0	387.3	422.5	449.6	470.2	485.5	342.0	379.4	407.6	428.7	444.2	455.3
Biomass (Fellings)	M Mg	63.6	88.4	108.6	125.1	139.0	150.4	63.6	84.6	99.9	111.4	120.3	127.3	63.6	82.7	95.7	105.0	111.9	117.0
Biomass (total)	M Mg	1325.8	1613.0	1854.5	2058.7	2228.7	2366.7	1325.8	1550.7	1727.5	1868.0	1977.8	2061.1	1325.8	1519.6	1666.1	1778.4	1863.0	1924.5
Carbon (Aboveground)	M Mg	436.8	532.4	613.4	682.3	739.6	785.9	436.8	512.3	572.1	619.9	657.1	685.0	436.8	502.3	552.1	590.5	619.3	639.9
Carbon (Underground)	M Mg	162.1	190.8	213.9	232.6	247.2	258.4	162.1	183.4	199.6	211.9	221.0	227.5	162.1	179.7	192.6	202.2	209.0	213.6
Carbon (Fellings)	M Mg	30.1	41.7	51.3	59.1	65.7	71.1	30.1	39.9	47.2	52.7	57.0	60.3	30.1	39.1	45.3	49.7	53.0	55.4
Carbon (total)	M Mg	629.0	764.9	878.6	974.0	1052.6	1115.4	629.0	735.6	818.9	884.5	935.1	972.8	629.0	721.0	790.0	842.4	881.3	908.9
	Mg/ha	38.6	46.9	53.9	59.8	64.6	68.4	38.6	45.1	50.3	54.3	57.4	59.7	38.6	44.2	48.5	51.7	54.1	55.8

Table 4. Total biomass and carbon (M Mg) per static factor under the three different wildfire scenarios in 2000 and 2050 and business-as-usual allocation (ABAU) in Spain.

	Total Biomass (M Mg)				Total Carbon (M Mg)			
	2000	2050			2000	2050		
	Present	Present	B2	A2	Present	Present	B2	A2
Forest type								
Broadleaf forests	481.1	782.5	658.9	604.2	225.6	359.2	302.9	277.9
Conifer forests	428.1	906.0	797.6	748.3	208.7	443.6	390.8	366.8
Mixed forests	105.1	190.4	160.8	147.8	49.3	87.9	74.4	68.5
Dehesas	104.5	148.6	146.9	146.0	49.0	67.7	66.9	66.5
Other Conifer forests	54.4	118.3	106.8	101.4	26.3	56.8	51.2	48.6
Conifer plantations	65.3	91.2	83.5	79.9	31.3	44.1	40.3	38.5
Broadleaf plantations	87.3	129.6	106.8	96.9	38.9	56.1	46.3	42.1
Wood supply								
FAWS	1233.0	2201.3	1918.8	1792.2	585.7	1038.2	906.1	846.8
FNAWS	92.8	165.4	142.3	132.3	43.3	77.2	66.7	62.1
Owner								
Private	765.3	1383.9	1207.4	1128.6	357.3	640.8	560.0	523.9
Public	560.4	982.7	853.7	795.9	271.7	474.6	412.8	385.0
Stand structure								
Even-aged	394.0	776.4	674.9	629.3	186.8	367.3	320.0	298.7
Uneven-aged	931.7	1590.3	1386.2	1295.1	442.2	748.1	652.8	610.2
Bioclimatic region								
Alpine	74.9	122.0	118.4	116.6	38.0	60.5	58.8	57.9
Atlantic	359.9	508.8	425.6	389.0	166.7	229.9	193.0	176.8
Macaronesian	12.9	16.2	11.8	10.2	5.7	7.0	5.1	4.5
Mediterranean	878.0	1719.6	1505.3	1408.5	418.6	818.0	715.8	669.6
TOTAL	1325.8	2366.7	2061.1	1924.5	629.0	1115.4	972.8	908.9

The higher fire frequency under the B2 and A2 scenarios (2 and 2.5 times the present frequency, respectively) results in a declining trend in the carbon stocks. The B2 scenario (Combination 2) shows a total carbon stock of 972.8 M Mg (+55%) at the end of the simulation, which is 22.7% lower than was simulated in the present scenario. Under the A2 scenario (Combination 3), the final value is 908.9 M Mg (+44%), which is 32.8% lower than under the present conditions scenario.

The most affected forest type under the two climatic change scenarios which consider increased wildfire frequency (B2 and A2) is Mixed forests (−27% and −39%) followed closely by Broadleaf forests, Conifer forests and Broadleaf plantations (−25% and −36%). In contrast, Dehesas (−1.6% and −2.4%) display greater stability in the face of changing fire occurrence (more details in Appendix A, Figures A1–A7). As regards wood supply, there is little variation in availability, with carbon stocks decreasing in 2050 by around −23% for scenario B2 and −33% for scenario A2 for FAWS, whereas the decrease is −24% and −35% in the case of FNAWS. Changes in carbon stocks are very similar for private and public forests, with around −23% under the B2 scenario and −33% for the A2 scenario. Even-aged forests seem more affected by forest fires (−25% and −37%) than uneven-aged forests (−21% and −31%). The Macaronesian region is the most affected, the decrease being −32% under the B2 scenario, and −44% under the A2 scenario. The Alpine region, with −5% and −7% under the B2 and A2 scenarios, appears to be the least affected by changes due to forest wildfires (Table 4).

3.2. Schoolbook Allocation (ASB) Management

Figure 3 and Table 5 show carbon stock for time series over the present and future 50-year period for the three different wildfire scenarios under ASB management. Over recent decades, ABAU in Spain has been lower than that associated with the silvicultural recommendations, so ASB management means an increase in harvests and consequently, a decrease in growing stock.

Simulation of total carbon stock for Spanish forests under ASB management (Combination 4) indicates an increase from 642.1 M Mg in 2000 to 1103.7 M Mg in 2050 (+72%). Compared to ABAU, the ASB resulted in a −3.0% drop in growing carbon stock (above-ground and below-ground carbon) in 2050 (from 1044.3 M Mg C to 1013.1 M Mg C). The accumulated harvest in a ten-year period increases from around 75–183 M m^3 to 102–230 M m^3, an increase of 36% in the first ten-year period and 26% in 2050.

Among the different forest types (Table 6), the highest carbon stock increment values (in percentages) were for Conifer forests (+107%) and Other Conifer forests (+95%). The lowest values were in Conifer plantations (+20%) and Dehesas (27%) (more details in Appendix B, Figures A8–A14). Because of the strict no felling policy in FNAWS, the carbon stock is +92% higher, whereas the increment in FAWS is +70%. Public (+66%) and private (+77%) forests present different increments. The total carbon stock for even-aged forests (+78%) is higher than that for uneven-aged forests (+69%). The Mediterranean area presents the highest increment (+92%), followed by Alpine areas (+43%). Lower increments are found for the Atlantic and Macaronesian areas (+29% and +23%) between 2000 and 2050 under the present scenario.

The simulations of climate scenarios reveal lower carbon stocks under both scenarios, although the decrease is a little less than under the business-as-usual allocation. Under the B2 scenario (Combination 5), the total carbon stock is predicted to be 968.6 M Mg (+51%) by the end of the simulation, this being 20.7% lower than for the simulation of the present condition scenario. Under the A2 scenario (Combination 6), carbon stocks reach 908.5 M Mg (+42%), although this is 29.9% lower than under the present scenario.

Considering static factors, the results are similar to the business-as-usual allocation, but there are slight differences. As for forest types, the B2 and A2 scenarios have a greater effect on Broadleaf, Conifer, Mixed forests and Broadleaf plantations (around −24% and −34% in all cases). The two scenarios have little if any influence on Dehesas (−1% and −2%). FNAWS are more sensitive (−26% and −38% carbon stock in 2050 for B2 and A2 scenarios) than FAWS stands (−20% and −29%). As regards ownership, the results point to a similar decreasing trend in carbon stock under both scenarios, around −20% under the B2 scenario and −30% under the A2 scenario. Under the B2 scenario, even-aged and uneven-age forest carbon decreases by around −21%. This similarity is maintained under the A2 scenario, with around −30% in both cases. As occurred under ABAU, the Macaronesian area is the most affected under both the B2 and A2 scenarios (−33% and −45%), followed by the Mediterranean (−23% and −33%) and Atlantic (−19% and −27%) areas. The Alpine area presents a much smaller decrease, with −4% under the B2 scenario and −6% under the A2 scenario (Table 6).

Table 7 summarizes all the differences between management allocation in total carbon stock in 2050 considering static factors and the different scenarios. With the exceptions of FNAWS (as mentioned, with a strict no felling policy) and the Macaronesian region, all cases show slightly better results with the schoolbook allocation than with the business-as-usual allocation. Schoolbook allocation shows a total improvement of 2% in Present-B2 scenarios and 2.9% in Present-A2 scenarios against business-as-usual allocation. The greatest differences were found in Mixed forests (3.4% and 5%), Conifer plantations (3.7% and 6%) and even-aged stands (4.2% and 6.3%), respectively.

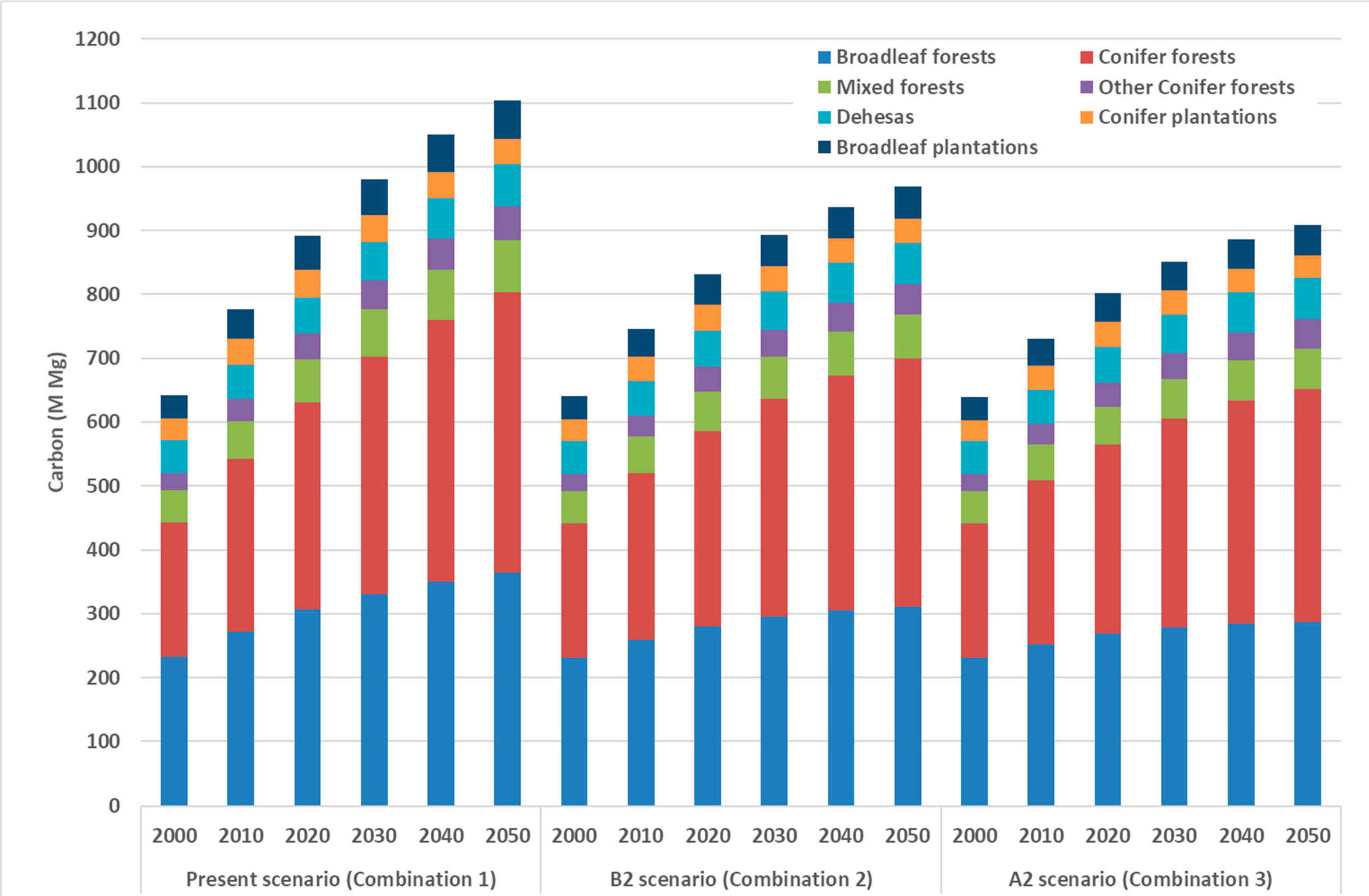

Figure 3. Projected carbon stock (M Mg) from 2000 to 2050 for all forest types in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

Table 5. Projected volume, biomass and carbon stock from 2000 to 2050 for all forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

		Present Scenario (Combination 4)						**B2 Scenario (Combination 5)**						**A2 Scenario (Combination 6)**					
		2000	**2010**	**2020**	**2030**	**2040**	**2050**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Area	**1000 ha**	**16,295.7**						**16,295.7**						**16,295.7**					
Volume (Growing stock)	M m^3	962.3	1190.0	1389.7	1551.0	1681.6	1786.5	962.0	1150.1	1301.4	1415.2	1500.7	1563.9	962.0	1130.4	1259.3	1352.1	1418.7	1465.4
Volume (Fellings)	M m^3	102.3	133.6	169.0	195.3	214.9	230.0	98.7	124.1	151.5	169.5	181.6	190.0	102.3	133.6	169.0	195.3	214.9	230.0
Biomass (Aboveground)	M Mg	920.3	1130.6	1301.2	1436.3	1543.5	1627.8	920.2	1088.7	1215.6	1309.9	1379.5	1430.1	920.2	1068.0	1174.4	1250.9	1304.8	1342.0
Biomass (Underground)	M Mg	342.0	398.7	449.8	489.3	520.4	544.9	342.0	383.5	420.5	447.5	467.5	482.2	342.0	376.0	406.4	428.0	443.3	454.1
Biomass (Fellings)	M Mg	90.3	113.1	142.4	165.4	182.7	196.0	87.2	105.2	127.8	143.6	154.6	162.1	85.6	101.4	121.1	134.0	142.3	147.7
Biomass (total)	M Mg	1352.6	1642.4	1893.5	2091.0	2246.6	2368.8	1349.3	1577.4	1763.8	1901.1	2001.5	2074.4	1347.7	1545.5	1701.9	1812.8	1890.4	1943.8
Carbon (Aboveground)	M Mg	436.9	535.1	614.0	675.9	724.6	762.5	436.8	515.4	573.9	617.0	648.4	670.9	436.8	505.7	554.7	589.4	613.6	630.0
Carbon (Underground)	M Mg	162.1	187.8	210.5	227.5	240.6	250.6	162.1	180.8	196.9	208.4	216.6	222.4	162.1	177.3	190.4	199.4	205.6	209.8
Carbon (Fellings)	M Mg	43.1	53.5	66.9	77.3	84.9	90.7	41.6	49.8	60.1	67.2	72.0	75.2	40.9	48.1	57.0	62.7	66.4	68.6
Carbon (total)	M Mg	642.1	776.4	891.4	980.7	1050.1	1103.7	640.5	746.0	831.0	892.6	937.0	968.6	639.8	731.0	802.1	851.6	885.6	908.5
	Mg/ha	39.4	47.6	54.7	60.2	64.4	67.7	39.3	45.8	51.0	54.8	57.5	59.4	39.3	44.9	49.2	52.3	54.3	55.7

Table 6. Total biomass and carbon stock (M Mg) per static factor under three different wildfire scenarios in 2000 and 2050 and schoolbook allocation (ASB) in Spain.

	Total Biomass				Total Carbon			
	2000	2050			2000	2050		
	Present	Present	B2	A2	Present	Present	B2	A2
Forest type								
Broadleaf forests	494.3	815.4	693.0	638.7	231.8	365.0	311.4	287.6
Conifer forests	433.0	897.2	791.9	744.4	211.2	438.9	387.7	364.5
Mixed forests	106.8	176.1	149.2	137.5	50.1	81.2	69.0	63.6
Dehesas	110.2	148.0	146.3	145.5	51.6	65.5	64.7	64.4
Other Conifer forests	56.4	111.4	101.0	96.1	27.3	53.3	48.2	45.9
Conifer plantations	69.5	83.0	76.6	74.1	33.3	39.9	36.8	35.6
Broadleaf plantations	82.4	137.6	116.3	107.4	36.7	59.9	50.7	46.9
Wood supply								
FAWS	1262.2	2196.3	1926.0	1805.9	599.9	1022.7	898.6	843.3
FNAWS	90.4	172.4	148.4	137.9	42.2	81.0	70.0	65.1
Owner								
Private	774.6	1397.7	1227.2	1151.8	361.8	639.0	562.4	528.4
Public	578.0	971.1	847.2	792.0	280.2	464.7	406.2	380.1
Stand structure								
Even-aged	399.0	718.6	629.6	591.0	189.4	338.1	296.9	279.0
Uneven-aged	953.7	1650.1	1444.8	1352.8	452.7	765.6	671.7	629.5
Bioclimatic region								
Alpine	78.5	115.9	112.5	110.9	39.8	57.0	55.4	54.6
Atlantic	367.4	494.2	416.5	383.3	170.3	220.4	186.7	172.3
Macaronesian	13.0	16.3	11.8	10.2	5.7	7.0	5.1	4.5
Mediterranean	893.8	1742.3	1533.6	1439.4	426.2	819.3	721.3	677.1
TOTAL	1352.6	2368.8	2074.4	1943.8	642.1	1103.7	968.6	908.5

Table 7. Total carbon stock differences (%) between management allocations in 2050 per static factor and wildfire scenarios in Spain.

	Business-as-Usual Allocation (ABAU)		Schoolbook Allocation (ASB)	
	Present-B2 Scenarios	Present-A2 Scenarios	Present-B2 Scenarios	Present-A2 Scenarios
Forest type				
Broadleaf forests	−25.0%	−36.0%	−22.8%	−32.9%
Conifer forests	−25.3%	−36.9%	−23.9%	−34.8%
Mixed forests	−27.4%	−39.5%	−24.0%	−34.5%
Dehesas	−1.6%	−2.4%	−1.4%	−2.1%
Other Conifer forests	−21.2%	−31.1%	−18.1%	−26.5%
Conifer plantations	−12.1%	−17.7%	−8.4%	−11.7%
Broadleaf plantations	−25.1%	−35.9%	−24.4%	−34.7%
Wood supply				
FAWS	−22.6%	−32.7%	−20.3%	−29.4%
FNAWS	−24.3%	−34.9%	−26.2%	−37.7%
Owner				
Private	−22.6%	−32.7%	−20.8%	−30.1%
Public	−22.8%	−33.0%	−20.5%	−29.7%
Stand structure				
Even-aged	−25.3%	−36.7%	−21.2%	−30.4%
Uneven-aged	−21.6%	−31.2%	−20.5%	−29.7%
Bioclimatic region				
Alpine	−4.6%	−6.8%	−4.0%	−5.9%
Atlantic	−22.1%	−31.8%	−19.3%	−27.5%
Macaronesian	−32.5%	−44.3%	−33.1%	−45.1%
Mediterranean	−24.4%	−35.4%	−22.7%	−32.9%
TOTAL	−22.7%	−32.8%	−20.7%	−29.9%

3.3. Validation

Table 8 presents the relative bias *rBias* (%) when EFDM is validated using the 13,667 plots currently available belonging to the SNFI4 using values from the SNFI2 as the initial state (20-year prediction). If we consider the total forest area, EFDM underestimates the total volume (M m^3) by 2.2%. Analyzing forest types, Mixed forest stands out with a high relative bias (11.5%). For the rest of the forest types, except for Broadleaf plantations (7.7%), the relative bias is less than ±5%. Wood supply and ownership present a similar error (1.7–2.2%) in all cases, while for stand structure there are differences between even-aged (5.5%) and uneven-aged forests (0.2%). The Macaronesian area shows the greatest underestimation (13.4%), followed by the Atlantic area (8.4%). The relative bias for the Alpine (0.4%) and Mediterranean (−1.9%) areas are much lower.

Table 8. Validation results using plots from the Fourth Spanish National Forest Inventory (SNFI4). Relative bias (%) for total volume per static factor using SNFI2 as initial state (20-year prediction).

	Validation Plots	EFDM 2010 Volume (M m^3)	SNFI4 Volume (M m^3)	Relative Bias 20 Year (%)
Forest type				
Broadleaf forests	4874	81.5	84.8	4.2%
Conifer forests	4664	86.2	83.3	−3.3%
Mixed forests	1323	27.1	30.3	11.5%
Dehesas	777	4.4	4.6	5.0%
Other Conifer forests	615	10.7	11.2	4.8%
Conifer plantations	897	32.7	32.9	0.8%
Broadleaf plantations	517	11.8	12.7	7.7%
Wood supply				
FAWS	12,211	235.4	240.5	2.2%
FNAWS	1456	19.0	19.3	1.7%
Owner				
Private	9709	176.3	180.2	2.2%
Public	3958	78.0	79.7	2.1%
Stand structure				
Even-aged	3768	95.6	100.8	5.5%
Uneven-aged	9899	158.8	159.0	0.2%
Bioclimatic region				
Alpine	618	16.0	16.1	0.4%
Atlantic	2946	89.6	97.1	8.4%
Macaronesian	791	5.3	6.1	13.4%
Mediterranean	9312	143.4	140.6	−1.9%
TOTAL	13,667	254.3	259.8	2.2%

4. Discussion

The Kyoto Protocol [5] requires every industrialized country to have a transparent and verifiable method for estimating the size and evolution of the carbon stored in forest ecosystems. More recently, the Paris Agreement [6] encourages action to be taken to implement and support both policy approaches and positive incentives for activities relating to reducing emissions. Alternative policy approaches are also proposed, such as joint mitigation and adaptation approaches for the integral and sustainable management of forests.

This is the first study to simulate the future living biomass and carbon stocks of the Spanish forests under any-aged management, using an area-based matrix model that considers different/alternative management and wildfires scenarios. The study focuses on harmonized definitions, assumptions, and methodology to account for the administrative restrictions affecting forest use.

A significant interaction was found between the disturbance effects of higher wildfire frequency (B2 and A2 scenarios) and decreasing forest management, which supports the hypothesis that warming and abandonment of forest management have a synergistic effect on the forest carbon balance, as reported in previous studies conducted in Spain [45,46]. The thinning response hypothesis [47] asserts that thinning does have a significant influence on stand volume stock at the end of the rotation period for a wide range of thinning intensities or stocking densities, whereas heavier thinning beyond the considered range reduces volume stock. Hence, although there are no large differences in total carbon stock, our results reveal the potential benefit of forest management regarding biomass and carbon stocks. Moreover, Ruiz-Peinado et al. [46] conclude that in Mediterranean areas, forest management is an effective way to maintain and enhance high carbon sequestration rates. Vauhkonen & Packalen [36] states that the carbon stored by Finnish forests can be higher by applying less intensive management systems, but the extensive shifts from conventional even-aged management to alternative management systems exhibited a strong impact on harvesting costs. In eastern North America (State of New York), a multicriteria decision analysis approach identified and quantified trade-offs among three important ecosystem services—timber, carbon and habitat quality—under commonly used management scenarios. The most intensive management yielded greater timber volumes but resulted in the weakest carbon and habitat quality scores. For carbon storage, No Management resulted in higher utilities than the two other scenarios [48].

One of the objectives of sustainable forest management is to reduce the competition among trees through silvicultural operations and release resources to the remaining trees [49]. In Spain, there has been a progressive abandonment of forest management operations over recent decades, which could have increased competition for resources (mainly water) and increased the vulnerability of forests to climate change [50]. With regards to the findings for the ASB management scenario, several studies have concluded that regeneration methods and thinning treatments that maintain a large proportion of mature trees are better, in terms of maintaining carbon stores, than those involving more intensive removals [51]. However, such treatments can provide the opportunity for long-term off-site carbon storage in forest products made from the felled wood [23]. In contrast, extended rotations with high stocking levels to maximize on-site stores lead to the lowest levels of live carbon increment [11] and higher carbon loss in the case of wildfire disturbance.

Regarding forest types, the results show Mixed forests to be one of the most affected by higher wildfire occurrence, although its complexity in terms of forest structure may foster self-regulation and provide greater adaptability to cope with increasing uncertainty due to global change [52]. Nevertheless, the stability of Dehesas is noteworthy under all scenarios, with a −2% variation under both management approaches. The open distribution of the mature oak tree population in the Dehesa woodlands protects them from the risk and severity of wildfires. The Spanish Dehesa is a noteworthy example of a managed, anthropogenic, Mediterranean ecosystem. Dehesas are agrosilvicultural open woodlands comprised mainly of Quercus sp., with holm oak (*Quercus ilex* L.) being the most common species, followed by *Quercus suber* L. These oak stands are not suited to traditional, intensive forestry because of the poor sandy soils and variable, dry Mediterranean climate [53,54].

Our findings show that the Macaronesian area (located in the Canary Islands) is the most affected by wildfires, with almost four times more occurrence than in the other three bioclimatic areas. According to the SNFI3, almost 12% of the plots located in the Macaronesian area experiences a wildfire between 1990 and 2000, as opposed to less than 3.5% in the other three areas. Our model shows that the effect of increasing forest wildfire occurrence on the Macaronesian area is particularly high, with carbon stock decreasing by −32% and −44% in 2050 under B2 and A2 scenarios, respectively. The frequency of wildfires in the Canary Islands has risen since the arrival of the human population to the islands [55] and the number of anthropogenic related fires quadrupled between 1970 and 2010 [56]. Burned subtropical cloud forests are more prone to increased wildfire events due to a greater presence of pioneer species, a higher density of trees, climatic variables which tend to range more widely throughout the day, and the long time span needed for recovery to a pre-fire state [57]. However, the Canary Island pine, which accounts for more than 30% of Macaronesian forest area, is characterized by its fire adaptation strategies [58].

The simulation results underestimate the values for all forest types in the validation data set. Simulation from SNFI2 data for the total area had a mean volume of 2.2% less than the SNFI4 real data

(20-year simulation). Higher relative biases correspond to forests with broadleaf species (Broadleaf plantations and Mixed forests). Broadleaf plantations are particularly difficult to project because the rotation is usually around 12 years, close to the ten-year measurement carried out in the SNFI. Moreover, not all forest types considered, such as Dehesas or Other conifer forest, are well represented in the validation database. Other studies using the SNFI to analyze forest dynamics and ecological processes covering a wide regional or national scale, including high variability, also found low or moderate predictive ability [53,59,60].

The production of forest biomass as a carbon-neutral alternative for renewable energy production [61] can be increased by using specific biomass crops or by changing forest management in plantations of exotic or native species [62]. Broadleaf and Conifer plantations together make up just over 7% of the total area and accounted for almost 12% of total carbon in 2000. They are not greatly affected by forest wildfire scenarios under ABAU, which suggests that the production of biomass from Eucalyptus species as well as products from other fast-growing species used in plantations such as *Pinus pinaster* Ait. and *Pinus radiata* D. Don, will be maintained.

Our simulations considered carbon stocks in above- and below-ground forest biomass, focusing on standing living trees included in the Spanish NFIs. Tree biomass represents one of the main carbon sinks in forests [63], but shrub biomass could be also important in terms of carbon sequestration, particularly in the context of the Mediterranean basin [64]. In Spain, the amount of area covered by shrubs accounts for more than 35% of the forested land [65] and will likely increase in the future due to the abandonment of crops and disappearance of forests, caused by increased temperatures and drought and the probable increase in the occurrence of forest fires [64]. Other important carbon reserves not included in the current study are soils, litter, and dead wood, which should be included in the future to correctly model the total capacity of forests as carbon sinks.

In this research, the fire hazard under different climatic scenarios was accounted for using the forecasts reported by Vázquez de la Cueva et al. [33]. These authors only considered the direct effects of climate change on wildfire activity for different IPCC climate change scenarios, although any conclusions will be limited by not including the possible effect of other factors, besides that of climate change, on fire occurrence probability. Weather and climate are among the main factors influencing wildfire potential, but human activities such as land-use change [66] and socio-economic factors [67] greatly influence fire regimes. Additionally, fire has other direct effects on the vegetation that we have not considered, such as species distribution, migration, substitution or extinction [68]. Furthermore, apart from wildfire risk and severity, changes in climate are expected to affect other ecological processes in the Mediterranean basin which are not considered in this research. Some examples of these processes include regeneration, growth and mortality rates [69].

The EFDM is a well-developed research tool to support the assessment of forest policy effects through management and the generation of scenarios for sustainable management of forests in Europe at sub-national, national and international level [28]. Nevertheless, it should be stressed that EFDM simulation results are assumed to be deterministic, so uncertainties associated with the state of the space, activities, transition probabilities, and output coefficients are not considered [28,30]. Additionally, the EFDM assumes fixed cycles (10 years in our study), but the measurements can often go on for longer or shorter periods than that.

According to Regulation 2018/841 of the European Union, the forest reference level (FRL) must be estimated by each EU Member State considering similar forest management practices to those of the period 2000–2009. Forsell et al. [70] state that there is an interval of the FRL in which predictions may vary depending on several factors such as the ecological bioregions. They also show that assumptions related to climate change, such as forest fires and the allocation of forest management practices, have the greatest impacts on the FRL estimates, while the start year of the projection or the stratification of the forest have lower impacts on the FRL estimates. Our results show that national projections can differ considerably due to the effects of disturbances depending on the different scenarios considered, especially for the Macaronesian and Mediterranean bioregions.

Because of the harmonized approach, the results can be easily compared with other projections at European Member State level. Vauhkonen et al. (2019) presented future projections of the forest above-ground carbon in 23 European countries using EFDM. Their results varied between 105.6 Mg C ha^{-1} (Switzerland) and 31.8 Mg C ha^{-1} (Finland) in 2040, with a growth ratio up to 59% (Ireland) between 2015–2040. Our results show 45.4 Mg ha^{-1} of above-ground carbon in 2040 and a growth ratio of 29.2% between 2015–2040. Furthermore, they can also be compared with those computed for the same area using less harmonized approaches such as national projection models. Previous studies have focused on quantifying biomass and carbon stocks in Spanish forests. Montero et al. [43] developed the first species-specific allometric equations for above-ground and below-ground fractions to calculate tree biomass and carbon content. Their calculation was 1806 M Mg CO_2 (492 M Mg C) in 1990 (from SNFI2 data) and an estimation of 2858 M Mg CO_2 (779 M Mg C) in 2004 based on annual carbon increments. A study by González-Diaz et al. [71] quantifies the mean value for total carbon stored as 43.35 Mg C ha^{-1} for the SNFI3, dated in 2000, using the same species-specific allometric equations developed by Montero et al. (2005). Both estimations are slightly higher than those of our simulations, which were 629.0 M Mg C (38.6 Mg C ha^{-1}) in 2000 and 764.9 M Mg C (46.9 Mg C ha^{-1}) in 2010, where biomass/volume and carbon/volume ratios specific to static and dynamic factors were applied to calculate biomass and carbon instead. Nevertheless, the national living biomass carbon value reported by Spain for FOREST EUROPE [3] for 2010 was 569.56 (423.6 M Mg C for above-ground and 140.1 for below-ground), which is lower than our estimations. This comparison may provide useful insights into the influence that harmonizing may have on both national and international policy and decision-making.

5. Conclusions

The EFDM harmonized approach allows us to simulate the capacity of forests to store carbon under different management and wildfire scenarios at the national scale in Spain. The results can be easily compared with other projections either at individual European Member State level, groups of countries, or at European level. However, the EFDM underestimated the total volume (m^3) by 2.2% in the tested validation for a 20-year simulation.

Since this is the first time that this type of model has been applied to Mediterranean forests, the consideration of forest wildfires has been key to achieving more realistic simulations. The most stable forest type under both wildfire scenarios would be Dehesas. Considering bioregions, the Macaronesian area is the most affected and the Alpine region, the least affected.

Regarding forest management regimes, the results show the potential benefit of forest management as regards biomass and carbon stocks, with slightly better results in ASB management compared to ABAU management.

The results for projected biomass and carbon stock variability under different forest wildfire and management scenarios provide valuable information, permitting optimal decision-making for the forest-based bioeconomy and ecosystem services and consequently, for forest-related policies.

Author Contributions: Conceptualization, P.A, I.A. and I.C.; formal analysis, P.A.; writing—original draft preparation, P.A.; writing—review and editing, P.A., I.A., L.H., D.M.-F., T.P. and I.C.; supervision, I.A. and I.C.; funding acquisition, I.A. and I.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

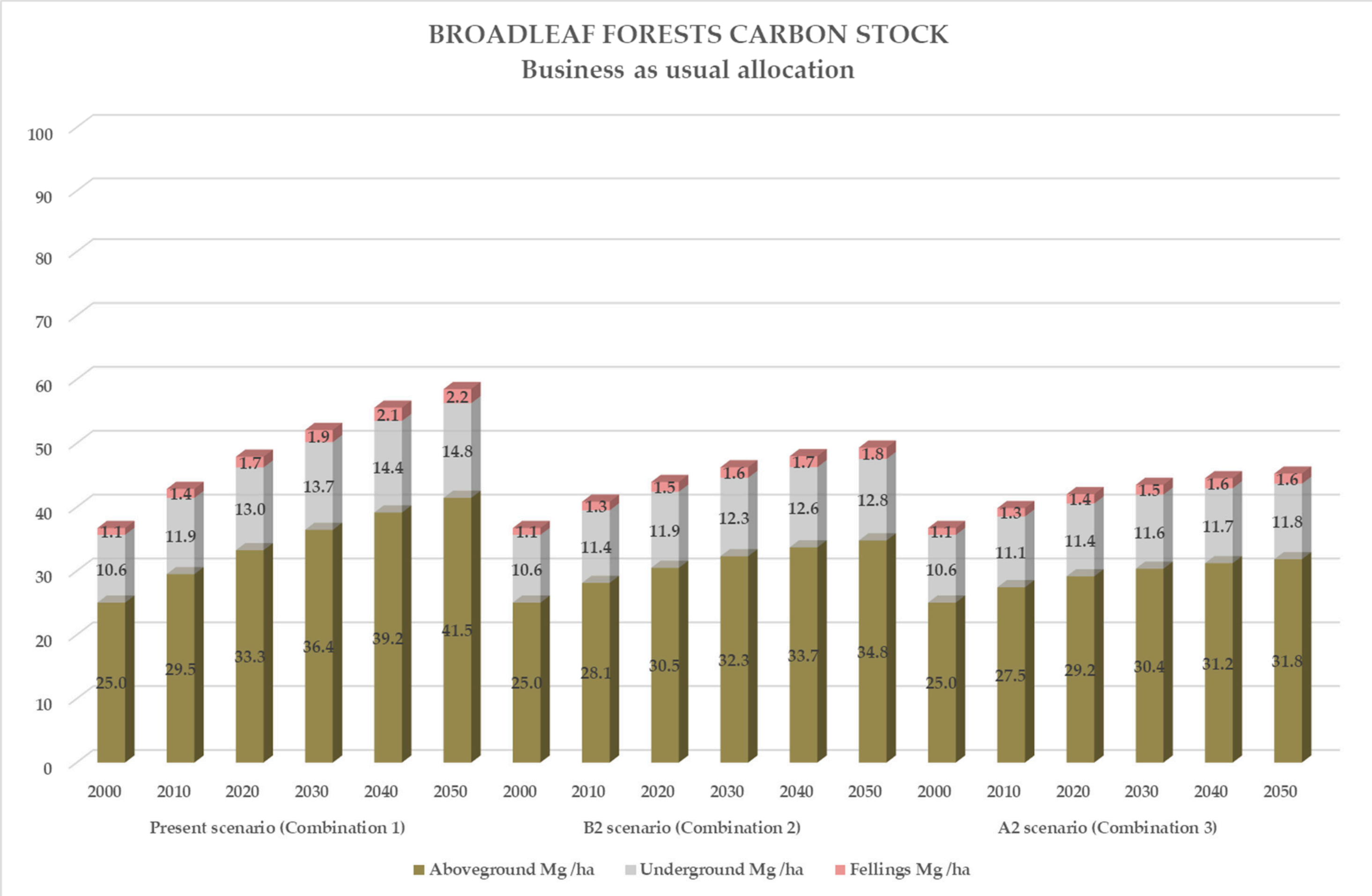

Figure A1. Projected carbon stock from 2000 to 2050 for Broadleaf forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

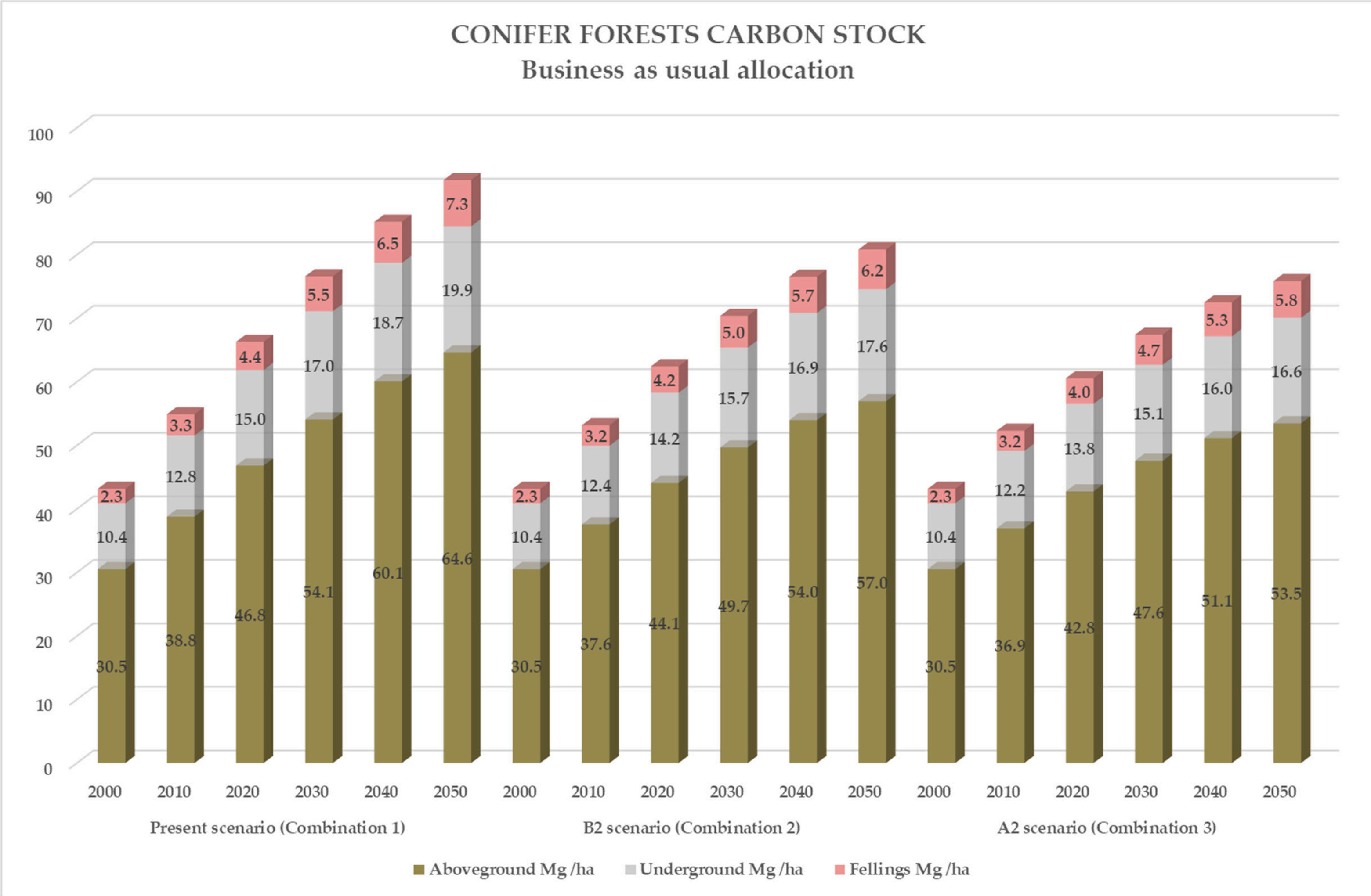

Figure A2. Projected carbon stock from 2000 to 2050 for Conifers forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

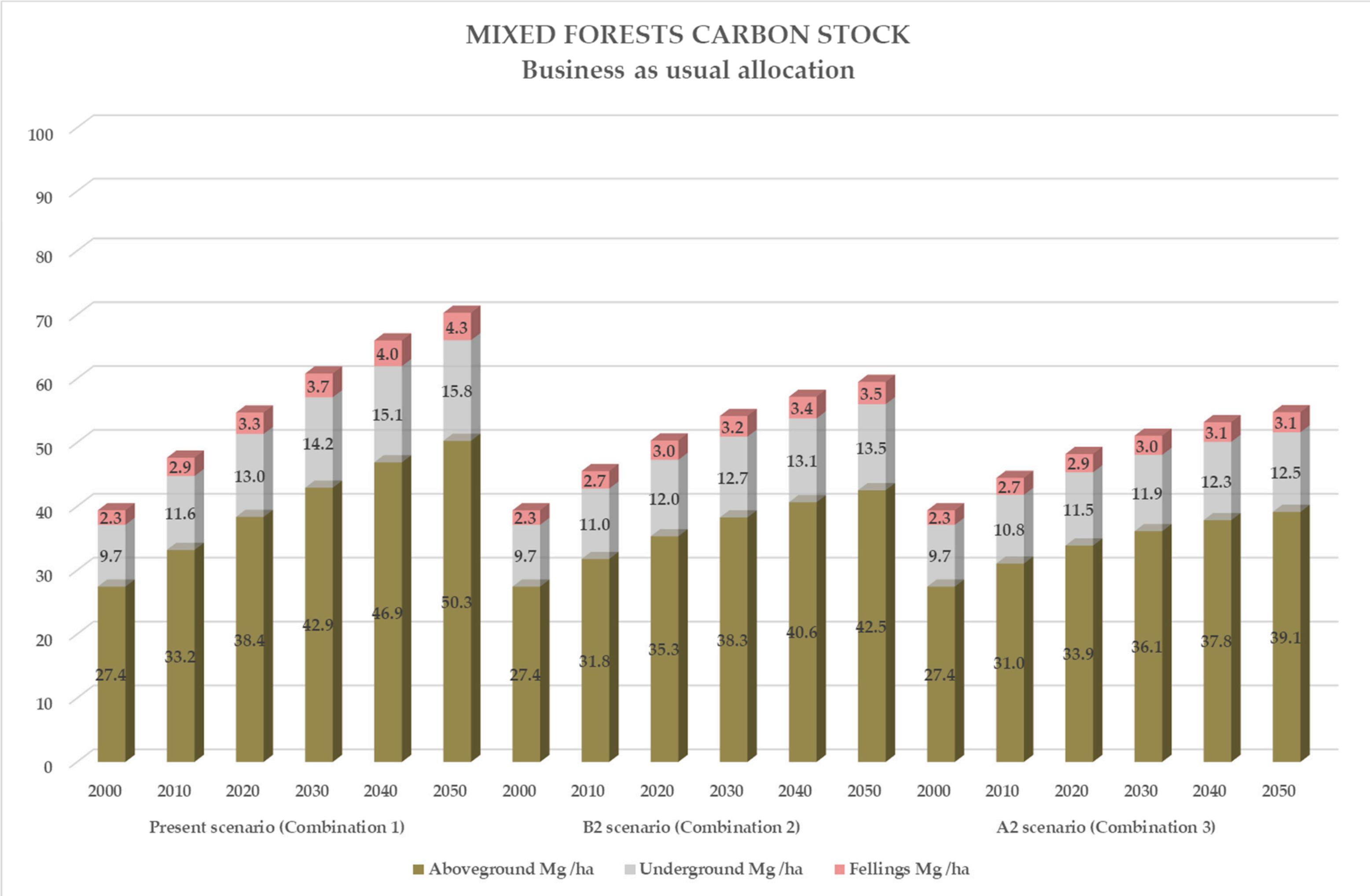

Figure A3. Projected carbon stock from 2000 to 2050 for Mixed forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

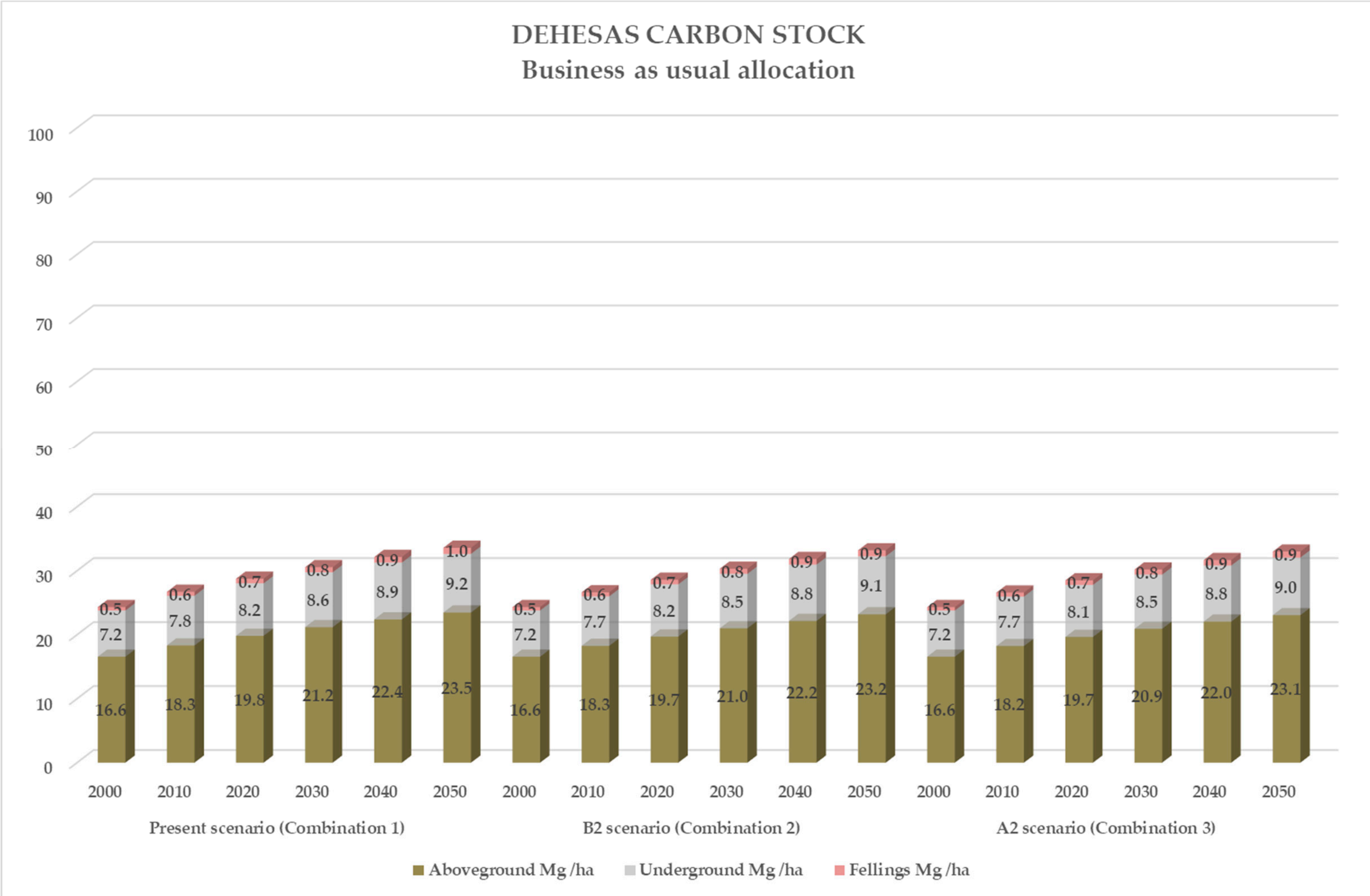

Figure A4. Projected carbon stock from 2000 to 2050 for Dehesas forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

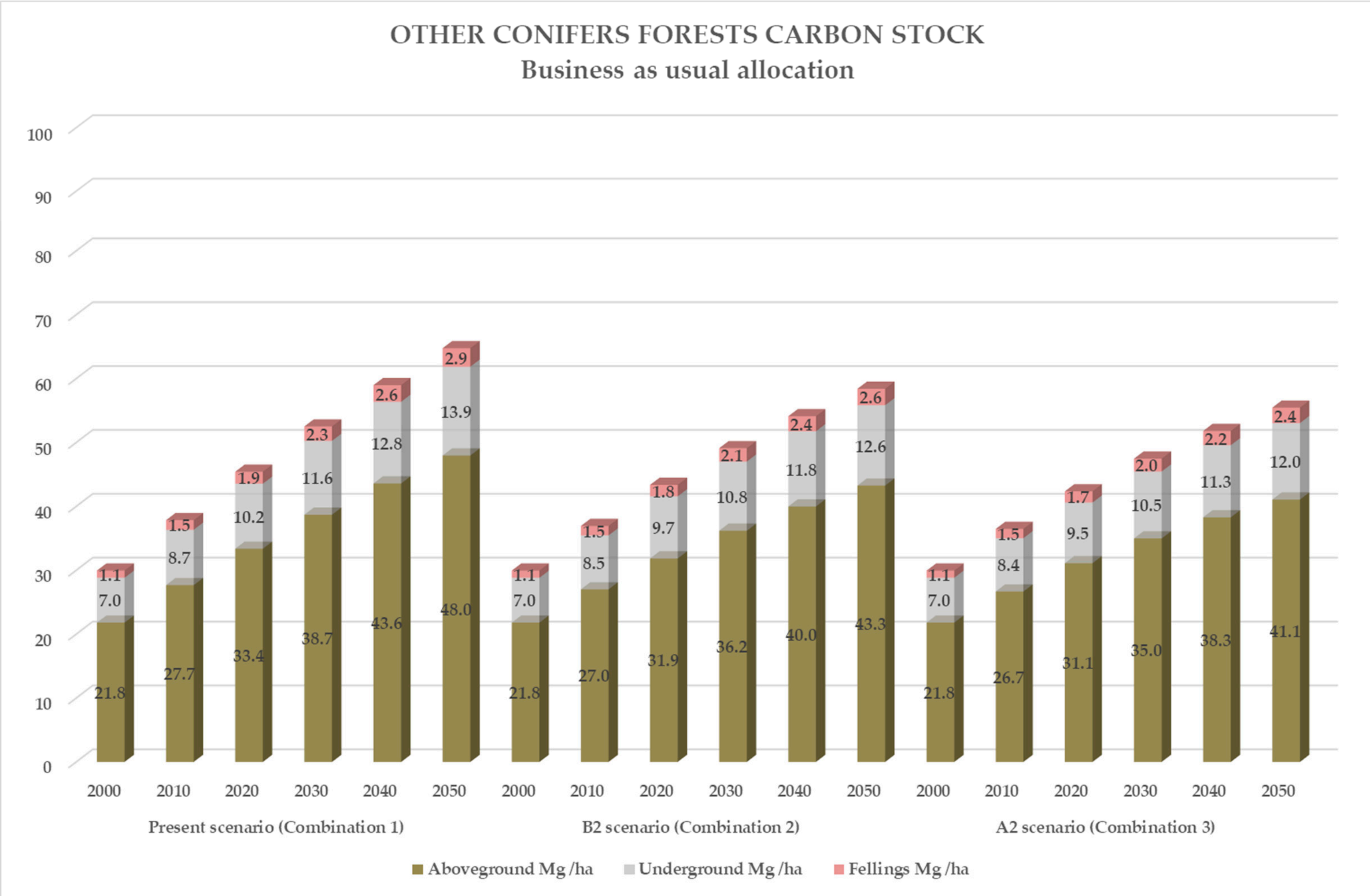

Figure A5. Projected carbon stock from 2000 to 2050 for Other Conifer forests in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

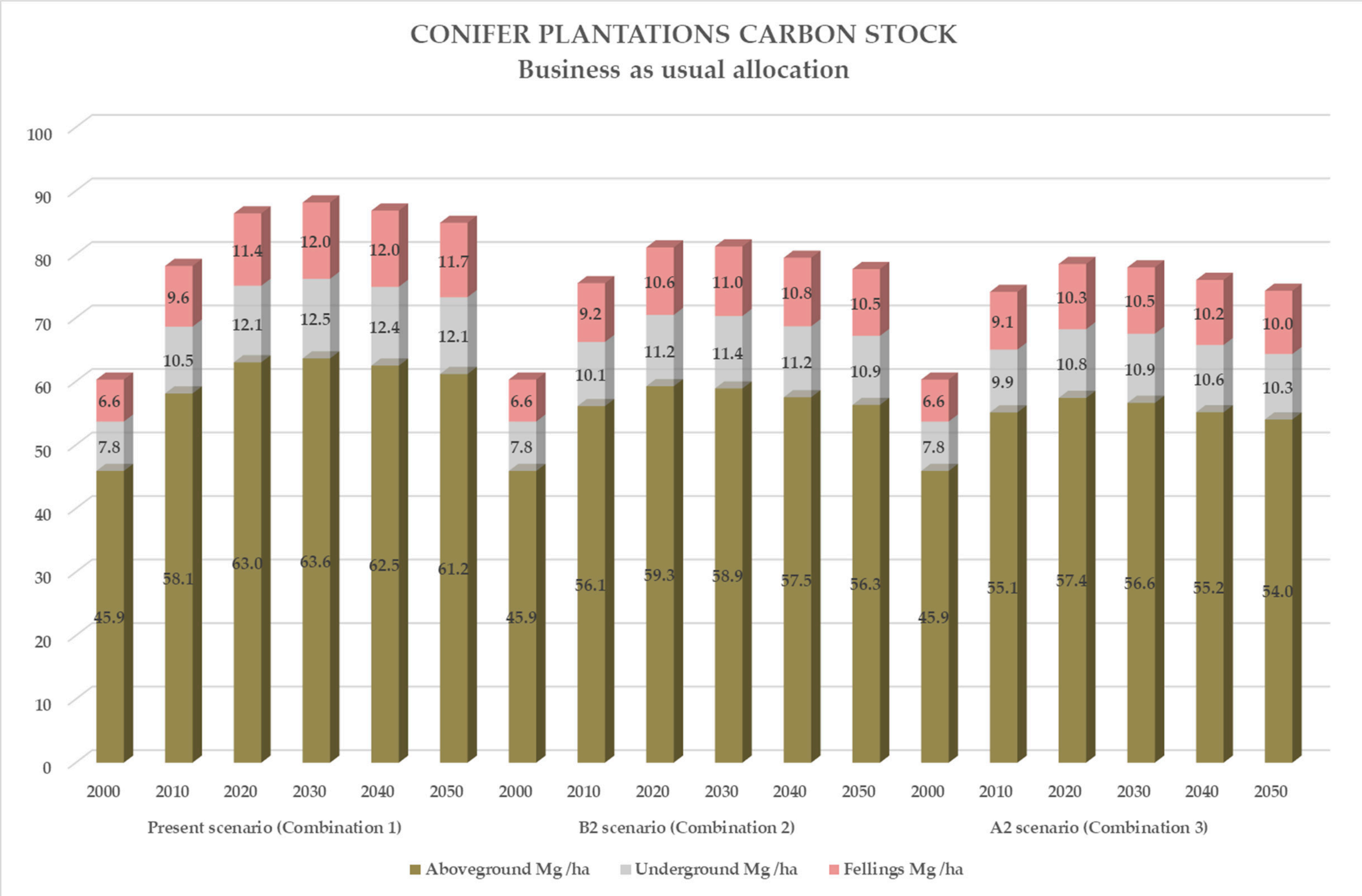

Figure A6. Projected carbon stock from 2000 to 2050 for Conifer plantations in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

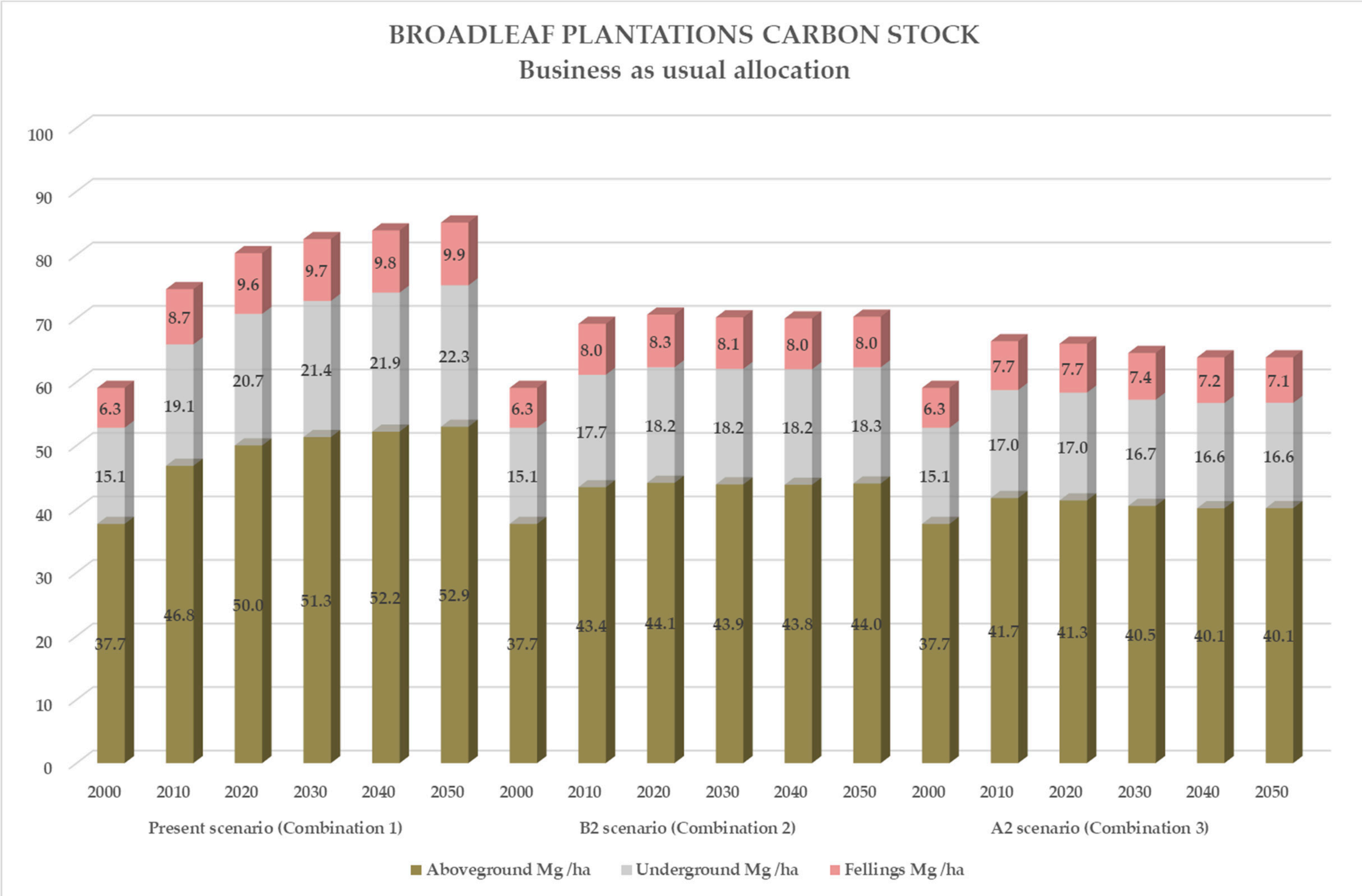

Figure A7. Projected carbon stock from 2000 to 2050 for Broadleaf plantations in Spain under three different wildfire scenarios and business-as-usual allocation (ABAU).

Appendix B

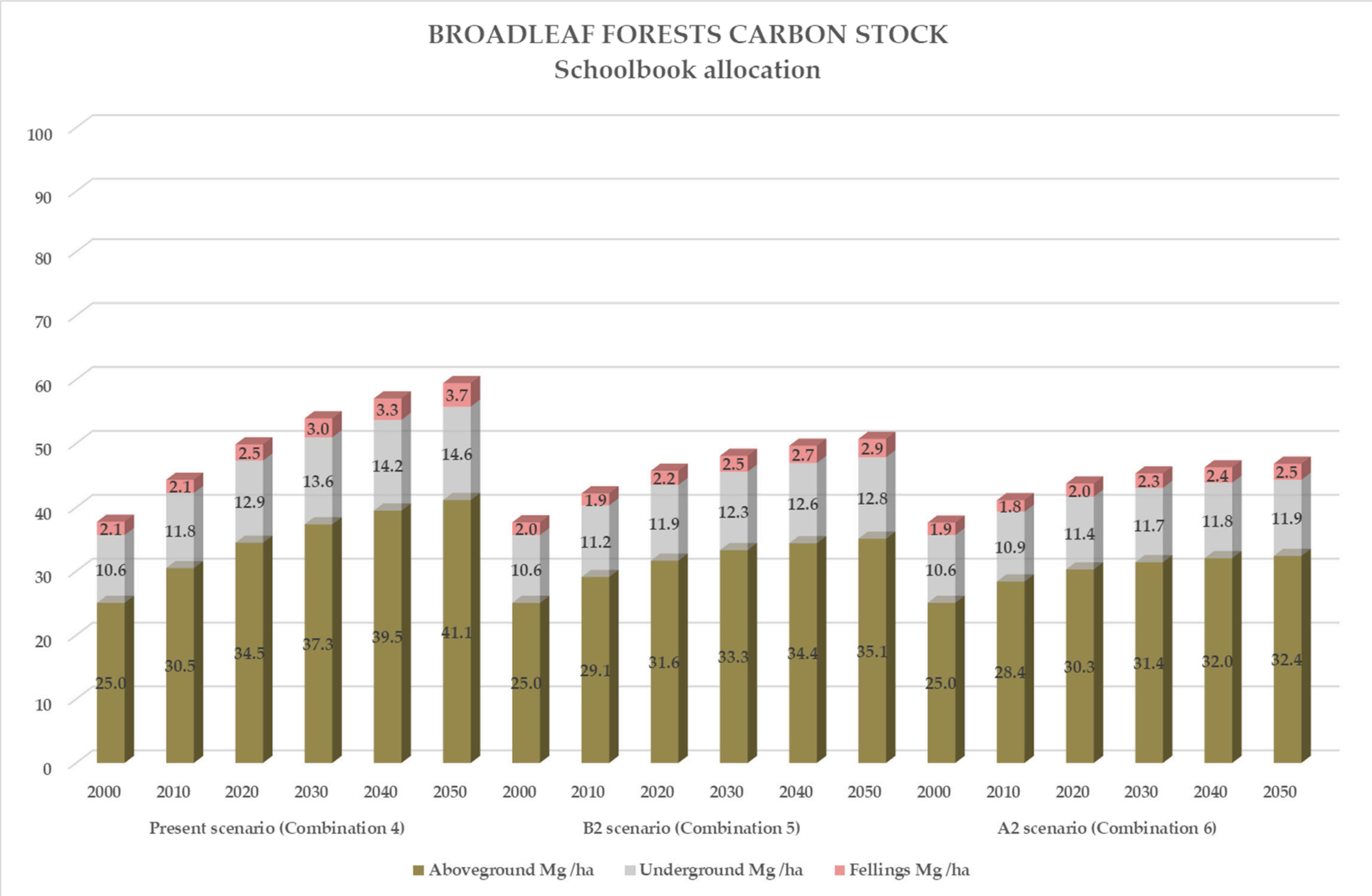

Figure A8. Projected carbon stock from 2000 to 2050 for Broadleaf forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

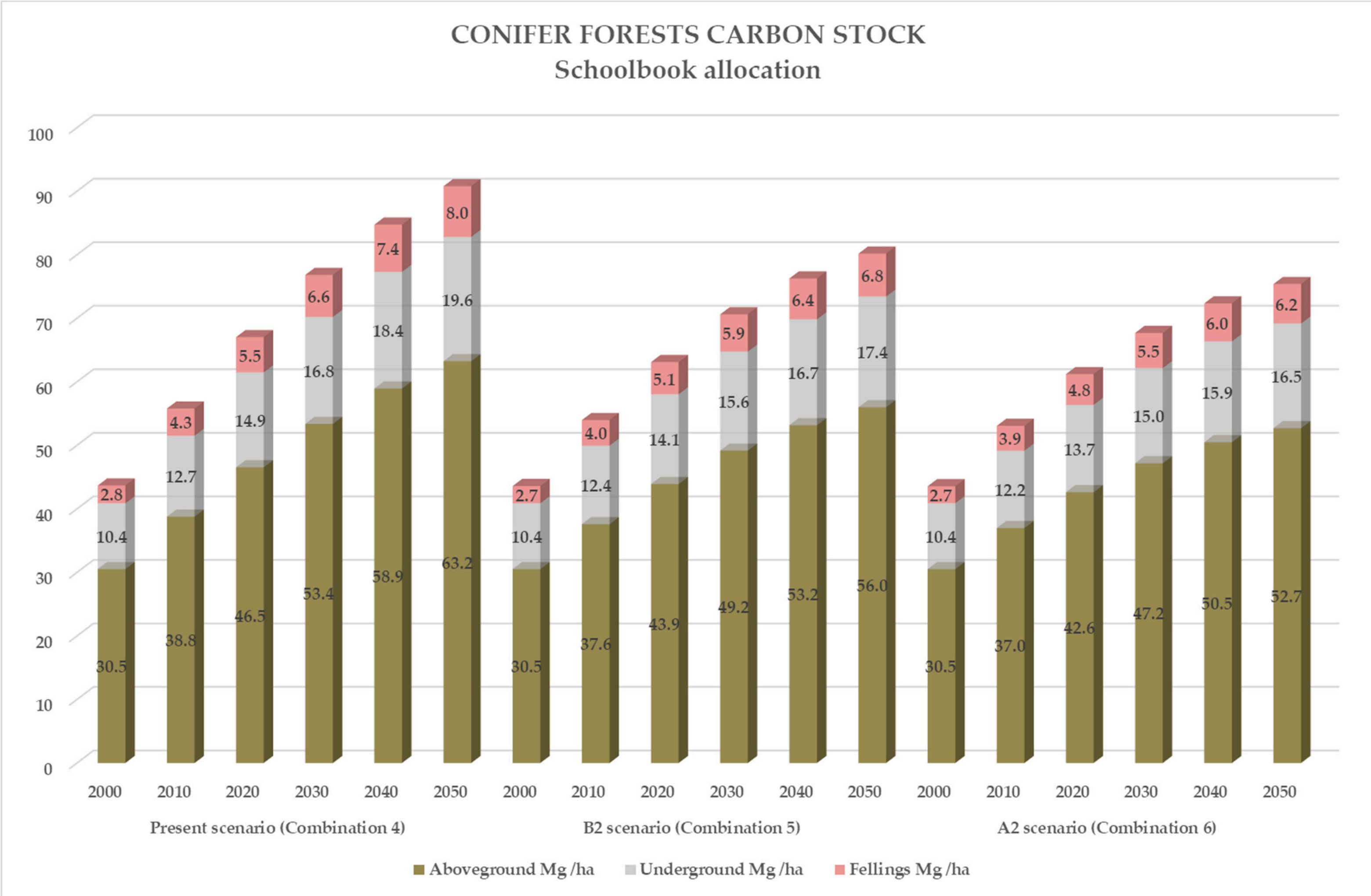

Figure A9. Projected carbon stock from 2000 to 2050 for Conifers forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

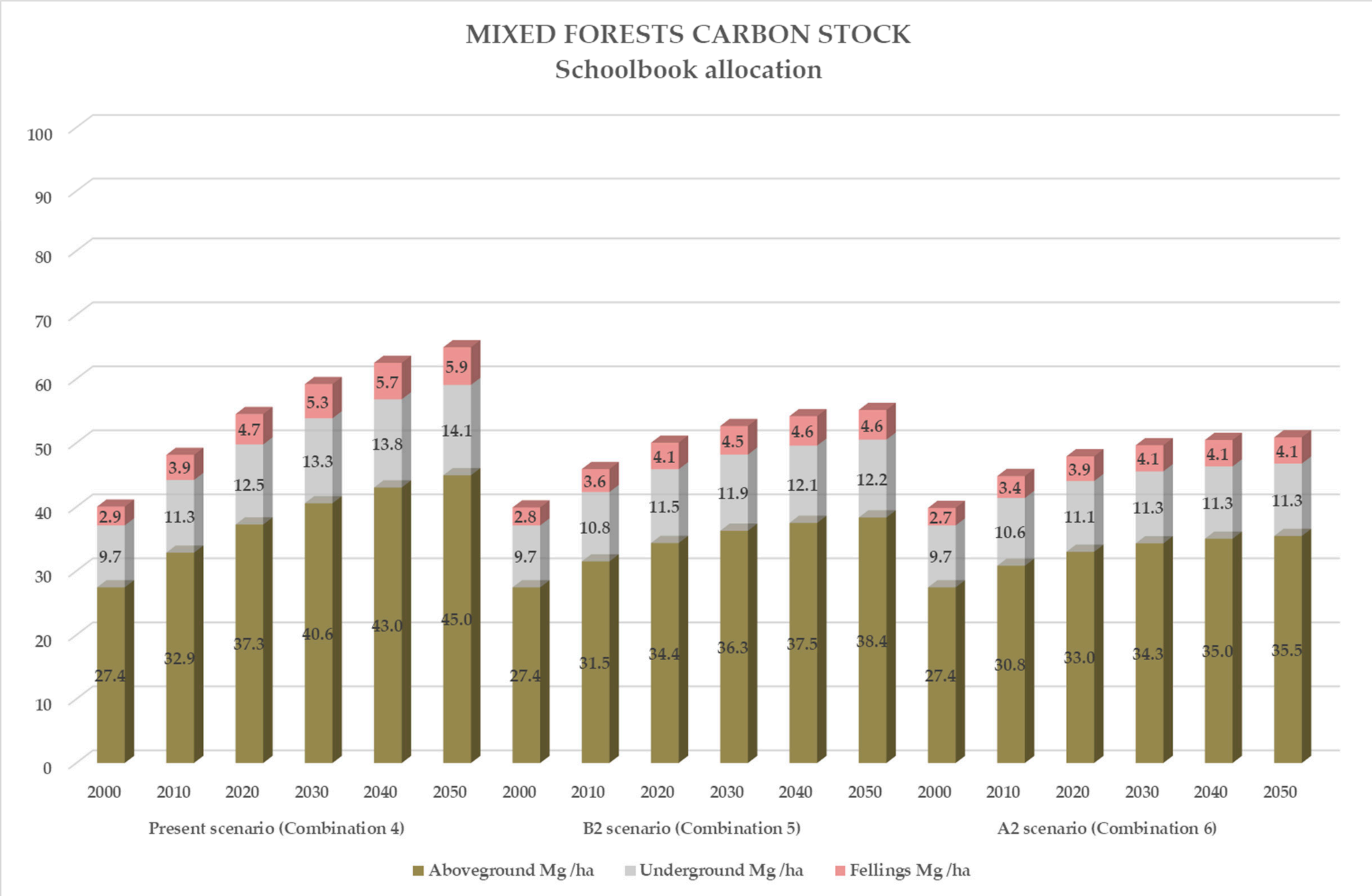

Figure A10. Projected carbon stock from 2000 to 2050 for Mixed forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

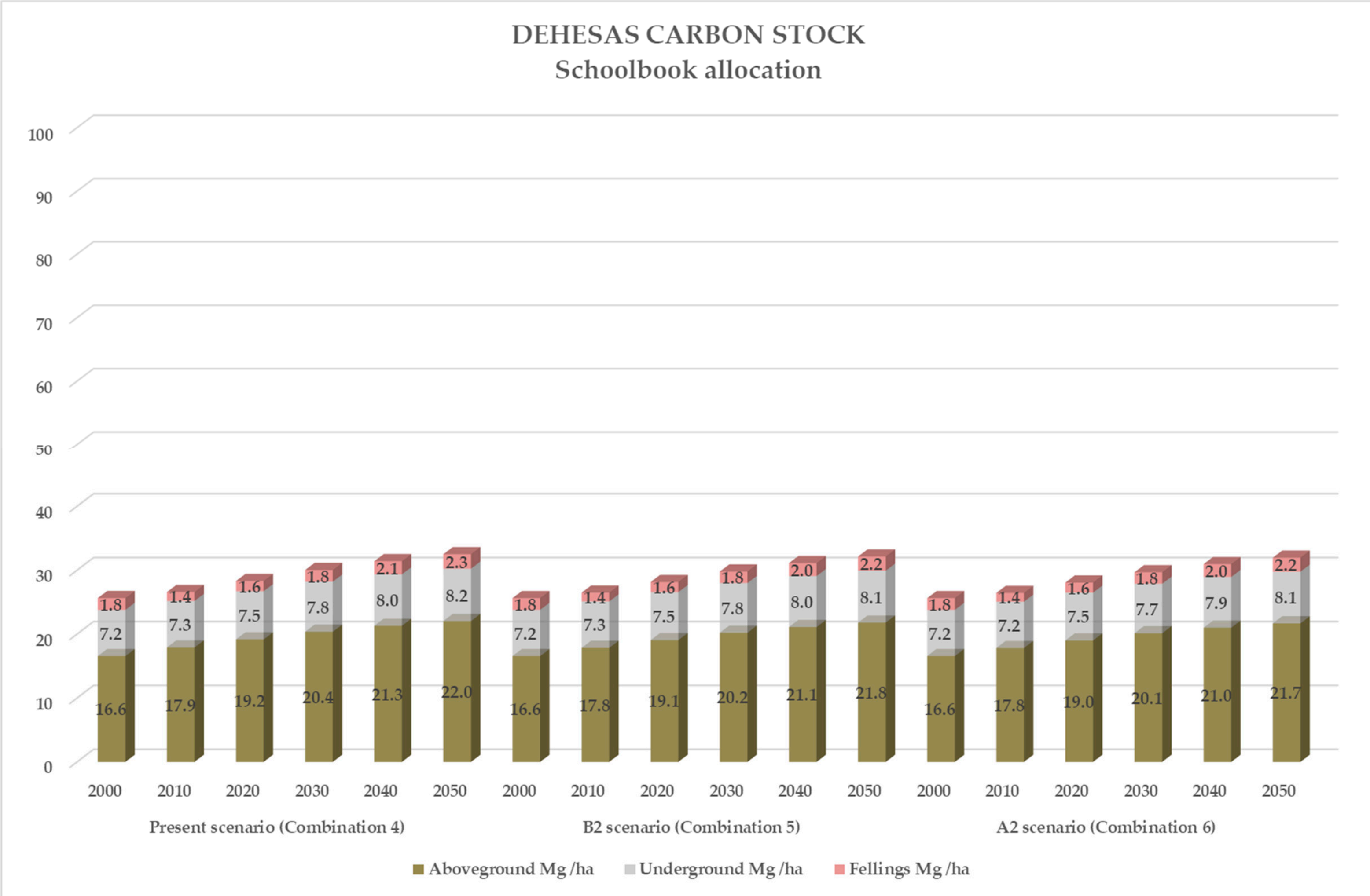

Figure A11. Projected carbon stock from 2000 to 2050 for Dehesas forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

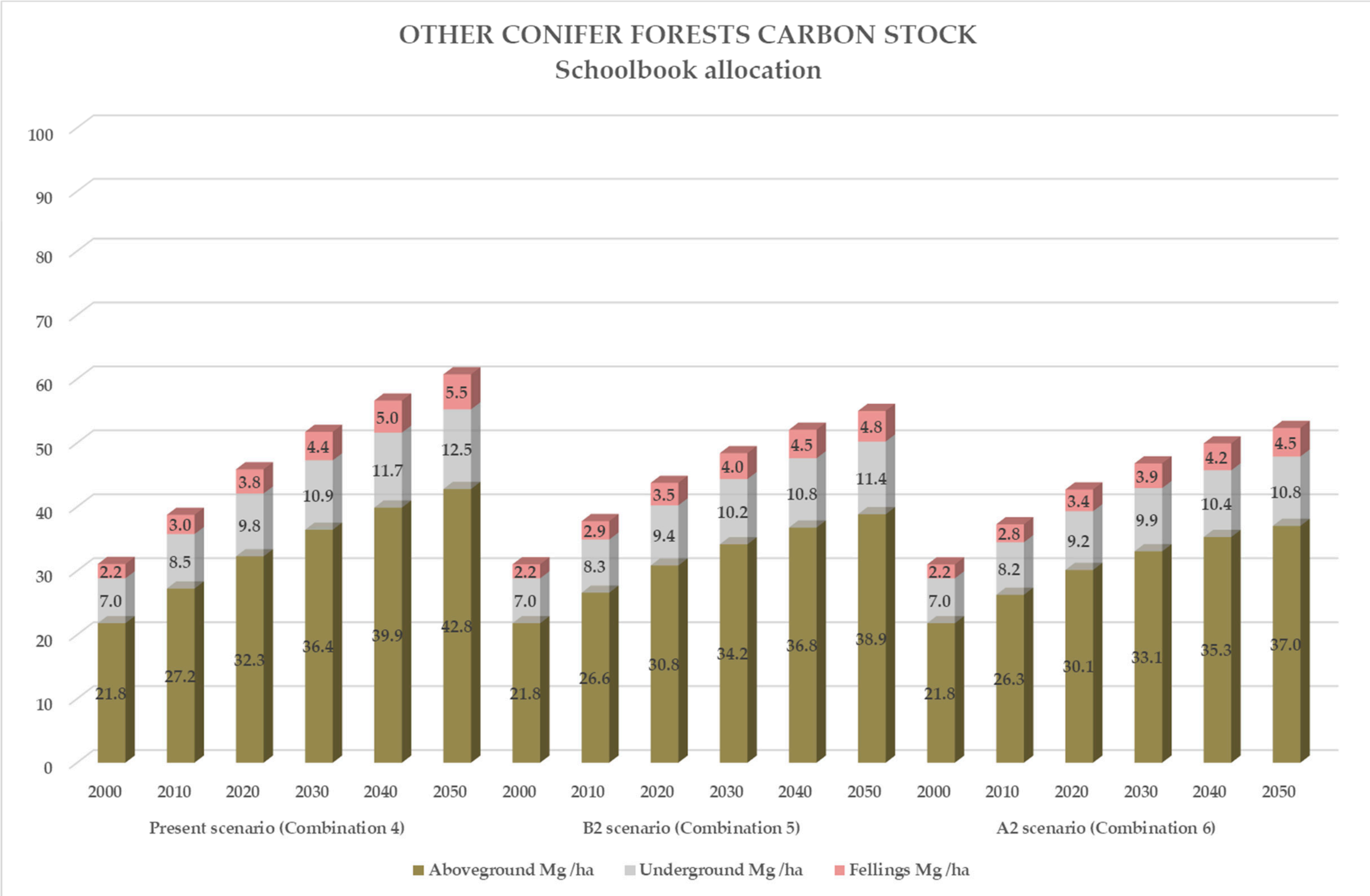

Figure A12. Projected carbon stock from 2000 to 2050 for Other Conifer forests in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

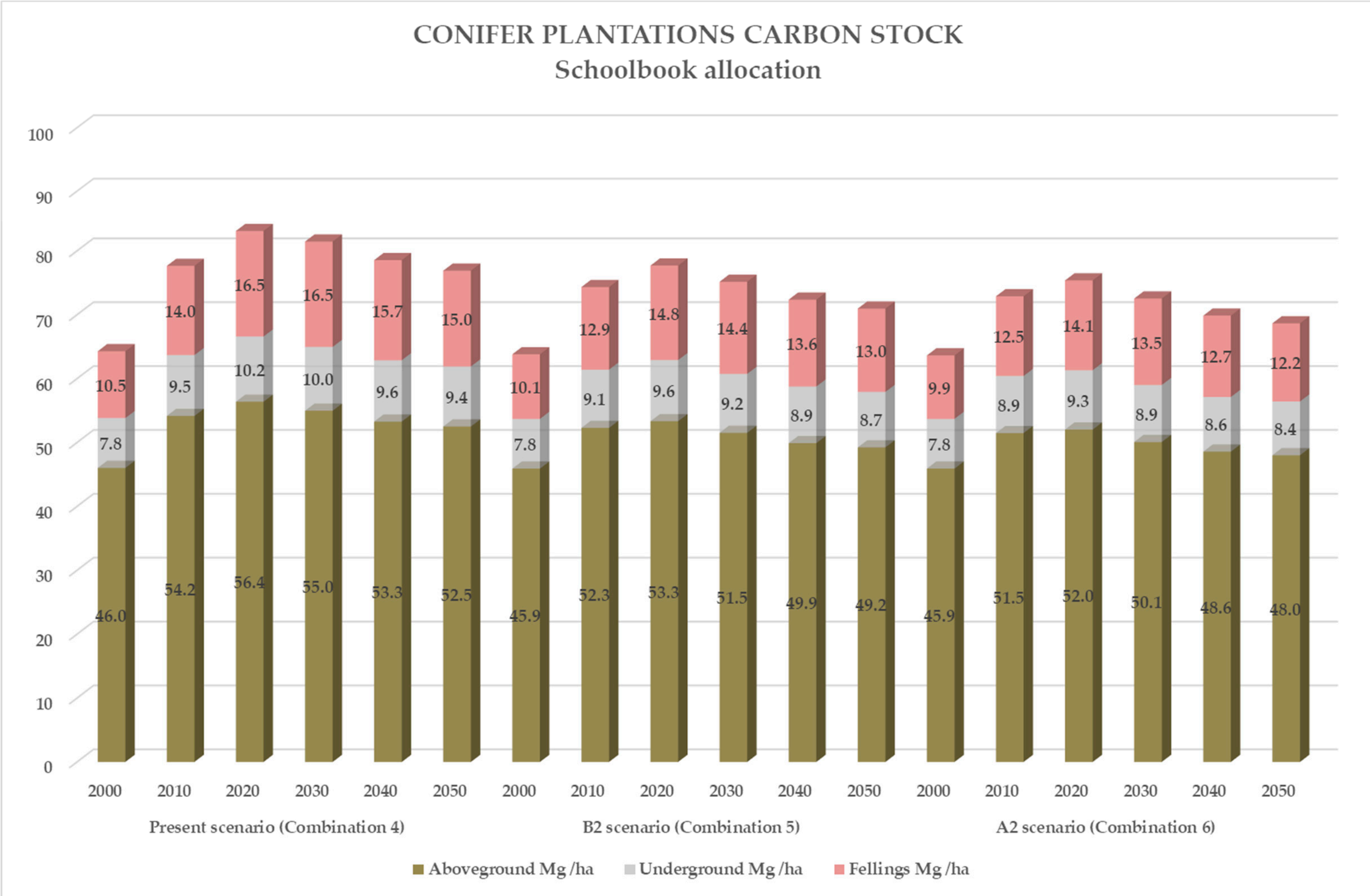

Figure A13. Projected carbon stock from 2000 to 2050 for Conifer plantations in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

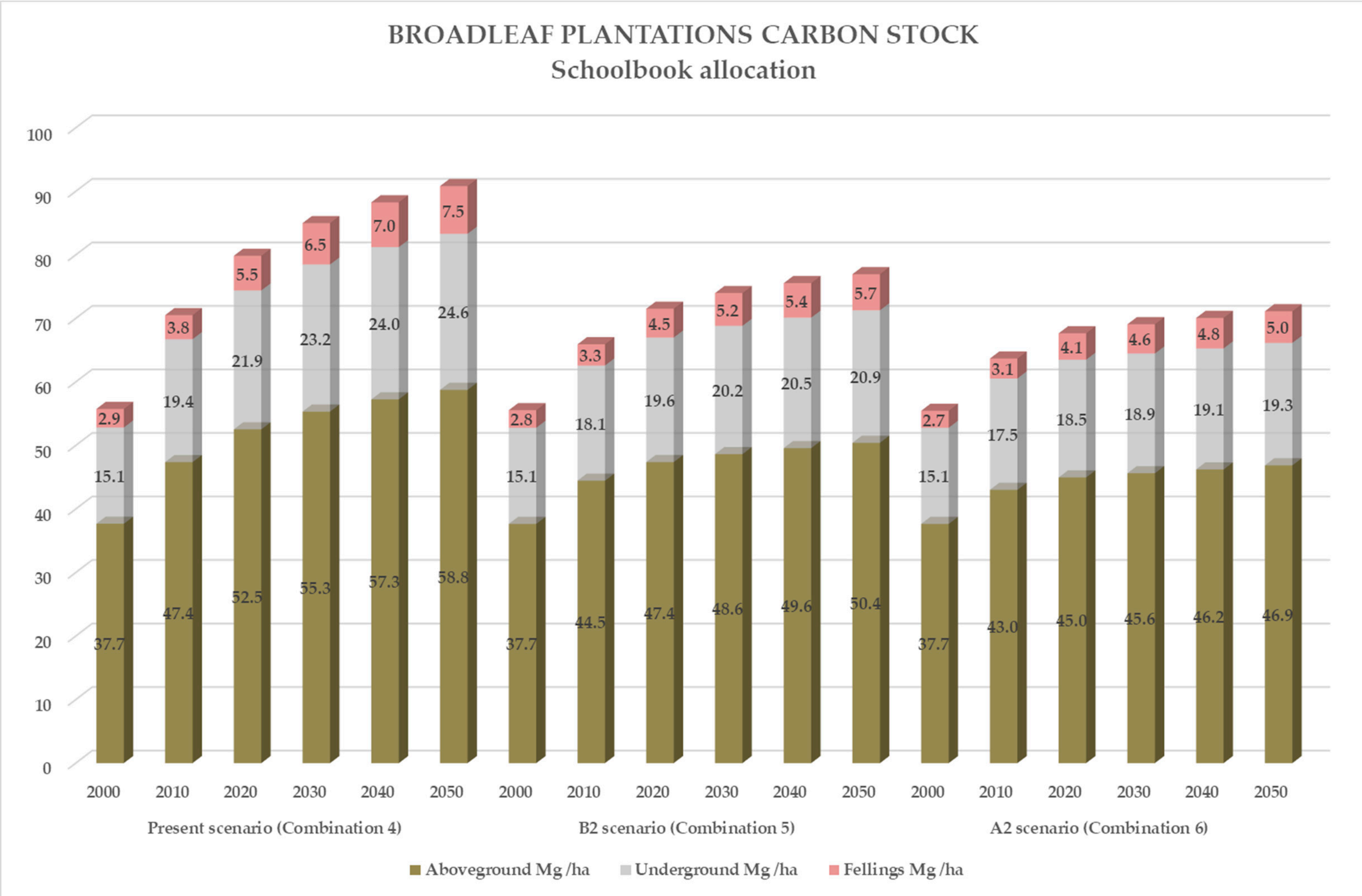

Figure A14. Projected carbon stock from 2000 to 2050 for Broadleaf plantations in Spain under three different wildfires scenarios and schoolbook allocation (ASB).

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