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A Multifactorial Approach to Value Supporting Ecosystem Services in Spanish Forests and Its Implications in a Warming World

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Abstract: Carbon storage and sequestration are key ecosystem services critical to human well-being and biodiversity conservation. In a warming context, the quantification and valuation of carbon storage and sequestration is important in ensuring that effective incentives are put in place to tackle climate change. The quantification and valuation of ES such as carbon storage and sequestration requires the calculus of actual values and prediction, however, it usually does not include key processes that can indirectly influence carbon dynamics (i.e., risk, conservation or management). Here, we define a multifactorial approach to value ecosystem services based on two stages: (1) a biophysical approximation that integrates yearly supporting ecosystem services (i.e., quantification of carbon storage and sequestration) and (2) a weighing approach including factors that indirectly influence carbon storage and sequestration or that deserve specific attention (i.e., risk, conservation or management factors). The quantification of carbon storage and sequestration indicated that Spanish forests store on average 43 Mg C ha^{-1} and sequestrate on average 1.02 Mg C ha^{-1} year^{-1}. Forest structure was a strong determinant of carbon storage and sequestration in Iberian forests, hence there was a strong spatial variation in the carbon sink. We adapted the weighting values to a financial cap and the monetary value of carbon increased more than four times when the weighting factors were taken into account. Finally, we argue that a multifactorial approach to value supporting ecosystem services incorporating aspects related to conservation and risk prevention can facilitate ecosystem service valuation and assist policy makers and stakeholders to establish payment service policies.

Keywords: climate change; drivers; ecosystem services; National Forest Inventory; valuation

1. Introduction

Forests are critical ecosystems that provide multiple ecosystem services (ES) [1] including supporting [2,3], provision (e.g., wood or non-wood resources, e.g., Reference [4]), regulation [5], and cultural services, which in many cases present synergies [6]. Forests are one of the major ecosystems on the global carbon cycle [7] with a reported 25–30% of anthropogenic CO_2 emissions absorbed by terrestrial ecosystems [8]. Therefore, forests are key components for climate change mitigation and adaptation with forest carbon storage and measurement being a priority at the international level [9,10]. However, climate change can impact the amount of carbon stored by forests as it has been shown to affect tree growth [11,12], tree mortality and die-off events [13,14] and changes in species composition [15,16]. The effects of climate change are particularly strong in Mediterranean forests when compared to other temperate forests [17,18], with effects expected to increase in the XXI century [19].

The implementation of forestry actions against carbon releases are crucial to cope with Paris goals and avoid exceeding a 2 °C limit due to global warming. Some international forestry actions aim for carbon sequestration by afforestation and reforestation as the LULUCF (Land-Use Change and Forestry) activities or the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) initiatives. Under the current climate change scenario, the quantification of CO_2 balance is critical to evaluate the carbon stored by forests and to propose specific mitigation and adaptation measures, which is a critical assessment at the national and continental levels [18]. Other ecosystem services and functions related to forest systems might also be critical for climate change mitigation, for example, the conservation of biodiversity as it promotes multifunctionality and ecosystem resilience [20]. However, little knowledge is available to quantify multiple services and it is usually not covered by national and continental assessments (but see References [21,22]). Furthermore, the provision of multiple ecosystem services can have certain trade-offs where some ecosystem functions can be promoted (e.g., biomass of actively restored forests ([23])). Nevertheless, the most common finding for Europe is that trade-offs among multiple ecosystem services are rare and generally forest functions can all be maximized [6].

Placing a value on supporting ES such as carbon sequestration is important in ensuring that effective incentives are put in place to tackle climate change. There are multiple strategies to include ES, especially carbon sequestration into markets such as The Economics of Ecosystems and Biodiversity (TEEB) initiative. Different efforts have been made to value forests as a source of carbon storage and their contribution to carbon sequestration [7]. However, the value of carbon sequestration in forests is generally determined by correlating their value with that obtained from converting forest to other land uses (e.g., agriculture) [24]. There are apparent difficulties for developing effective schemes of carbon valuation [25], but the conservation of key ecosystems as forests is critical for human well-being. At an international level, there are large differences on carbon sequestration evaluation between countries [26]. At a local level, landowners face many challenges maintaining forests, and stakeholders usually do not have adequate payment tools based on objective procedures. In addition, the payment for forest carbon sequestration constitutes a financial recognition for forest owners that might help to sustain forests in the long-term (see e.g., Reference [27]) and contribute to the Paris goals at the local level.

In terms of carbon dynamics, the quantification of carbon sequestration does not include key processes that can indirectly influence carbon dynamics such as risk (e.g., fire or erosion [28,29]) or conservation factors (e.g., underestimation of the biodiversity value for ecosystem services [20]). Biodiversity can positively influence forest carbon stocks and sequestration [30,31]. Therefore, valuing aspects of biodiversity that allows carbon sequestration might favor an effective management of forests that contributes to the Paris goals at the local and regional levels. Protecting areas, especially forested ones, can be an important strategy for climate change mitigation for example through land use change protection [32]. Specifically, the system of protected areas available in developed countries represents one of the largest biodiversity and conservation measures of natural ecosystems where management plans allow the protection from change in land use either in Nationally Designated Areas or in the Natura 2000 network in Europe [33,34]. On the other hand, fire regimes and soil erosion are critical risks for future forest conservation. In regions that are increasing their aridity due to global change, fire regimes are being largely altered, increasing in frequency and intensity [35], but conservation strategies and forest management appear as an opportunity to protect forests in the long-term.

Here, we sought to (1) quantify carbon storage and sequestration for the main Spanish forest types and its variation due to biotic, abiotic and anthropic factors and (2) design a new multifactorial approach to value and rank key ecosystem services building upon supporting ecosystem functions (i.e., carbon storage and sequestration). Firstly, we defined key factors determining carbon storage and sequestration and the relative importance of each of them (forest structure, climate and diversity). Secondly, we calculated the economic value of the yearly supporting ecosystem service (i.e., carbon sequestration). Finally, we weighted carbon sequestration by risk, conservation and management factors. By developing these aims we have estimated the primary production ecosystem services (i.e., support services) which are linked to the specific services such as carbon storage (i.e., regulation services).

2. Materials and Methods

2.1. Inventory Platform and Study Area

We used national forest inventory data over continental Spain from the second and the third Spanish Forest Inventory (SFI2: 1986–1996 and SFI3: 1997–2007, respectively), that distributed plots systematically over forest ecosystems on a 1-km^2 cell grid [36]). Each SFI stand included four concentric circular sub-plots of 5,10, 15 and 25 m radius. In these sub-plots, an adult tree was sampled if its diameter at breast height (d.b.h.) was 7.5–12.4, 12.5–22.4, 22.5–42.5 and $\geq$42.5 cm, respectively. Height, d.b.h. and species name were recorded for each adult tree included in the plot.

We classified each plot of the SFI based on species abundance (i.e., species basal area >50% total stand basal area) into the 17 most dominant species considering 15 native species (*Pinus sylvestris*, *P. uncinata*, *P. pinea*, *P. halepensis*, *P. nigra*, *P. pinaster*, *P. canariensis*, *Quercus robur*, *Q. petraea*, *Q. pyrenaica*, *Q. faginea*, *Q. ilex*, *Q. suber*, and *Fagus sylvatica* and *Castanea sativa*) and the 2 exotic species (*Eucaliptus globulus* and *P. radiata*, Figure 1).

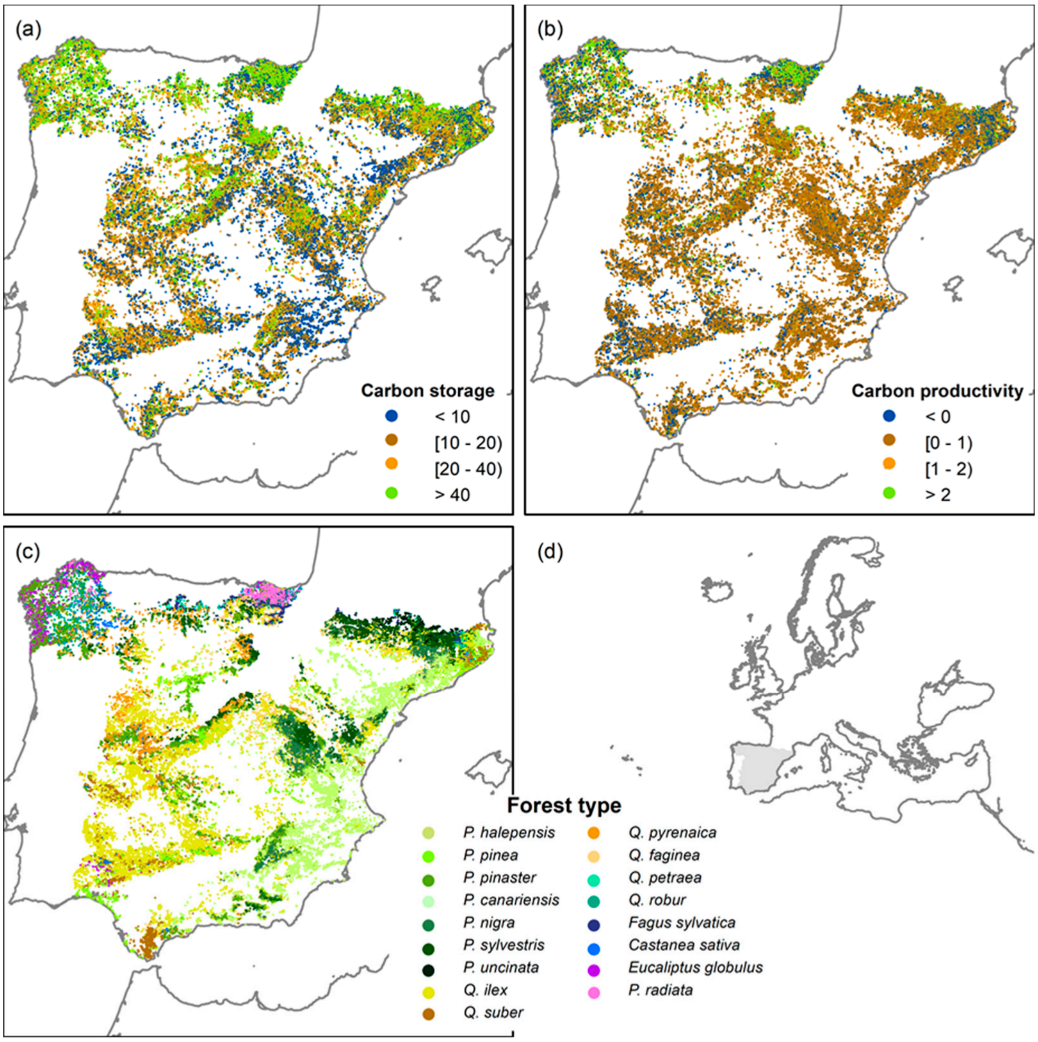

Figure 1. Map of the (**a**) aboveground carbon storage (Mg C ha^{-1}) in the third Spanish Forest Inventory, (**b**) aboveground carbon sequestration or productivity (Mg C ha^{-1} $year^{-1}$) between the second and third Spanish forest Inventories in the Iberian Spain, (**c**) the forest types considered to calculate carbon storage and sequestration in Iberian Spain in the plots of the third Spanish Forest Inventory and (**d**) the location of Spain within Europe.

2.2. Drivers of Carbon Storage and Sequestration

Each forest inventory plot was characterised by variables defined as explicative of the carbon stored or produced in Spanish forest (i.e., forest structure, climate and diversity) and weighting factors (i.e., related to risk, conservation or management, see a complete list in Table 1).

Table 1. Variables used and type (response, explicative or weight) for the multifactorial valuation of carbon storage and sequestration in Spanish forest. We include the group and variable description, the source used for each database and temporal period covered.

Type	Group	Variable Description	Database Source	Temporal Period
Response	Carbon	Carbon sequestration (Mg C ha^{-1} $year^{-1}$)	SFI2 and SFI3 [36,37]	SFI period (1986/1996–1997/2010)
		Carbon storage (Mg C ha^{-1})	SFI3	SFI period (1997/2010)
Explicative	Forest structure	Stand density (No. trees ha^{-1})	SFI2	Current
		Mean tree size (mm)	SFI2	Current
	Diversity	Tree richness (No. tree species)	SFI2	Current
	Climate	Annual precipitation (mm)	Iberian Climatic Atlas [38]	Mean 1971–2000
		Mean annual temperature (°C)	Iberian Climatic Atlas [38]	Mean 1971–2000
		SPEI (adimensional)	SPEI database [39]	SFI period (1986–2010)
Weight	Erosion risk	Soil fragility (adimensional)	Spanish Soil Inventory [40]	Current
		Potential erosion risk (adimensional)	Spanish Soil Inventory [40]	Current
		Erosion level (adimensional)	Erosion Map [41]	Current
	Fire risk	Fire frequency	[42]	SFI period
	Conserv.	Natura Net 2000	[43]	Current
		Nationally designated areas	[44]	Current
		Species richness (No. species)	Spanish Inventory of Terrestrial Species [45]	Current
	Managem.	Recent forest management	SFI3 [36]	SFI survey (1986–2010)

To represent forest structure, we selected stand density (No. trees ha^{-1}) and mean d.b.h. (mm). We used the inventory plot coordinates to extract plot-level climatic variables form the Iberian Atlas [38]. We selected annual precipitation (mm) and mean annual temperature (°C) to describe the climate gradient. As a descriptor of recent climate change due to drought events we selected mean SPEI (mean standardised precipitation-evapotranspiration index value for the period between the inventory surveys, adimensional) calculated from SPEIbase v2.2. [39]. As a representative of richness, we selected tree species richness in the 3SFI (see e.g., Reference [46]). We tested if the variables were strongly correlated with each other and if the explicative variables had a low correlation and Variance Inflation Factor (i.e., $r < 0.6$ and $VIF < 4$, see Reference [47]).

To select the weighting factors, we firstly identified factors that can indirectly influence carbon dynamics or could be used to penalize/promote the carbon stored in certain areas. Therefore, risk, conservation and management group of factors were selected. In a second step, we broke down those groups by considering the availability of public spatial databases at the National level and selecting objective information that could be applied to any system. We selected weighting factors from the available databases at the Spanish level related to risk, conservation and management factors (see Table 1 for references to each database). As weighting factors related to erosion risk, we considered soil fragility, potential erosion risk and erosion level (Table 1 and Figure A2 in Appendix A). Soil fragility is a quantitative estimation of soil loss using the RUSLE model (Revised Universal Soil Loss Equation) that calculates seven levels of soil fragility and relates them with minimum loss [40,48]. Potential erosion risk also defines seven levels through the estimation of the potential risk depending only on climatic and topographic conditions without considering vegetation cover or other human-induced modifications [40]. The erosion level calculates seven categories depending on slope, precipitation intensity, lithology (see Reference [41]). As weighting factors related to fire risk, we considered annual fire frequency as the number of fires per year for the SFI period in each plot from a database at the municipality level (MAPAMA, http://www.mapama.gob.es, see Figure A3), which was later converted to semi-quantitative as low (lower than the 1st quartile or no data), medium (between the 1st and 3rd quartile) and high (higher than the 3rd quartile).

As weighting factors related to conservation we considered if the SFI plot was in the Natura 2000 at the end of 2017 [43] and in the Nationally Designated Areas CDDA [44]. We also considered total richness using the Atlas of Biodiversity in Spain available in a grid of 10 × 10 km [45]. The richness was scaled from 1 to 100, being classified in four levels from 1: low, to 4: very high. As weighting factors for recent forest management, we considered the qualitative information available in the SFI (managed or unmanaged).

2.3. A Multifactorial Approach to Value Carbon Storage and Sequestration

We performed a multifactorial model to calculate the monetary value of the Supporting Ecosystem Value (SEV) [49] (€ $year^{-1}$) depending on four different parts:

$$\text{Supporting Ecosystem Value (SEV)} = f(x) \times S(x) \times \alpha(x) \times \lambda(x)$$

where f(x) quantify is the carbon produced in a certain stand (Mg C ha^{-1} $year^{-1}$), S(x) determines the extrapolation for the area to value (ha); α(x) makes the economic conversion (€ Mg C^{-1}) and λ(x) weights the relevant factors.

2.3.1. Quantification of Carbon Sequestration and Stored (f(x))

Carbon sequestration is critically related to climatic regulation services but it is also the outcome of ecosystem functionality (e.g., functional and structural biodiversity) [50]. Firstly, we calculated tree biomass, considering adult trees (i.e., d.b.h. ≥ 75 mm and height ≥ 130 cm) in the plots of the 3SFI using the following equation:

$$\text{Ln}\,(b_i) = \alpha + \beta \cdot \text{Ln}\,(\text{d.b.h.}_i) \tag{1}$$

where, b is the dry biomass of the above- or belowground fraction of the tree i, d.b.h. is the diameter at breast height (1.30 m) of each tree i, and α and β are species-specific parameters for aboveground and belowground fractions available in Montero's studies [51]. To obtain total carbon storage (Mg C ha^{-1}), we multiplied biomass by the species-specific carbon content of the biomass [51], scaled-up to hectare, and aggregated total carbon storage at the plot level. We calculated the percentage of error as the basal area of the plot without an allometric equation with respect to the total stand basal area and we did not include in the analyses any plot with an error greater than 20%.

Carbon sequestration for each tree (f(x) considering both aboveground and belowground biomass, Mg C ha^{-1} $year^{-1}$) was measured through the sum of the temporal variation in carbon storage of adult trees alive between the 2SFI and 3SFI (i.e., without including dead trees). Therefore, the calculus of carbon sequestration by each target tree i was done:

$$f(x)_i = (C_{i,SFI3} - C_{i,SFI2})/t_i \tag{2}$$

where $C_{i,SFI3}$ and $C_{i,SFI2}$ are the carbon accumulated in the 3SFI and the 2SFI, respectively, and t_i is the number of years between both inventories. To calculate stand carbon sequestration (Mg C ha^{-1} $year^{-1}$), we scaled-up to hectare and aggregated at plot level. We consider negative growth as an error and we did not include any plot with more than 10% of the individuals with negative growth (99.41% of total plots) (See Reference [31] for more details about the methods used to estimate carbon stored and sequestration).

We conducted error identification and we did not include those plots where species-specific allometric equations were not available for more than 20% of the individuals. Therefore, the total number of plots used here was lower than the total number of pots available in the SFI (e.g., we used 67,167 plots for carbon storage from the 79,301 plots with at least one adult tree, 84.69%). It should be also considered that we could not include the entire area of each forest type. This is because our extrapolation is based on the SFM polygons with at least one SFI plot. Furthermore, we test for differences in carbon storage and sequestration among forest types by using analysis of variance (ANOVA).

2.3.2. Extrapolation of the Carbon Sequestration Value to Area (S(x))

To extrapolate the value of carbon sequestration or storage calculated in each stand (Section 2.4.1) the area must have similar conditions in terms of dominant species, forest structure, climate, diversity, and risk and conservation factors. To actually extrapolate the carbon stored and produced in Spain we used the Spanish Forest Map 1:50,000 (SFM) [52] and followed a plot-based extrapolation methodology. The SFM database was the cartographic base of the SFI and, therefore, it is perfectly adapted to the SFI, with similar species composition and distribution, as well as land use [53]. We spatially joined SFI plots and SFM polygons and we extrapolated the mean carbon measured in the SFI plots within each SFM polygon (see similar method for wood production in Reference [2]). For those polygons with plots with two or more forest types we calculated the carbon produced and stored for the proportional area of each forest type (e.g., in a SFM polygon with three plots of *Pinus sylvestris* and two plots of *P. nigra*, then the extrapolated area is 3/5 for *P. sylvestris* and 2/5 for *P. nigra*). We also extrapolated the SFM polygons without any SFI plot; we predicted the carbon stored and produced in each polygon as mean carbon stored and produced for the main species present in the polygon. In sum, we extrapolated carbon storage and sequestration to the total area cover by the 17 most dominant forest types in Spain. The area of forests from the most dominant Spanish forest used as a basis for estimating carbon stocks and sequestration is 15.89 mill ha, representing 84% of the total Spanish forest (18.89 mill ha).

2.3.3. Economic Conversion (α(x))

The economic conversion aims to place a monetary value on carbon and, therefore, give financial incentives for forest owners and stakeholders to sustain and enhance carbon stocks in the long term. The market value of carbon in monetary terms is changeable across time and international policies. Therefore, to convert the amount of carbon stored and produced within a certain forest to a monetary value, we used the mean market value of carbon for the last 10 years available: 10.005 € per Mg C data from SENDECO$_2$ webpage.

2.3.4. Weighting Relevant Factors Depending on Risk, Conservation and Management (λ(x)) and Weighting Values

The weighting factors aim to value relevant factors that can indirectly influence carbon dynamics and therefore increase the monetary value of carbon alone. We used the weighting factors previously identified depending on the risk, conservation and management (see details in Section 2.2). The weighting method is based upon realistic budgets provided by authorities rather than establishing absolute economic values that are not coupled to specific and realistic payment policies and mechanisms. In this way, total weighting can be based for example on an annual budget which can be used as a reference maximum value. The weighing value for each factor can be defined through stakeholder and expert consultation to establish and rank priorities among seemingly conflicting goals (i.e., among conservation priority management vs. production priority management). In our case study, the weights proposed aim to multiply the carbon value by a maximum value of approximately four (e.g., financial cap providing potential budget) which is reached when all the maximum weights are assigned (see detailed weights in Table A1 in Appendix A). As risk factors, we considered erosion (from 1: no erosion, to 7: very high erosion levels weighted from 1 to 1.6), fire risk (from 1: no risk, to 4:

very high fire risk weighted from 1 to 1.6). As conservation factors, we included the protection level (i.e., if it belongs to a national or European protection it is weighted by 1.1 and if it belongs to both national and European protection it is weighted by 1.2), biodiversity (i.e., global richness weighted from 1 to 1.2). As management factors, we included recent forest management (i.e., recently not managed or managed respectively weighted as 1 or 1.2). Relative weights can also be parameterized to include potential tradeoffs among policy goals providing quantitative evidence (e.g., a tradeoff between carbon sequestration and soil water infiltration and runoff) by having relative weights summing up a constant value.

2.4. Quantifying the Drivers of Carbon Storage and Sequestration and Potential Changes along Environmental and Biotic Gradients

2.4.1. Quantification of Carbon Produced and Stored Using Maximum Likelihood

We used maximum likelihood to identify the main drivers of carbon storage and sequestration and to develop a model as a function of these factors; chiefly climatic, structural and diversity drivers. Carbon storage (Mg C ha^{-1}) and sequestration (Mg C ha^{-1} year^{-1}) were predicted as a function of maximum potential carbon storage (PCSt) and maximum potential carbon sequestration (PTSe), respectively, and three scalar modifiers ranging from 0 to 1 that quantified the effect on the average maximum PCSt/PTSe of local climatic conditions, stand structure and diversity effects (see Reference [53,54]). We defined different models of carbon storage and carbon sequestration that were analyzed separately for each forest type based on the following functional form:

$$\text{Predicted} = \text{Potential} \times \text{Climatic effect } (\delta) \times \text{Structural effect } (s) \times \text{Diversity effect } (\beta) \quad (3)$$

where Potential is a parameter that represents the maximum value when the other factors are at optimal values (i.e., the maximum carbon storage or carbon sequestration that can be obtained for a certain forest type). The climatic effect was modeled using a bivariate Gaussian function:

$$Climatic\ effect\ (\delta) = exp\left[-\frac{1}{2}\left(\frac{Temperature - XT_a}{XT_b}\right)^2\right] \times exp\left[-\frac{1}{2}\left(\frac{Precipitation - XP_a}{XP_b}\right)^2\right] \quad (4)$$

where the parameters XT_a and XP_a represent the mean annual temperature and annual precipitation at which maximum carbon storage or sequestration occurs, and XT_b and XP_b are the parameters that control the variance of the normal distribution (i.e., the breadth of the function). The structural effect was modeled using a bivariate Gaussian function including density and structural heterogeneity effects:

$$Structural\ effect\ (S) = exp\left[-\frac{1}{2}\left(\frac{Density - XD_a}{XD_b}\right)^2\right] \times exp\left[-\frac{1}{2}\left(\frac{Heterogeneity - XH_a}{XH_b}\right)^2\right] \quad (5)$$

where the density effect is measured in terms of stand density (No. trees ha^{-1}), and the structural heterogeneity effect is measured through the mean d.b.h. in the stand. XD_a and XH_a are the tree density and mean d.b.h., respectively, at which maximum carbon storage or sequestration occurs, and XD_b and XH_b are estimated parameters that control the breadth of the function.

The diversity effect was modeled using a variation of the exponential:

$$Diversity\ effect\ (\beta) = [1 - \exp(XR_a \cdot Richness - XR_b)] \quad (6)$$

The exponential form selected to model the effect of diversity on carbon storage and sequestration varied between 0 and 1. The parameter XR_a determines the shape of the effect of richness on the predicted variable and XR_b defines the intercept of the function.

We compared alternate models using differences in AIC (Akaike Information Criterion) as an indicator of both parsimony and likelihood [55]. We used two units difference in AIC as a support interval to assess the strength of evidence of individual maximum likelihood parameter estimates, being roughly equivalent to the 95% support limit defined using a likelihood ratio test [55]. The full model was compared with models that ignored the effect of climate, stand structure or diversity, and with the null or intercept-only model (i.e., ignoring the effect of climate, stand structure and diversity) for each response variable (i.e., carbon storage and sequestration) and each forest type. The parameter estimates provide the basis for determining the magnitude of the effect of a given process, with maximum likelihood estimates of parameter values close to zero indicating no effect. We used simulated annealing optimization procedures to determine the parameters that maximize the log-likelihood of observing carbon storage and sequestration with a normal error distribution given our data [56]. The R2 of the regression was used as a measure of goodness of fit (1 − SSE/SST, SSE: sum of squares error, SST: sum of squares total) and the slope of the regression (with a zero intercept) of observed and predicted data was used as a measure of bias (an unbiased model having a slope of 1). All the analyses were performed in R.3.4.2 [57]. We used the likelihood package 1.6 [58].

2.4.2. Quantification of Carbon Storage and Sequestration Using Random Forests

We performed the non-parametric models of carbon storage and sequestration using the random forest algorithm [59] to test the relative influence of stand structure, climate, diversity and the weighting factors on carbon storage and sequestration. This machine learning technique allows to incorporate predictors being relatively insensitive to multicollinearity and overfitting and, therefore, allowing the inclusion of many predictors [60]. We used the randomForest library [60] in R 3.4.2 [57].

3. Results

3.1. Carbon Storage and Sequestration of Spanish Forests

Total carbon stored in the tree component of Spanish forest had a mean value of 43.35 Mg C ha^{-1}, from which the 73% was in aboveground biomass and 27% was belowground. Carbon storage had significant differences depending on the forest type (d.f. = 16, F = 1005.8; $p < 0.001$), being lower in Mediterranean pines and sclerophyllous forests and greater in mountain pine and deciduous forests (Figure 2a). Total carbon sequestration had a mean value of 1.02 Mg C ha^{-1} year^{-1} from which the 75% was in aboveground biomass (Figure 2b) whereas the 25% left was sequestered belowground. Carbon sequestration significantly varied among forest types (d.f. = 16, F = 44.63; $p < 0.001$), ranging from exotic species (e.g., *Pinus radiata* and *Eucalyptus globulus*) and mountain pines to Mediterranean pines and scherophyllous species (Figure 2b).

Total carbon stored in forests calculated through the extrapolation from the SFI plots to SFM polygons was 275.38 mill Mg C (196.11 mill C aboveground and 79.28 mill C belowground). Total carbon sequestration calculated through the extrapolation from the SFI plots to SFM polygons was 4.84 mill Mg C year^{-1}. Carbon storage was extrapolated to 15.89 mill ha and carbon sequestration to 4.97 mill ha (i.e., only polygons of SFM with at least one SFI plot were used). Carbon sequestration reached a value of 20.84 mill Mg C year^{-1} when extrapolated to 15.89 mill ha through the use of the multifactorial model for all combined forest. Total carbon storage distributes in each forest type with the highest carbon storage and area in *Quercus ilex* forests, followed by *Fagus sylvatica*, *Castanea sativa*, *P. pinaster*, *P. sylvestris* and *Q. robur* (*c.* 70% of total carbon stored, Table 2).

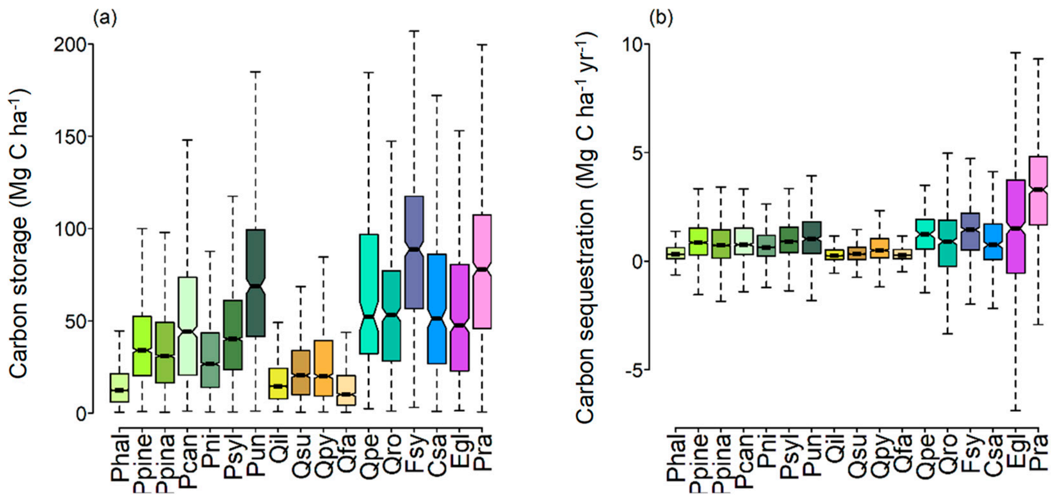

Figure 2. Boxplot of (**a**) aboveground carbon storage and (**b**) aboveground carbon sequestration in each forest type using the Spanish Forest Inventory. Phal = *Pinus halepensis*, Ppine = *P. pinea*, Ppina = *P. pinaster*, Pcan = *P. canariensis*, Pni = *P. nigra*, Psyl = *P. sylvestris*, Pun = *P. uncinata*, Qil = *Q. ilex*, Qsu = *Q. suber*, Qpy = *Q. pyrenaica*, Qfa = *Q. faginea*, Qpe = *Q. petraea*, Qro = *Q. robur*, Fsy = *Fagus sylvatica*, Csa = *Castanea sativa*, Egl = *Eucayptus globulus*, Pra = *P. radiata*.

Table 2. Aboveground, belowground and total carbon storage (Mg C) calculated for the area covered by each forest type. We only considered the polygons of the Spanish forest map with at least one Spanish forest plot in a total area of 15.89 mill ha.

Forest Type	Aboveground Carbon Storage (mill. Mg C)	Belowground Carbon Storage (mill. Mg C)	Total Carbon Storage (mill. Mg C)
P. halepensis	9.03	3.17	12.20
P. pinea	11.32	2.13	13.45
P. pinaster	21.87	4.76	26.63
P. canariensis	3.42	0.86	4.28
P. nigra	5.78	1.53	7.31
P. sylvestris	14.11	4.14	18.25
P. uncinata	2.95	1.03	3.98
Q. ilex	41.98	21.10	63.08
Q. suber	6.79	1.83	8.62
Q. pyrenaica	5.54	1.54	7.08
Q. faginea	1.35	0.51	1.86
Q. petraea	3.62	0.96	4.57
Q. robur	13.94	3.50	17.44
F. sylvatica	22.18	11.94	34.12
C. sativa	12.01	19.49	31.50
E. globulus	15.78	-	15.78
P. radiata	4.44	0.79	5.23

3.2. The Multifactorial Approach to Value Supporting Ecosystem Services

Carbon storage and sequestration were strongly affected by stand structure and in some forest types by climate and diversity (see Table 3). Most models produced unbiased estimates of carbon storage and sequestration (i.e., slopes of predicted versus observed values were all close to one, Table 3). The explained variance (R^2) for carbon sequestration ranged from 5% for *Fagus sylvatica* forests to 90% for *P. canariensis* forests and for carbon storage from 48% for *Fagus sylvatica* forests to 96% for *P. canariensis* forests (Table 3). Stand structure was much more important explaining carbon sequestration than climate and diversity (Table 3). The relative importance of variables using the maximum likelihood and random forest approach were similar, with structural and climatic variables having a greater importance than diversity and soils (see Figure A5 and Table 3, variance explained random forest was 43%). Predicted values of carbon storage and carbon sequestration in the main Spanish forest types (see Table A2 in Appendix A) were similar to the observed values (Figure 2).

We weighted carbon storage and sequestration depending on the values of each factor in the Spanish forest (see values in Appendix A and raw vs. weighted value in Figure 3). Weighted carbon storage and sequestration was always greater than carbon alone, but the magnitude of this change depended on the specific area. The weighted carbon ranged between 43.35 to 258 Mg C ha^{-1} for the mean carbon storage and between 1.02 to 4.50 Mg C ha^{-1} year^{-1} for the mean carbon sequestration in Spanish forests. Finally, the economic value from the weighted carbon ranged between 433.72 and 2581.29 € ha^{-1} for the mean carbon storage and between 10.20 and 45 € ha^{-1} year^{-1} for the mean carbon sequestration in Spanish forests.

Table 3. Models of carbon sequestration and comparison of Akaike Information Criterion (AIC) of the full model versus the models without stand structure effects (No structure), climate (No climate) or diversity (No richness effects). The variables which were supported by the model are marked in bold, indicating a poorer fit when the variable was removed from the model (greater values of AIC indicate a poorer fit). The R^2 of the model and slope is also shown.

	Full	**No Structure**	**No Climate**	**No Richness**	R^2	**Slope**
P. halepensis	10,803.60	**12,621.57**	**10,931.76**	**10,830.37**	0.34	1.00
P. pinea	5587.39	**5806.27**	**5592.47**	**5589.90**	0.18	1.00
P. pinaster	17,531.33	**18,308.31**	17,519.00	**19,010.80**	0.20	1.01
P. canariensis	42.04	34.94	34.74	38.69	0.90	1.29
P. nigra	10,759.92	**11,385.90**	**10,760.25**	10,757.27	0.26	0.99
P. sylvestris	14,263.20	**14,796.07**	**14,264.00**	14,259.33	0.20	1.01
P. uncinata	1851.28	**1876.83**	**1852.94**	1842.90	0.15	0.98
Q. ilex	16,909.71	**18,130.11**	**16,987.87**	16,905.94	0.36	1.01
Q. suber	3422.65	**3506.47**	**3425.36**	**3423.42**	0.11	1.08
Q. pyrenaica	4928.74	**5085.78**	4914.68	4920.81	0.16	1.01
Q. faginea	1941.55	**2114.26**	1931.25	**1948.08**	0.26	1.02
Q. petraea	637.05	633.13	627.04	634.10	0.19	1.01
Q. robur	2056.02	**2091.73**	2040.48	2049.00	0.17	1.00
F. sylvatica	2770.49	**2771.78**	2757.89	2765.43	0.05	1.01
C. sativa	1851.68	**1852.12**	**1852.17**	**1853.14**	0.14	1.08
E. globulus	3102.80	**3177.23**	3091.98	3098.48	0.44	1.00
P. radiata	3633.87	3628.05	3622.96	3627.22	0.21	1.00

The applications of the weights to carbon storage and sequestration had a generalized increase, but were not very pronounced (see Figure 3a,c for carbon storage and Figure 3b,d for carbon sequestration). The hotspots for carbon storage and sequestration can be observed in the Iberian Peninsula (e.g., mountain regions such as Pyrenees, Cordillera Cantábrica, Sierra de Guadarrama, Sierra Morena or Cordilleras Béticas among others, and some temperate areas such as the Atlantic regions of Galicia and the Basque Country, Figure 2).

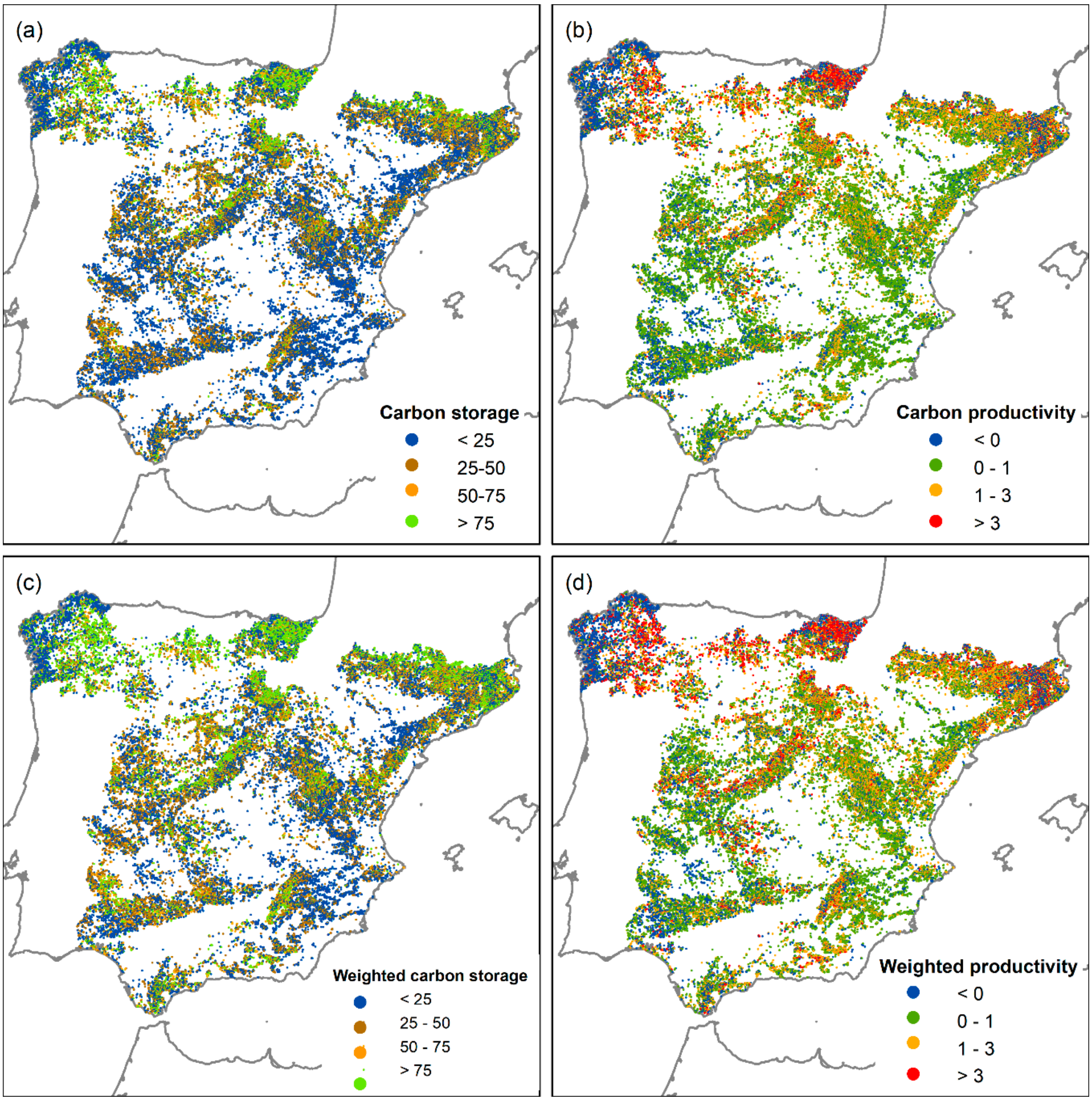

Figure 3. Map of total carbon storage and sequestration (**a**,**b**, respectively) and carbon storage and sequestration weighted (**c**,**d**, respectively) using the risk (soil and fire) and conservation (protected area, total richness and management) weights from Table A1 for all the permanent plots in the Spanish forest inventory.

4. Discussion

Our study aims to value supporting forest ecosystem services based on a multifactorial approach including the quantification of carbon storage and carbon sequestration together with the weighting of conservation, risk and management factors resulting from stakeholders and decision-making agents inputs. The valuation method presented here could be applied to other countries and continents upon the availability of a forest inventory network and spatial environmental and socioeconomic information, which is increasing exponentially in Europe [61,62] and worldwide [63].

Initial biophysical assessment is crucial to verify the state of ecosystems and to quantify the natural capital [64]. In our study, the mean values of carbon storage and sequestration that we obtained in Spanish forest (*c.* 43 Mg C ha^{-1} and 1.02 Mg C ha^{-1} yr^{-1}, respectively) were slightly lower than values for temperate forests which vary between 58-155 Mg C ha^{-1} for aboveground carbon [65–68], and 62-78 Mg C ha^{-1} for belowground carbon [67]. However, the range of values obtained for the different forest types are in the range of values calculated using the same database [69] and for the forest types of Mediterranean evergreen forests and broad-leaved deciduous forests [53]. Therefore, the biophysical assessment through quantification of carbon storage and carbon sequestration indicates that the Spanish forest provides a significant ecosystem service, which should be considered.

While a portion of studies addressing carbon quantification rely on other researcher's estimates of carbon storage and sequestration (e.g., References [70,71]), we used a tree-based approach and derived the carbon fixed in each forest plot considering tree size and species-specific allometric equations to convert tree size to biomass and carbon. However, we identified a trade-off between carbon specificity accuracy and the number of plots used. We conducted error identification in plots (see Section 2.3.1) with the number of plots resulting in the 84.69% of available plots. Another limitation in our study was that we could not include the entire area of each forest type for the plot-based extrapolation. This is because our plot-based extrapolation builds on the SFM polygons with at least one SFI plot (see Section 2.3.3). Therefore, for those SFM polygons without any SFI plot we used a less precise extrapolation method based on the mean carbon stored and produced for the main species present on the polygon. Despite some mentioned limitations, our approach (i) allows us to quantify carbon sequestration and storage for each species in the entire national territory, (ii) the extrapolation based on the SFM has already been done in previous studies quantifying wood production [4] and (iii) the method could be applied to any specific forest in the territory helping owners and stakeholders to apply the method proposed here (i.e., through a computer or cellular phone based application).

Given that ecosystems provide a number of intangible benefits, ecosystem service valuation is a complex task [72]. We found that the monetary value of the yearly ecosystem service (i.e., carbon sequestration) was 10.20 € ha^{-1} $year^{-1}$. However, we showed that the value of carbon is variable across a broad range of situations and the justified monetary value can significantly increase beyond 10.20 € ha^{-1} $year^{-1}$ when other key goals are considered. In our case study, combining high erosion and fire risk, high level of protection, high species richness and presence of management, the value of the ecosystem supporting function that can be justified can almost reach 45 € ha^{-1} $year^{-1}$. Our method, based on the combination of a biophysical assessment through carbon quantification and a weighted approach, is adaptable to different environmental situations and integrates management criteria and priorities (i.e., carbon sequestration in areas of high risk of erosion might be given a greater valuation). For example, the most ambitious scenario for maximizing carbon sequestration together with conservation priority management might value forest management and protected areas positively, however, the scenario for production priority management might value forest management positively without protected areas. Moreover, it allows the adjustment of (top-down) annual budgets with management priorities avoiding a detailed bottom-up ecosystem service valuation which is completely decoupled from current policies and administration budgets.

The variables used to predict carbon storage and sequestration (e.g., stand structure, climate and diversity) have been extensively used before (e.g., References [69,73]). Our study agrees with previous studies that found that forest structure is a strong determinant of tree biomass and therefore carbon storage and sequestration in Iberian forests [69,73,74]. The quantification of carbon through the multifactorial approach parameterized with structural, climatic and diversity variables allows for the applicability of this method in predicting carbon storage and sequestration in any of the 17 forest types considered in this study and under similar conditions.

The consideration of the weighting factors responds to achieve international agreements that support sustainable development and aim to link environmental conservation and financial instruments. Thus, for instance, soil risk associated with erosion, fire and conservation are key issues for the three "Rio Conventions" [48] (i) the United Nations Convention on Biological Diversity (CBD), (ii) the United Nations Framework Convention on Climate Change (UNFCCC) and (iii) the United Nations Convention to Combat Desertification (UNCCD) which aim to promote sustainable development and protection of biological diversity, to reduce atmospheric concentrations of greenhouse gases and to combat desertification. Conservation and management also became a key aspect in the Natura 2000 network. In addition, the network supports financing needs for management and restoration of sites in the Natura 2000 network. Additional financial instruments can provide supplementary budgets to national instruments that can help to finance forest ecosystem services.

The weighting approach applied based on the spatial distribution of aspects related to risk, conservation and management might help to modulate the payment of key ecosystem services (see Figure 2). The main advantage of the weighting approach is that it could help to further protect priority areas (see Figures A2 and A3 in Appendix A) and/or promote or penalize different risk, conservations or management measurements. The use of different weights by stakeholders could, therefore, help to promote different policies and adjust them through time, allowing for the further promotion/penalization of different factors. We used the best available information regarding risk, conservation and management across peninsular Spain, but further information could be important to further promote/penalize certain areas. For example, we only use recent management information in our study whereas further information on the legacy effect of forest traditional uses [75], species selection, exotic species and the planted or natural forest character [76] may improve the accuracy of the management criteria.

Our study has limitations because it only provides information about live tree biomass within forests. Other important carbon reserves are missing such as soils (which stores c. 44% of carbon reserves in forests [7], organic litter layer (about 5% of total aboveground carbon storage [7,77]), dead wood and shrubs (which can be particularly important in the Mediterranean region [78–80]). Forest inventory data also measures shrub and dead wood information and provides the opportunity to further explore the importance of this carbon fraction along the large climatic gradient of the Iberian Peninsula and in combination with other remote sensing information can be used to measure carbon in different fractions on the forests [81]. On the other hand, land use and land cover changes can lead to changes in the total amount of carbon stored [82]. However, its absolute importance is much higher in tropical than in European regions on the second half of the XX century [7]. However, in the current century, the Iberian peninsula and Mediterranean areas are one of the hotspots of land use change in Europe, mainly due to forest expansion [83]. Therefore, to properly quantify carbon storage and sequestration, land use and land cover changes might need to be included in future valuations. The use of long-term databases such as CORINE Land Cover in Europe (see Reference [33]) could be also used to further estimate changes in carbon storage (e.g., Reference [84]).

Our quantification of carbon storage and sequestration could be applied to other areas with forest inventory data, with its increasing availability and accessibility worldwide (see e.g., European forest inventory network (e.g., References [53,64]), Amazon forest inventory (e.g., Reference [85]) or permanent plots in tropical forest (e.g., Reference [86]) among others)). Together with the periodical surveys of the NFI data, this should update the national statistics and track some temporal trends of carbon storage and sequestration into the future. The long-term and large-scale applicability of the methods might help with national and continental assessments to further assist mitigation policies [87]. It is unclear if the implementation of forestry actions for the promotion of carbon sequestration could be detrimental for other services, for example due to potential trade-offs between ecosystem services [88]. European forests have displayed a high and unrealized potential in forest multifunctionality [6], which suggests that forestry actions could lead to win–win strategies. Therefore, trade-offs in European forests are generally rare, and a maximization of forest multifunctionality and differential management objectives in carbon sequestration, climate regulation or biodiversity conservation could be achieved. We found high carbon sequestration of exotic forests dominated by *Pinus radiata* or *Eucalyptus globulus*, which agrees with the promoted biomass provision in planted forests when compared to other forest functions [23]. Further studies are needed on the valuation of multiple ecosystem services to further analyse total carbon stored by forest and the relationship with other ecosystem services, particularly on the effect of forest management with soil functions and biodiversity.

In conclusion, we found that carbon storage and sequestration in Spanish forest provides a relevant ecosystem service, similar in magnitude to previous studies and with a strong variation along climate and species identity. We suggested the incorporation of processes that can indirectly influence carbon dynamics (i.e., risks, conservation and management) as weighting factors when valuing carbon, which can help to further promote/penalize important factors in carbon valuation. The monetary value of carbon was increased more than four times when the weighting approach was taken into account, which might give forest owners more incentives to tackle climate change. The approach presented here agrees with policy goals for forest adaptation and mitigation to climate change: effective, efficient, fair and legitimate. Effectiveness is based on the use of a key support service on which other ecosystem services depend on, and its conservation is needed for other ecosystem services. Efficiency is based on the use of available public resources and it avoids extra costs. Equity is based on the transparency of the method that can be applied to all territories at the National scale, and it is legitimate because it is based on international policies. The multifactorial approach also intends to serve as a decision-making tool in situations when multiple management objectives are in conflict (e.g., forest conservation priority management vs. forest production priority management) from local scales to international policies.

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Appendix A. Supporting Methods

Table A1. Weighted value proposed for the risk and conservation factors.

Weighting Factor	Variables Used	Level	Description	Weight
Erosion risk	Mean weight (Fragility, erosion, potential risk)	1	No risk	1
		2,3	Low	1.2
		4,5	Medium	1.4
		6,7	High	1.6
Fire risk	Fire frequency	1	No risk	1
		2	Low	1.2
		3	Medium	1.4
		4	High	1.6
Conservation	Protected area	0	No	1
		1	Natura 2000 network or Nationally designated areas	1.1
		2	Natura 2000 network & Nationally designated areas	1.2
	Global richness	1–25%	Low	1
		26–75%	Medium	1.1
		>75%	Very high	1.2
Recent management		0	No management	1
		1	Management	1.2

Table A2. Predicted values of carbon storage (Mg C ha^{-1}) and carbon sequestration (Mg C ha^{-1} $year^{-1}$) in the main Spanish forest types.

Forest Type	Carbon Storage (Mg C ha^{-1})	Carbon Sequestration (Mg C ha^{-1} $year^{-1}$)
P. halepensis	14.890	0.728
P. pinea	40.318	2.040
P. pinaster	36.827	1.708
P. canariensis	17.409	0.010
P. nigra	31.807	1.302
P. sylvestris	45.002	1.818
P. uncinata	91.096	1.881
Q. ilex	29.681	0.798
Q. suber	31.383	0.647
Q. pirenaica	31.653	1.065
Q. faginea	20.736	0.715
Q. petraea	98.790	2.048
Q. robur	77.203	1.363
F. sylvatica	175.223	2.614
C. sativa	156.906	2.729
E. globulus	39.679	2.906
P. radiata	66.229	4.947

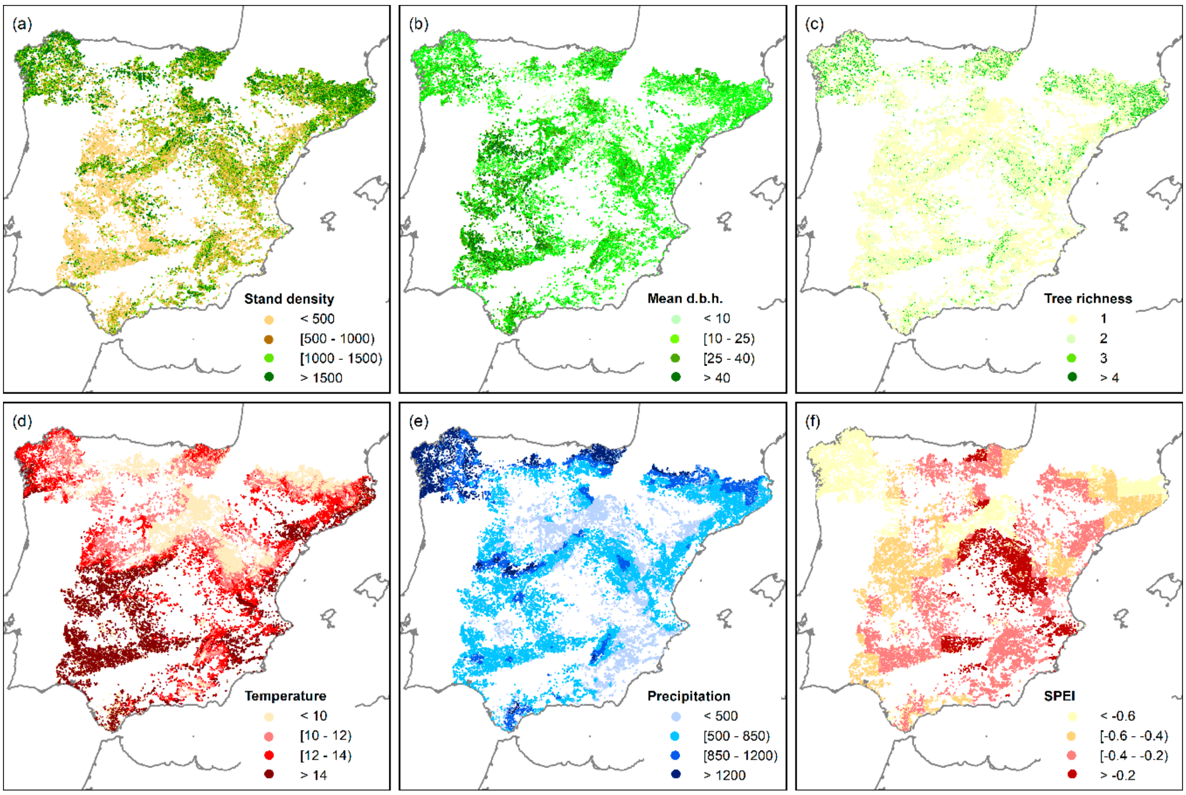

Figure A1. Map of the Iberian Peninsula showing (**a**) stand density (No. trees ha^{-1}), (**b**) mean d.b.h. (cm), (**c**) tree richness (No. tree species), (**d**) mean annual temperature (°C), (**e**) annual precipitation (mm) and (**f**) SPEI (adimensional) in permanent plots of the Spanish Forest Inventory.

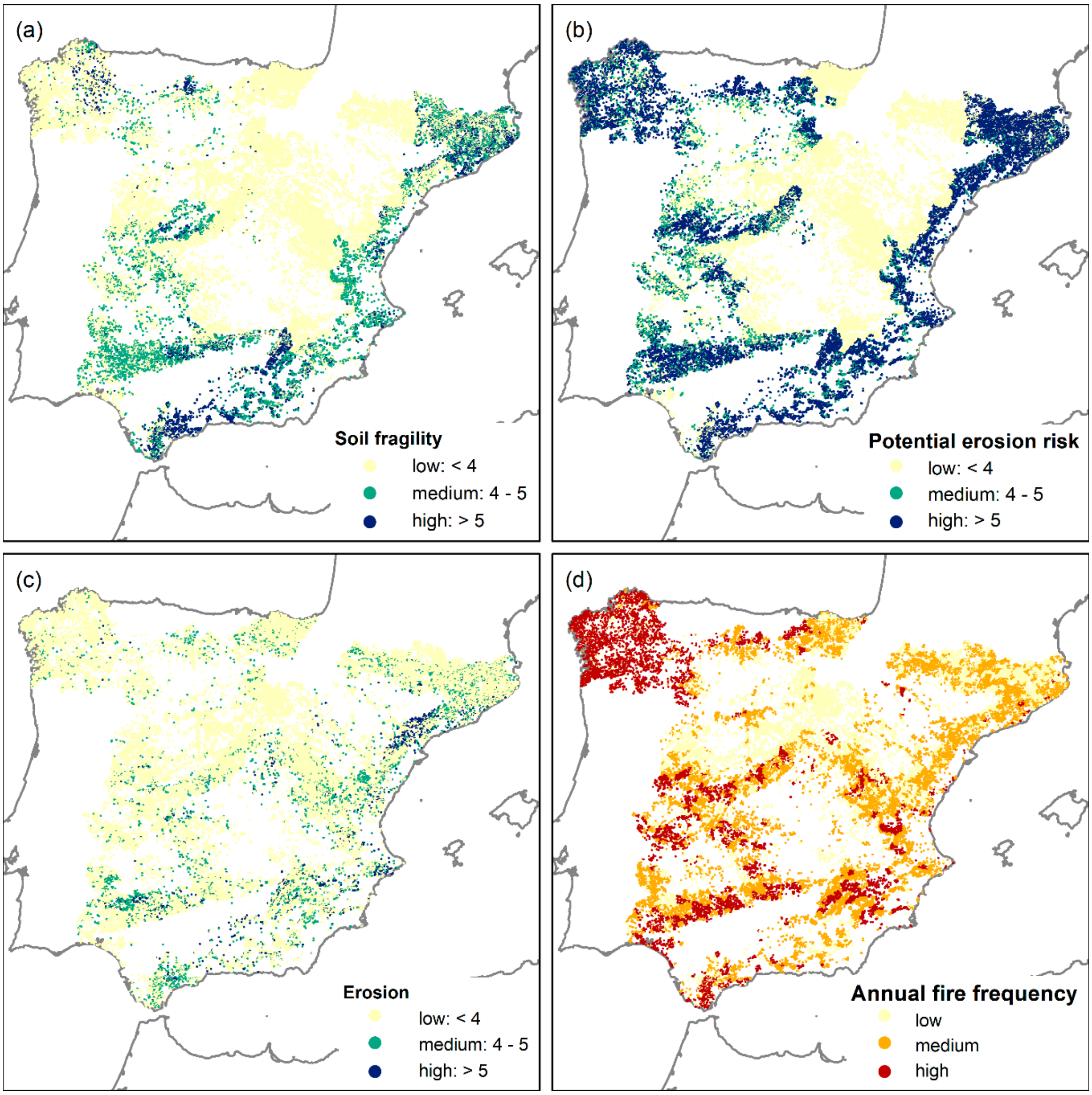

Figure A2. Map of the Iberian Peninsula showing risk factors available in permanent plots of the Spanish Forest Inventory (**a**) soil fragility (**b**) potential erosion risk, (**c**) erosion (for the three soil variables seven levels classified as low, medium, high), and (**d**) fire frequency categorized at low, medium and high.

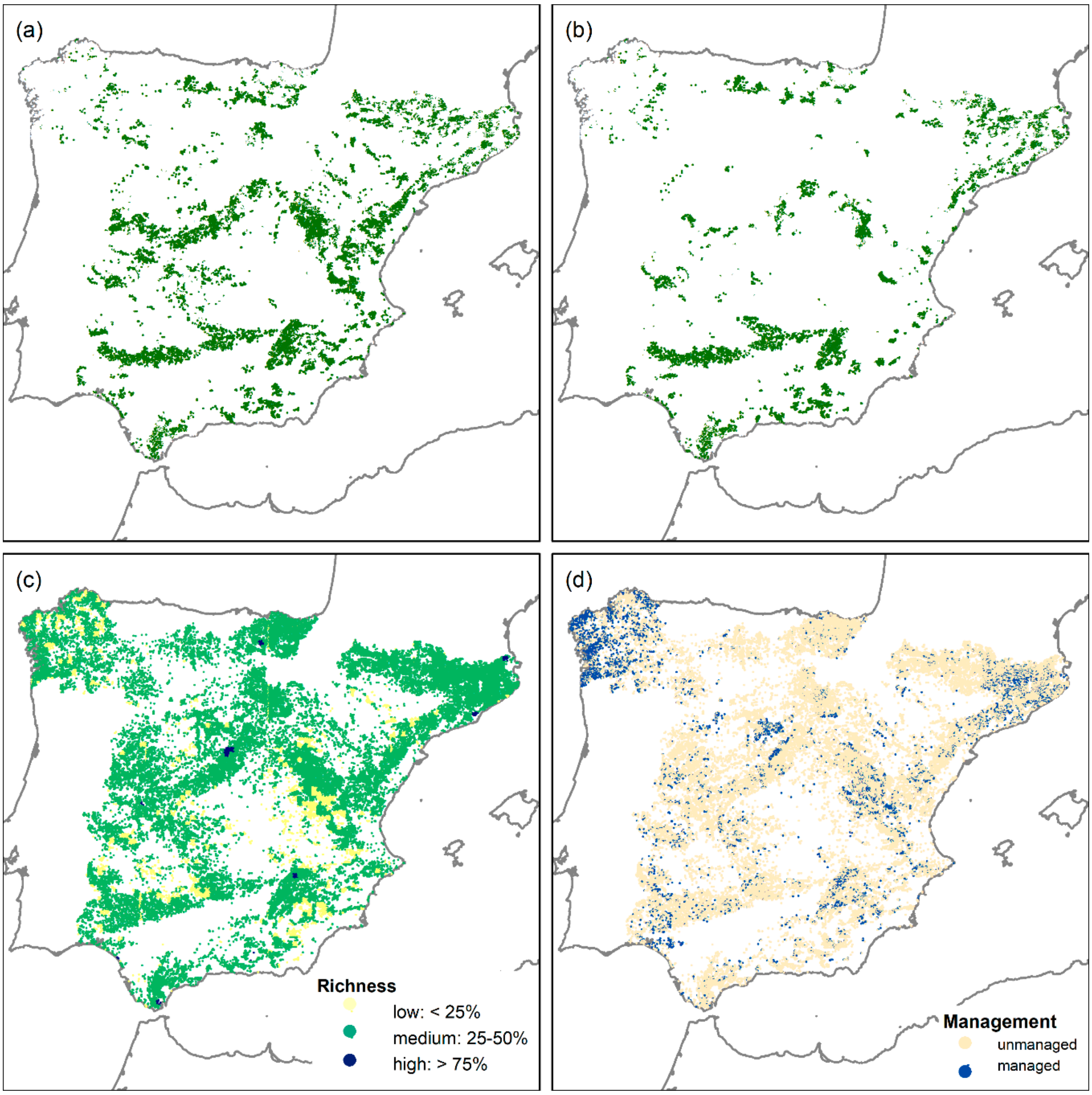

Figure A3. Map of the Iberian Peninsula showing conservation factors in permanents plots of the Spanish Forest Inventory (**a**) Nationally Designated Areas, (**b**) Natura Net 2000, (**c**) global richness.

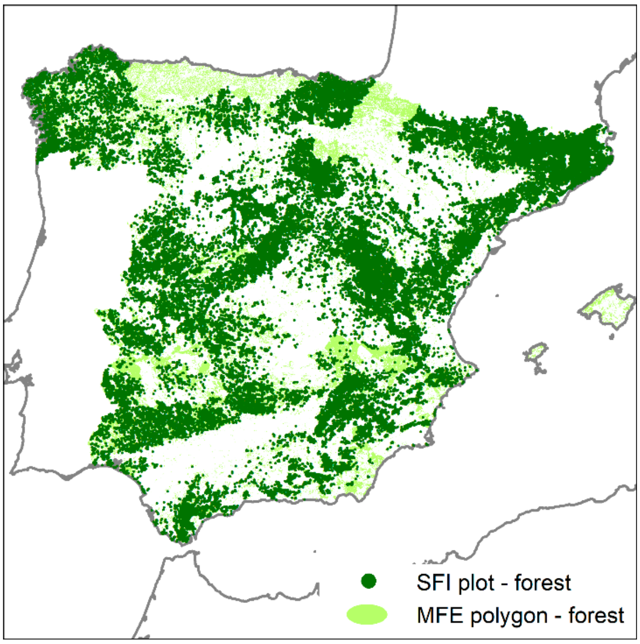

Figure A4. Map of the available permanents plots of the Spanish Forest Inventory and polygons of the Spanish Forest Map used to extrapolate carbon storage and sequestration. In the provinces Asturias, Baleares there were no permanents SFI plots between the second and third Inventory.

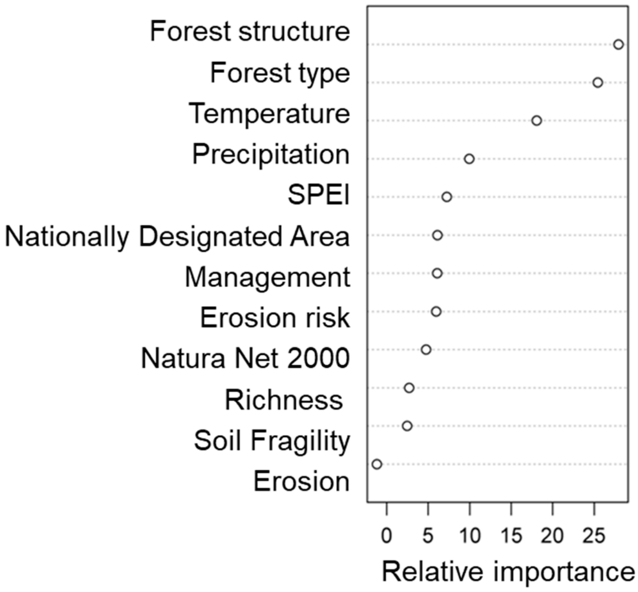

Figure A5. Relative importance of the variables included in the random forest measured as the mean decrease in accuracy.

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