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Spatial Distribution of Biomass and Woody Litter for Bio-Energy in Biscay (Spain)

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Abstract: Forest management has been considered a subject of interest, because they act as carbon (C) sinks to mitigate CO_2 emissions and also as producers of woody litter (WL) for bio-energy. Overall, a sustainably managed system of forests and forest products contributes to carbon mitigation in a positive, stable way. With increasing demand for sustainable production, the need to effectively utilise site-based resources increases. The utilization of WL for bio-energy can help meet the need for renewable energy production. The objective of the present study was to investigate biomass production (including C sequestration) from the most representative forestry species (*Pinus radiata* D. Don and *Ecualyptus globulus* Labill) of Biscay (Spain). Data from the third and fourth Spanish Forest Inventories (NFI3-2005 and NFI4-2011) were used. We also estimated the potential WL produced in the forest activities. Our findings were as follows: Forests of Biscay stored 12.084 Tg of biomass (dry basis), with a mean of 147.34 Mg ha^{-1} in 2005 and 14.509 Tg of biomass (dry basis), with a mean of 179.82 Mg ha^{-1} in 2011. The total equivalent CO_2 in Biscay's forests increased by 1.629 Tg year^{-1} between 2005 and 2011. The study shows that the energy potential of carbon accumulated in the WL amounted to 1283.2 million MJ year^{-1}. These results suggest a considerable potential for energy production.

Keywords: carbon stock; woody litter; bioenergy potential; resources map; aboveground biomass, underground biomass

1. Introduction

In recent years there has been an increasing interest in the estimation of forest biomass, mainly in the context of the rules established in the Kyoto Protocol. According to this protocol, the CO_2 emissions limit for each nation must be estimated taking the carbon sinks and sources into account, including the carbon dioxide absorbed and stored by trees [1,2]. The carbon content in forests is the highest of all terrestrial ecosystems, being considerably higher than that in pastures and fields [3]. Some studies have shown that the simultaneous consideration of carbon sequestration in forest ecosystems and forest biomass production (e.g., wood and energy) in forest management could offer important means to reduce carbon emissions to the atmosphere in the future [4,5]. Temperate forests currently act as carbon sinks since they absorb more carbon from the atmosphere through photosynthesis than the carbon they produce through breathing. Notwithstanding, in a climate change environment, carbon dynamics may be altered. Hence, it is essential to engage in a sustainable forest management in which the annual average stock of carbon and its sequestration can be increased. On the other hand, the use of biomass for energy production has recently created a great deal of interest, which is partly due to environmental reasons. These reasons are mainly the problems caused by climate change and the need to search for a solution to the foreseeable exhaustion of fossil fuels.

The classical energy model based on the massive use of fossil fuels is unsustainable from both the environmental viewpoint and from the point of view of using up these resources. Thus, a new energy model must be established, based on the diversification of resources, consumption rationalization and efficiency, as well as environmental respect. With increasing energy costs, society is searching for alternative energy sources. The mean value of forest biomass used in Europe is 61%, while in Nordic countries or Austria this percentage is close to 90%. However, despite its potential forest biomass, Spain only exploits some 38% of the biomass that grows annually in its forests. In local terms, the goal for the Autonomous Community of the Basque Country (ACBC) in 2010 was to reach 795,000 MJ of biomass exploitation. As far as the contribution of forests and lands from the ACBC as carbon sink is concerned, the net drain effect has been estimated as 1.33×10^6 Mg CO_2 [6].

The use of forest biomass as an energy resource is closely related to employment, since for each job in the fossil fuel businesses, as many as fourteen jobs are generated with biomass. Especially in rural areas, this provides territorial equilibrium. Moreover, the use of this residue as an energy source helps to reach the compromises acquired by the European Union in the Kyoto protocol—by 2020, 20% of all energy consumption must come from renewable sources-[7]. In Spain, the 2011–2020 Renewable Energy Plan set the target of 20% of total primary energy needs to be met by renewable sources, and about 10% of these by bioenergy [8]. One of the most important advantages of biomass use is its low atmosphere-pollutant production when compared with conventional fuels: minimum production of SO_2 due to its low S content; the emission of NO_x is also significantly reduced since biomass combustion can take place at lower temperatures, almost without affecting its yield [9]. Apart from this, the use of forest biomass for energy purposes has a null CO_2 emissions balance since CO_2 emissions that occur as a result of its recovery as energy are offset by the amount absorbed by organisms for the production of biomass through photosynthesis.

Forest biomass fulfills a double aim from the environmental point of view: (a) capacity to produce renewable energy from it and (b) to keep an adequate degree of maintenance and cleanliness of our forests [10]. However, the energy valuation of forest biomass presents some problems due to its low energy density and the scattered production of the resource. As a result of this, the quantity of biomass becomes essential, since its supply to the energy plant must be guaranteed. Quantifying the amount of forest biomass is fundamental and essential in order to be able to calculate carbon storage, as well as to study climate change, health of forests, forestall productivity, and nutrients cycle [11].

Due to the quick change of forest masses (new hydraulic work, fires, etc.), it is difficult to establish the available biomass quantity at any given moment [12,13]. To overcome this problem, different techniques have been used in this project, the main ones being tele-detection and Geographic Information System (GIS). The use of these systems presents numerous advantages over traditional inventories since they allow very detailed spatial information to be gathered at a higher periodicity and a lower cost [14–18].

The methodologies used in recent years to determine the amount of forest biomass can be classified into two categories: (a) direct estimations in the field and (b) indirect methods [19,20]. In the direct methods, once the trees have been selected, they are subjected to destructive sampling: after being felled, the different parts of the tree considered (trunk, branches, leaves, etc.) are cut up into pieces. The weight of each of these parts is determined by means of different techniques in a number of sampling plots [21]. In the case of young trees, the complete parts are weighed once the tree has been felled. Nevertheless, for large-size trees this procedure is unviable and sampling techniques must be used [22]. After reviewing the different forest biomass estimation methods, the one chosen was the so-called indirect method, since this methodology provides similar results to those obtained through direct methods. Moreover, the indirect methodology is non-destructive, whereas the direct one is destructive and it involves a laborious procedure. Moreover, a higher quantity of quantitative information is used in indirect methods, and this methodology can be applied to data from future forest inventories [16,20].

In this study, the biomass accumulated in forests in Biscay is quantified using indirect methods based on forestry inventory data, basically using biomass equations or biomass expansion factors (BEFs) [23–27]. We used biomass equations in this research, because this method may provide more precise estimations than BEF and because it is used more frequently to estimate the biomass of forests [25,28,29].

In order to select the indirect method that best adapts to the model, an exhaustive analysis was made of those developed both at national and international levels. In recent decades, a compendium of equations gathered from different countries has been drawn up [30–34], but these are difficult to apply in our case due to a lack of data about their construction. Although the area analysed in this paper (Biscay) has great potential for the generation of forestry biomass, very few studies have been carried out on this area. Cantero et al. [35] did a preliminary study in order to establish growth models in plantations of *Pinus radiata* D. Don in Biscay, but new tools are still required to improve biomass generation predictions, taking the latest forestry inventories into account.

The objectives of this study were (a) to estimate biomass (aboveground and underground) and the carbon accumulated by the main forest species in Biscay, (b) to assess the annual woody litter (WL) for bio-energy obtained in the forestry treatments and its geographical distribution.

Among the numerous studies carried out in recent years about the estimation of forest biomass, some are located in areas with similar climatic characteristics and tree species to our study area, and therefore a number of equations used in these studies can be applied to the current project [36–38].

In the previous research undertaken in the study area, the estimation of WL was done considering the residues obtained after a ten-year average forestry management and silviculture periodicity. In each phase, 1/3 of the trees were cut for *P. radiata*. It was done according to data obtained in several parts of Spain [13]. In this previous research the influence of forest management and cutting rotations on carbon sequestration in forest biomass was not considered. In Biscay, the traditional method of forest management has usually been the production of timber (pulpwood and sawlogs). However, the current environmental concerns, in response to global warming caused by human beings, have forced a change in the traditional forest management of our forests to a more sustainable approach, attempting to balance economic performance with environmental aspects. Among these new approaches is the optimization of CO_2 sequestration in relation to forest biomass. In the current research, the quantity of forest biomass residues obtained in each rotation stage was estimated considering the periodicity, the age of the mass, and the number of trees cut according to a sustainable forest management, which optimizes the quantity of timber obtained and the carbon sequestration related to the process [4,39–41]. Pyörälä et al. [4] analyzed the effects of management on the economic profitability (NPV) of forest biomass production and the carbon neutrality of bioenergy use in Norway spruce stands. According to the study, maximizing the highest mean annual timber production and carbon neutrality of bioenergy use simultaneously was not possible. In general, higher carbon sequestration and carbon stock of the forest ecosystem provides higher carbon neutrality, but not higher NPV, and vice versa. In general, the net ecosystem CO_2 exchange is the highest at the younger stand age and starts to saturate after intermediate age, affecting the average carbon stock and biomass production over rotation. However, the mean annual carbon stock and carbon sequestration may be increased over a rotation by maintaining stocking higher than that currently recommended [39,41].

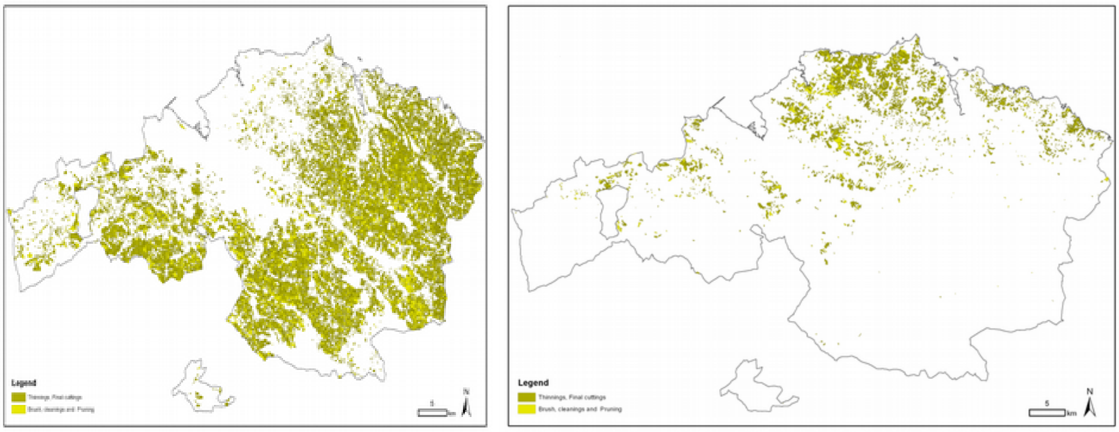
This study estimated the annual WL for bio-energy in Biscay, obtained in the forestry treatments and its geographical distribution. Data were taken from the Fourth National Forestry Inventory of the Province of Biscay (NFI4) [42].

2. Materials and Methods

2.1. Study Area

The study comprises the whole province of Biscay, one of the three provinces of the ACBC, located in the north of Spain at latitude 43″16′ N and longitude 2″56′ W (see Supplementary Material, Figure S1).

The mean annual rainfall is 1200 mm and the mean annual temperature is 12.5 °C. Frosts are infrequent and no physiological drought is apparent. Data from Fourth National Forest Inventory (NFI4 2011) depict that forest surface in this province is 131,748 ha, representing about 60% of its surface (221,232 ha). Thus, Biscay is considered the epicenter of Basque forest activity. The main forest species are *Pinus radiata* D. Don and *Eucalyptus globulus* Labill. Both are fast-growing forest species which have properly adapted to the climate conditions of the Atlantic coast of Biscay. *P. radiata* is the predominant species in this province, with 70,562 ha. This species is distributed in areas near the sea and at elevations lower than 360 m (Figure 1a). The production of timber on these plantations is primarily based on the rotational clear-cutting of even-aged stands [43]. The rapid growth and good productivity of *P. radiata* have made this species the dominant tree species in Biscay, providing 90% of timber production in this area. With 10,123 ha, *E. globulus* is an abundant species at low altitudes. Near the coast of Biscay (Figure 1b), forest managers of the province are are promoting the expansion of eucalyptus plantations to obtain biomass for the pulp and paper industry and for bioenergy.



(a) *P. radiata* (b) *E. globulus*

Figure 1. Plot map in Biscay in its different states.

2.2. Estimations of Biomass and Carbon Stock

Data from the Fourth National Forestry Inventory (NFI4) obtained in 2011 in Biscay were used in order to estimate the forest biomass fractions and the carbon sequestration (Figure 2). The NFI4 divides the province of Biscay into strata, which are defined as associations of areas with vegetation of similar characteristics. A stratum characterises the type or arboreal vegetation according to the species present in a particular zone, their states in terms of mass, and the fraction of tree cover per area [44]. Specific information concerning such strata is available at http://www.geo.euskadi.eus/mapa-forestal-del-pais-vasco-ano-2010/s69-geodir/es/. In this work we decided to select those species that fulfill two criteria: (a) high presence in the area of study, according to data obtained from the NFI-4, and (b) high potential for exploitable residue generation from the viewpoint of energy. Following both criteria, the species *P. radiata* and *E. globulus* were selected. Originally, we selected all the plots from the NFI4 whose areas were occupied by the species *P. radiata* and *E. globulus*, according to the forest map of Basque Country in 2010.

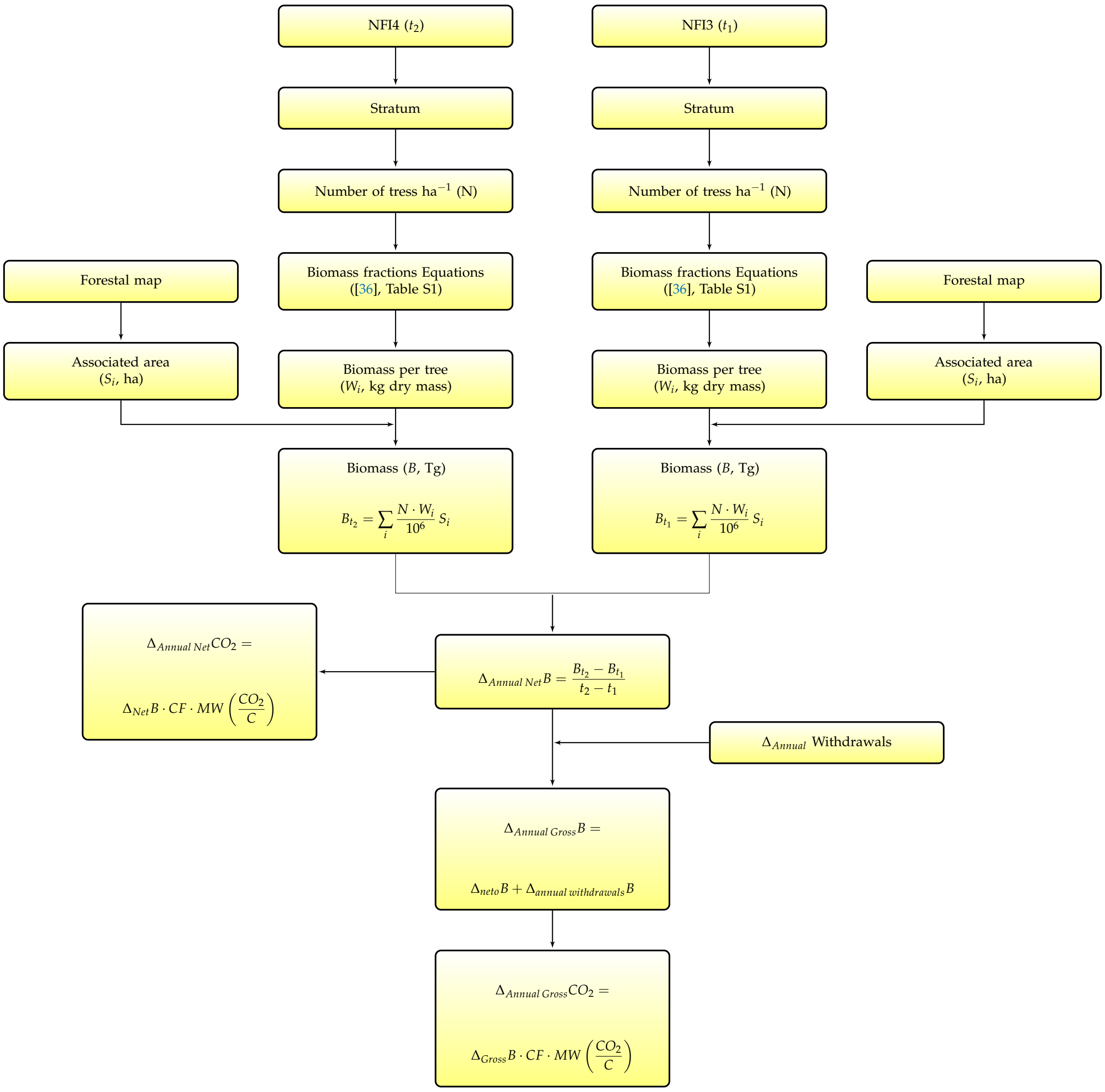


Figure 2. Schematic diagram of the method followed to determine biomass and carbon stock.

The usual methods proposed in the literature to determine the total biomass and its fractions use different independent variables such as tree diameter at breast height (DBH) measured 1.3 m above the ground; height basal area; circumference; or combinations of all of these. The general expression of these models is $W = a\,X^b$, where X is the variable which determines the dimension of the tree; W is the total biomass or the biomass of some elements (leaves, branches, etc.) expressed in kilograms (oven-dry weight); and a and b are the parameters to estimate [30,36,45,46].

After reviewing different estimation methods for forest biomass, we used allometric equations with DBH (cm) as the only explicative variable, because the DBH is the most used explanatory variable since it is very easy to measure and is related to the volume of the wood and the age of the tree [22,36,45,47–49].

In each selected plot, the biomass fractions of every *P. radiata* and *E. globulus*, W_i, tree were calculated using allometric equations by Montero et al. [36] (see Supplementary Material, Table S1). The biomass of each tree was analysed taking into account the expansion factor (EF) from the NFI4 which corresponds to that tree due to its diameter rating (see Supplementary Material, Table S2) as the plots in the NFI4 have variable radius. Consequently, a tree may or may not be measured depending on its diameter and its distance to the centre of the plot. Summing the biomass of all the analysed trees, we obtained the values of the biomass fractions, total aboveground and underground biomass in kg ha^{-1}. All the biomass data obtained are expressed on an oven-dry basis.

Total biomass was obtained using the forest map at http://www.geo.euskadi.eus/mapa-forestal-del-pais-vasco-ano-2010/s69-geodir/es/. Total biomass was converted into carbon by multiplying the oven-dry matter values by the carbon fraction (CF) of dry biomass. This value varies slightly depending on the forest species and the fractions (trunk, leaves, branches, roots, etc.) [50]. We used 51.3 for *P. radiata* [51] and 45.1 for *E. globulus* [52]. From the data about carbon stock [50], the accumulated equivalent CO_2 amounts were calculated considering the relationship of the molecular weights ($MW(C/CO_2)$). We compared the results of both 2005 (NFI3) and 2011 (NFI4) in order to calculate the annual increment of biomass and fixed CO_2. It was assumed that the loss of biomass was reduced due to extractions by cutting, without considering incidents such as pests, bacterial diseases, burnings, frosts, hailstorms, etc., which are assumed to be included in the expected rate of growth.

2.3. Estimation of Woody Litter (WL) for Bioenergy

At this stage of the study, we have not tried to estimate the total WL (non-timber) existing in the forests of Biscay, but that obtained after the forest exploitation and which shows nonexistent or very low commercial demand. Therefore, they are materials which can be considered as "final residues"—that is, residues which are no longer useful for any destiny other than their use as energy sources, and can be used for energetic applications owing to their excellent characteristics as fuel [8,12,53]. Potential residues (WL) consist of medium-sized branches (diameter range: 2–7 cm) and small branches (diameter: less than 2 cm) obtained from forest treatments. The NFI4 defines 12 strata in Biscay, among which those strata in which *P. radiata* and *E. globulus* were the main species were selected for this study. Thus, we selected those plots belonging to strata 1, 2, and 3, which have *P. radiata* as the main species; and stratum 9, with *E. globulus* as the main species (Table 1).

Table 1. Basic features of the strata from the Fourth National Forestry Inventory of the Province of Biscay (NFI4).

Stratum	Predominant Forest Species	Occupation * (%)	Mass Stage †	Forest Operation	Canopy Fraction ‡ (%)	Surface (ha)
1	*Pinus radiata*	≥70	Sawtimber, Poles	Thinning, Cutting	70–100	45,210
2	*Pinus radiata*	≥70	Sawtimber, Poles	Thinning, Cutting	5–69	5589
3	*Pinus radiata*	≥70	Saplings, Seedlings	Brush cleanings	40–100	12,382
9	*Eucalyptus* spp.	≥70; 30 < Esp. < 70	Sawtimber, Poles	Cutting	5–100	9183

* represents the percentage occupation of the predominant forest species. † represents the stage in the development of the referred species. ‡ represents the percentage of land covered by the horizontal projection of vegetation.

For estimation of the annual quantity of woody litter (Q_{WL}) in Biscay (Mg year^{-1}), two factors must be determined: (a) Forest residue per unit of surface and time derived from a forest mass (E_r, Mg ha^{-1} year^{-1}) in terms of estimation of the species and forest treatment each mass has been subjected to, and (b) the surface S_n (ha) occupied by the forest mass this residue will generate. The annual available quantities of dry biomass (expressed in Mg) are obtained as:

$$Q_{WL} = \sum_i S_i \, E_{r_i}. \tag{1}$$

The estimation of remains from WL was carried out in two different ways: stratum-by-stratum on the one hand, and all of them together on the other. In each situation, the estimation was accomplished by means of a confidence interval at a 95% level. Normality tests of the data were also carried out to determine if the values of the random variable E_r presented a normal distribution.

WL was obtained after a type of forestry management called rotation forest management (RFM) was used. This involves a sustainable forest management system in which repetitive cycles of silviculture consisting of several stages are applied, from planting or natural regeneration until felling [16]. This forestry management model is the one which is most widely used throughout the world, and is based on the intensive exploitation of rapid growth forestry species. It is done in 30-year rotations for *P. radiata* and 10-year rotations for *E. globulus* (Figure 3).

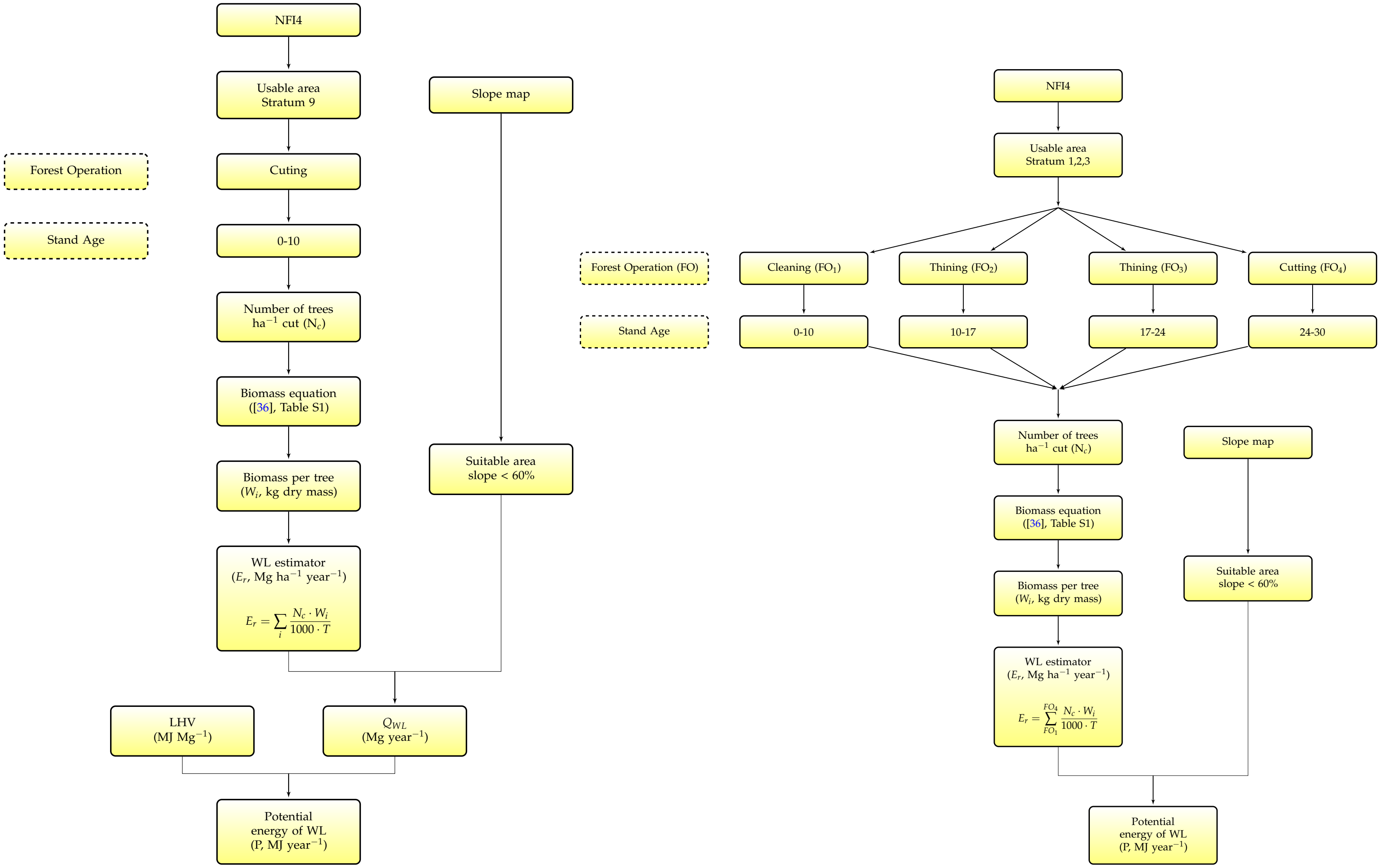
The evaluation method should consider the different phases across the complete rotation of a forest stand and the forest tasks performed in each phase [48]. In this way, and considering an adequate forest action, the WL production of a certain forest mass (Q_{WL}) can be predicted through its production cycle. Consequently, the different processes applied to stands in distinct cycles (e.g., brushings, first thinning, intermediate thinning, and regeneration fellings) generate different forest by-products.

With regard to the forestry applied in Biscay, the rotation cycle of *P. radiata* is an average of 30 years. After the final cutting, a reforestation with an initial average density of 1500 trees ha^{-1} is applied. In the tenth year, the first regeneration cutting takes place, removing 600 trees ha^{-1}. At this stage, all the usable biomass is aimed at woodchips, mainly for pulpwood or the cellulose pulp industry. The first commercial thinning takes place in the seventeenth year, removing 330 trees ha^{-1}. At this stage, 40% of the biomass is aimed at sawn wood and 60% at pulpwood or cellulose pulp. The second commercial thinning takes place in the twenty-fourth year, removing 220 trees ha^{-1}. At this stage, 20% of the usable biomass is used as woodchips for the pulpwood or cellulose pulp industry, 60% as sawn wood, and 20% as high-quality heavy timber for furniture or building. After 30 years, the last cutting takes place, removing 100% of the existing timber volume, whose products are about 15% for the pulp or cellulose industry, 20% for woodchips or sawn wood, and 65% for heavy timber destined for furniture or building. For *E. globulus*, a shift of 10 years was considered in this work. Clearing processes are not applied in the productive cycle of eucalyptus, and a one-time cut is made at rotation age (Table 2).

Table 2. Management regimens and main forestry by-products for *P. radiata* and *E. globulus*. DBH: diameter at breast height.

Forest Species	Stand Age	Forest Operation	By-Products	Equation	Source
P. radiata	10	Cleaning	Small trees DBH< 7.5 cm Branches	$e^{\frac{0.193270^2}{2}} e^{-2.61093}\ D^{2.48}$ $e^{\frac{0.615400^2}{2}} e^{-4.12515}\ D^{2.1173}$	[36]
	17	First thinning	Branches	$11.8224469\ D^{1.95}$	[37]
	24	Second thinning			
	30	Final cuttings	Branches		
E. globulus	10	Final cuttings	Branches	$0.08459716\, D^{1.7564}$	[38]

The amounts of WL that might be obtained in each stratum considering such treatments were estimated. To sum up, the indirect methodology that was selected to obtain an annual forest residue estimator (E_r; Mg ha^{-1} year^{-1}) for each species from the tree stratum, considering the forest treatment applied, consists of determining the residual biomass of each forest species. Moreover, to know how and how often this residue will be produced, the turnover of the species and its corresponding forest treatment were determined. The forest biomass residue quantities that could be obtained in each stratum were estimated from those treatments (Figure 3).



(a) *E. globulus* (b) *P. radiata*

Figure 3. Methodological diagram for determining WL estimator and potential energy of WL.

The methodology selected to estimate forestry mass waste consisted of determining the residual mass of each tree sampled in the NFI4. This methodology is appropriate for larger-size trees ($D \geq 7.5$ cm). However, when acting on smaller trees, most of the tree is unusable for timber and as a result virtually the entire tree is made up of WL. Nevertheless, in this paper, a more conservative criterion has been considered, in which waste represents 80% of the total weight.

For estimation of the amount of annual biomass Q_{WL} (Mg year^{-1}) that might be generated by current forest masses in Biscay, the methodology applied uses a GIS. In order to carry it out, the forestall species distribution vectorial information is analyzed with a spatial resolution pixel of 2 m terms of its most characteristic species. In this way, it is possible to process an important amount of data and to manage the results obtained. The area occupied by each subregion and stratum was obtained from NFI4 and the corresponding subregion map, provided that this inventory includes the pertinent areas and stratum.

Once the potential quantities were calculated, the next step was the evaluation of constraints that can limit or reduce the harvestable amounts and energy utilization of such potential quantities For both environmental and economical reasons, the collection of WL should not be carried out in areas of steep slopes. The extraction of biomass was considered only for slopes less than 60%, since, in addition to not being economically viable, steeper terrain might involve erosion and soil loss problems. The slope map had to be previously digitised for its use by GIS (http://www.mapama.gob.es/es/cartografia-y-sig/visores/). The area of Biscay with slopes less than 60% was determined according to the following procedure: (a) the zone was reclassified starting from its slope layer in the GIS, assigning the value "1" to the areas involving slopes below slopes; (b) layers of slopes below 60%, which were obtained with the GIS from the basic topographical data, were merged [44].

The estimation of remains from WL was carried out in two different ways: stratum-by-stratum, and all strata together. In each situation, the estimation was accomplished by means of a confidence interval at a 95% level for the mean residue in metric Mg per year. Normality tests of the data were also carried out to determine if the values of the random variable E_r presented a normal distribution.

2.4. Biomass Potential Energy

The energy potential represents the total amount of forest residues from the selected species that is available for energy production purposes, and may be regarded as the upper limit for the value of energy that can be obtained from this kind of residues. Once the quantity of forest residue generated by the main forest species of Biscay was calculated in the strata in which those species are predominant, the potential energy that could be achieved with those residues, considering their sustainable exploitation, was estimated. The potential energy of the residues (P) is a function of the lower heating value (LHV) times the total residue for each species considered:

$$P = \mathrm{Q}_{WL} \times \mathrm{LHV}, \quad (2)$$

where P represents potential energy (MJ year^{-1}) and LHV represents the lower heating value in humid base (MJ Mg year^{-1}) of the forest residue obtained at the same humidity level at which productivity is considered. The humidity considered in this study was 30%, being the humidity of the WL after a few days of being on the soil. For this reason, it was necessary to obtain the LHV of each fuel at this humidity level. The LHV can be calculated from the higher heating value (HHV) [54–56].

2.5. Determination of Humidity, Chemical Property of Woody Litter (WL)

Fieldwork was focused on WL sample gathering from those forest treatments of the most representative species in Biscay. A random sampling per-stratum was carried out. The samples were collected during December 2011 through March 2012. In each of the sampling areas, the samples of forest biomass collected—roughly 2 kg per sample—came from forest treatments of branches (with a varying diameter ranging between 3 cm and 1 cm). The forest residue samples used in the experiments were taken from previously-chopped bulk samples which were introduced in polyethylene bags for transport to the laboratory, since they can be sealed and thus loss of humidity can be minimized. The time needed for taking the samples to the laboratory never exceeded 10 h. Hence, the level of humidity determined in the laboratory could be considered as the humidity of the sample itself. This fieldwork consisted of gathering samples of the most representative species in different locations of the province of Biscay.

With the aim of characterizing WL from the viewpoint of energy, elemental analyses (%C, H, and N), moisture, and higher heating value (HHV) of each sample were estimated. The samples were air-dried then oven-dried (65 °C, 24 h) to a constant weight and milled (0.25 mm). Moisture levels were determined by thermogravimetric analysis in a forced air convection oven (Digitronic-TFT, Selecta, Barcelona, Spain). The concentrations of total C, H, and N were determined by means of combustion in a LECO (Corporation St. Joseph, Michigan, MI, USA) automated analyzer. An adiabatic bomb calorimeter (IKA C 5012, IKA, Staufen, Germany) was used for determination of HHV. All determinations were carried out in triplicate.

2.6. Data Analysis

Once the fieldwork was carried out by obtaining the representative samples of the main forest species in the area, and after completing the necessary laboratory analyses, the project was fed into a personal geo-database (GDB), which in turn was implemented in a GIS from version ArcGIS TM 10.2, ESRI, Inc., Redlands, CA, USA. This enabled the combined use of the different data sources needed to quantify the biomass and its potential in the target area in a reliable and easy-to-update form.

Normality tests of the data were also carried out to determine if the values of the random variable E_r (estimator of residue in Mg ha^{-1} year^{-1}) presented a normal distribution. In order to do so, five different tests that belong to the R statistical software package Nortest were used (Anderson–Darling; Kolmogorov–Smirnov; Cramer–von Mises; Pearson; and Shapiro–Francia) [57,58]. The different statistical tests were carried out using statistical software packages in R.

3. Results and Discussion

3.1. Biomass and Carbon Stock Estimates

Table 3 shows the results of the estimations of biomass and CO_2 fixing in the forests of Biscay and the annual growth considering the difference between the forest inventories NFI4 (2011) and NFI3 (2005). The stock of total forest biomass (aboveground and underground) (TB) existing in the forests of the province of Biscay in the year 2011 amounted to 14.509 Tg of dry material, which implies a sequestration of 26.462 Tg of CO_2, of which 20.217 Tg of CO_2 correspond to *P. radiata* and 6.245 Tg to *E. globulus*. The estimated total aboveground biomass in 2011 was 10.352 Tg (dry material), of which 8.335 Tg was timber aboveground biomass susceptible to commercial exploitation. The annual net growth of total forest biomass obtained, comparing the values of both inventories, was 0.404 Tg year^{-1}. This value is not the real potential of biomass which could be used, but the increment which is not extracted and which is accumulated in the mass.

In order to estimate the annual gross growth of biomass and to identify the level of extractions (exploitation rate) which is being done, it was necessary to include the amount of biomass extracted by exploitation cuttings. To obtain this, the data related to the quantity of wood cut in Biscay between 2005 and 2011 was considered, as given by the county council as it is the administrative management entity of the forests in this province (Table 4). It was assumed that the loss of biomass was reduced to the extractions by cutting, without considering incidents such as pests, bacterial diseases, burnings, frosts, hailstorms, etc., which are assumed to be included in the expected rate of growth.

Data about forest cuttings showed that the amount of wood from *E. globulus* extracted during the period 2005–2011 was 920,092 m^3, 77% of which (710,884 m^3) corresponded to private forests and only 27% (209,208 m^3) to public ones. In relation to *P. radiata*, in the same period 2,720,509 m^3 of wood were extracted, of which 81.6% (2,220,197 m^3) corresponded to the exploitation of private forests and only 18.4% (500,312 m^3) to public ones. Consequently, the average extraction of *E. globulus* was 15.15 m^3 ha^{-1} $year^{-1}$, and of *P. radiata* was 6.426 m^3 ha^{-1} $year^{-1}$. Using the basic wood density as a conversion factor, it is possible to transform this data of the timber volume of this fraction into oven-dry weight [59,60]. Then, the percentages of weight were used in each biomass fraction of the forest species to obtain the amount of biomass of the different fractions extracted by cuttings [36]. The quantity of timber biomass taken annually by cuttings was 0.266 Tg $year^{-1}$, which added to the net growth result in a timber biomass annual gross growth of 0.479 Tg $year^{-1}$ (Table 3). These values show that only 56% of the total annual growth of forest biomass was commercially exploited. The total annual gross growth of non-timber aboveground biomass was estimated as 0.124 Tg $year^{-1}$, susceptible to energetic valuation.

Table 3. Biomass fractions (Tg), annual increments (Tg $year^{-1}$), and accumulated equivalent CO_2 (Tg).

	Aboveground Biomass (AB)						Underground Biomass	Total Biomass (TB)
	Timber Biomass	Non-Timber Biomass				Total AB		
		b * > 7 cm	2 cm< b * <7 cm	b * < 2 cm	Needles			
Biomass 2005	7.059	0.313	0.674	0.484	0.184	8.714	3.370	12.084
Biomass 2011	8.335	0.360	0.751	0.579	0.327	10.352	4.157	14.509
Accumulated CO_2 (2011)	15.202	0.657	1.370	1.056	0.596	18.880	7.582	26.462
Δ_{net} annual biomass	0.213	0.008	0.013	0.016	0.024	0.273	0.131	0.404
Δ annual withdrawals	0.266	0.011	0.024	0.018	0.010	0.3306	0.159	0.489
Δ_{gross} annual biomass	0.479	0.019	0.037	0.034	0.034	0.603	0.290	0.893
Δ_{gross} annual CO_2	0.874	0.035	0.067	0.062	0.062	1.100	0.059	1.629

* b = branches.

Table 4. *P. radiata* and *E. globulus* cuttings carried out in Biscay between 2005 and 2011.

Year	*E. globulus*		*P. radiata*	
	Vpriv (m^3) *	Vpub (m^3) †	Vpriv (m^3)	Vpub (m^3)
2005	118,325	17,163	270,374	60,343
2006	96,484	26,857	39,864	120,446
2007	114,834	17,798	416,166	73,839
2008	126,992	25,143	287,474	65,079
2009	62,627	54,711	157,846	39,822
2010	83,577	31,971	345,713	71,961
2011	108,045	44,898	343,984	68,822
TOTAL	710,884	209,208	2,220,197	500,312

* Amount of timber extracted by cuttings in private forests. † Amount of timber extracted by cuttings in public forests.

3.2. Chemical and Energy Characterization

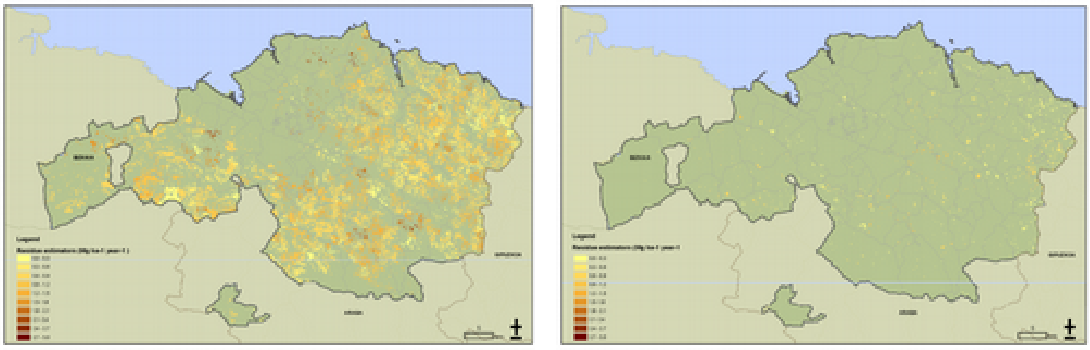
Table 5 shows the mean values obtained after the chemical and energy characterization of representative WL samples in Biscay. The results obtained show that WL had a similar composition of C in both forest species (*P. radiata* and *E. globulus*), close to 50%. With respect to N, it can be observed that *E. globulus* had a slightly higher percentage than *P. radiata*. Thus, the removal of forest residue of this species (mainly leaves) might increase the soil erosive processes, the avoidance of which would require fertilizers.

Table 5. Average values of moisture (wt. %) and heating values (MJ kg^{-1}) mass forestry of woody litter (WL). HHV: higher heating value.

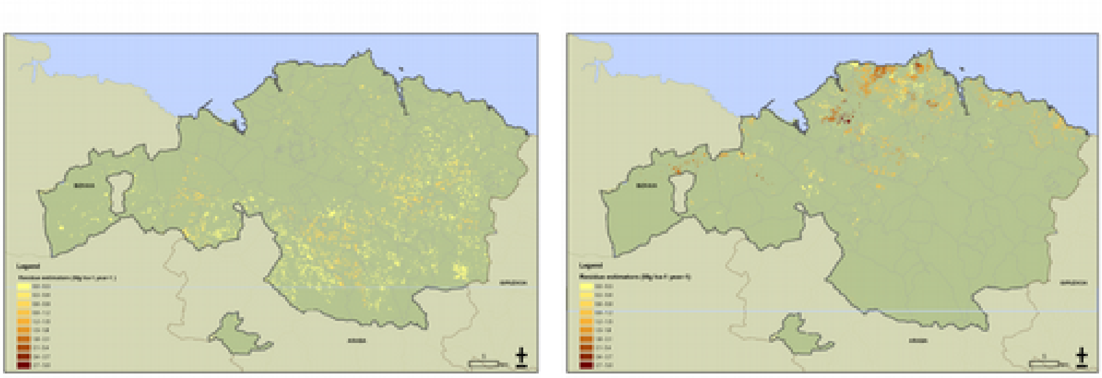
Forest Species	C (% dm)	H (% dm)	N (% dm)	Moisture (bhcut)	HHV (MJ kg^{-1})	LHV (MJ kg^{-1})
P. radiata	51.768	6.078	0.974	44.0	21.2	19.8
E. globulus	51.046	6.422	1.197	52.5	21.1	19.7

3.3. Woody Litter (WL, Mg Year^{-1}) for Stratum 1

Studying normality by means of the above-mentioned five tests, it can be observed that the random variable E_r did not follow a normal distribution. The histogram of E_r suggests a certain positive asymmetry (see Supplementary Material, Figure S2), so the following transformation was accomplished $E'_r = \log(E_r + 1)$. In this case, the transformed variable E_r passed the five normality tests perfectly well (see Supplementary Material, Table S3). The annual mean WL obtained for stratum 1, with a 95% confidence interval, was (47,483, 51,335) Mg year^{-1}. The annual WL estimator (E_r) in this stratum took values of (1.050, 1.135) Mg ha^{-1} year^{-1} (dry mass) or (1.500, 1.622) (wet mass) (Table 6 and Figure 4a). As mentioned in previous sections, a humidity of 30% was considered when the WL for energy valuation was collected.



(a) according to stratum 1 (b) according to stratum 2



(c) according to stratum 3 (d) according to stratum 9

Figure 4. Annual WL estimators (E_r, Mg ha^{-1} year^{-1}).

Table 6. Average values of residue estimator on dry basis (E_r, Mg ha^{-1} year^{-1}). Annual woody litter (WL) usable for energy production on dry mass (WL, Mg year^{-1}) and theoretical and currently available energy potential in the province of Biscay (10^6 MJ year^{-1}).

Stratum	**Forest Species**	**Area (ha)**	**E$_r$**			**Annual Woody Litter**	**Available Energy Potential**
			Minimum	**Medium**	**Maximum**		
1	*P. radiata*	45,210	1.050	1.095	1.135	49,489.3	979.888
2	*P. radiata*	5589	0.272	0.312	0.353	1746.5	34.581
3	*P. radiata*	12,382	0.283	0.359	0.436	4446.5	88.041
9	*E. globulus*	9183	0.875	0.999	1.113	9172.1	180.690
Total		72,364				64,854.4	1283.200

3.4. Woody Litter (WL, Mg Year^{-1}) for Stratum 2

In this case, it was not necessary to carry out any transformation of the data since the E_r values adjusted to a normal distribution. Particularly, three out of the five normality tests used had a *p* value greater than 0.05 (see Supplementary Material, Table S3). The annual mean WL obtained, with a 95% confidence interval, was (1520, 1972) Mg year^{-1}. The values of the annual WL estimator (E_r) took values (0.272, 0.353) Mg ha^{-1} year^{-1} (dry mass) or (0.389, 0.504) Mg ha^{-1} year^{-1} (wet mass), with 30% humidity (Table 6 and Figure 4b).

3.5. Woody Litter (WL, Mg Year^{-1}) for Stratum 3

The values of E_r for stratum 3 did not follow a normal distribution, since they did not pass any of the five tests suggested. However, using the following transformation, root x, the data presented a normal aspect and passed all of the tests with high enough significance as indicated by *p* values (see Supplementary Material, Table S3). The annual mean WL obtained in stratum 3, with a confidence interval of 95%, was (3,496, 5396) Mg year^{-1}. The annual WL estimator (E_r) in this stratum took the values (0.283, 0.436) Mg ha^{-1} year^{-1} (dry mass) or (0.404, 0.623) Mg ha^{-1} year^{-1} (wet mass) (Table 6 and Figure 4c).

3.6. Woody Litter (WL, Mg Year^{-1}) for Stratum 9

The E_r values in stratum 9 followed a normal distribution, since they passed four out of the five tests with high enough significance ($p > 0.1$; see Supplementary Material, Table S3). The 95% confidence interval obtained for the annual mean WL was (8039, 10,305) Mg year^{-1}. Figure 4d shows the annual WL estimator (E_r) values obtained from mean values (0.875, 1.113) Mg ha^{-1} year^{-1} (dry mass), or 1.250–1.590 (wet mass) (Table 6 and Figure 4d).

3.7. Woody Litter (WL, Mg Year^{-1}) in Biscay Considering All Strata

When estimating the total residue considering all strata (1, 2, 3, 9) together, global data did not follow a normal distribution, but if data was transformed by means of $\log(x+1)$, the *p* values obtained in the normality tests had a high enough significance (see Supplementary Material, Table S3). The estimation per 95% confidence interval for all the stratum together was (63,780, 69,542) Mg year^{-1}. Table 6 lists the amount of WL for each stratum usable for energy production and current energy potential in the province of Biscay. The results obtained after the statistical analyses of the data showed that the amount of mean forest biomass residue achieved with a 95% confidence interval was 64,854.4 Mg year^{-1}, from which 55,682.3 Mg ha^{-1} corresponded to *P. radiata* residue and 9172.1 Mg ha^{-1} to *E. globulus*. This means a potential energy supply of 1283.2 million MJ per year.

In this study, leaves and needles were excluded from the consideration of the energetic exploitation of WL. They are left on the ground, as they accumulate a high quantity of essential nutrients (N, P, K, Ca, and Mg) [37]. For this reason, and due to their lower calorific power in relation to the rest of the forest residue, leaves should not be extracted together with the rest of the forest biomass for its energetic use [20].

4. Conclusions

The main conclusions obtained in this work can be summarized as follows:

- *P. radiata* is still the main species in Biscay, although its extension has slightly fallen from 72,674 ha in 2005 to 70,562 ha in 2011 as a consequence of the drop in the demand of wood, the fall in prices, and cuttings caused by the economic crisis in this region, especially during 2008–2009 (Table 4). Thus, there has been an increase in the extension of plantings of overripe *P. radiata* of high height [61]. This led to an increase of 21% in this species' stock from 2005 to 2011, implying an annual growth of BT of 6.16 Mg ha^{-1} year^{-1}. In terms of the stock of C, it implies an annual growth of 3.01 Mg ha^{-1} year^{-1}.

E. globulus showed an increment of 12% in its stock from 1.134 Tg of BT (121.46 Mg ha^{-1}) to 1.269 Tg of BT (125.40 Mg ha^{-1}) in 2011, which represents an annual growth of BT of 0.63 Mg ha^{-1} year^{-1} in 2011. In relation to the stock of C, it represents an annual growth of just 0.328 Mg ha^{-1} year^{-1}. Overall, the total stock of carbon in these two species was 156.62 Mg ha^{-1}, but it could be increased by applying forest management practices such as increasing the age of rotation and/or decreasing the intensity of cuttings [22]. In relation to the Q_{WL} susceptible to energetic valuation, obtained after the forest treatments in the species *P. radiata* and *E. globulus* (Table 6) of 64,854.4 Mg year^{-1}, this quantity represents about 72% of the annual growth obtained from non-timber without leaves biomass and the 52% of that increment including the leaves (Table 3).

- *P. radiata* is mainly concentrated in stratum 1 in Biscay, where about 50,000 Mg year^{-1} residual biomass is annually obtained, which represents around 80% of the total forest residues, whereas in stratum 9, 9200 Mg year^{-1}1 are obtained, which represents almost the total amount of residual biomass from *E. globulus*. The estimated mean values of E_r generated every year from this forest species in this stratum were (1.50, 1.62) Mg $\text{ha}^{-1}\text{year}^{-1}$ (wet mass). These figures represent an amount of (0.84, 0.91) Mg $\text{ha}^{-1}\text{year}^{-1}$ (dry mass) biomass residue. The estimated values are similar to those obtained in previous studies carried out in other regions of Spain (e.g., Dominguez [62]).
- *E. globulus* is mainly located in areas near the coast (see Supplementary Material, Figure S1b). These correspond to stratum 9 in Biscay. The estimated annual mean value of forest residue in the area was (1.03, 1.32) Mg $\text{ha}^{-1}\text{year}^{-1}$ (wet mass) or (0.72, 0.92) Mg $\text{ha}^{-1}\text{year}^{-1}$ (dry mass). Similar studies were carried out in other areas of Spain (e.g., Zabalo [20]).

The essential and traditional aim of forest management in the Basque Country has been to maximize the economic profits without risking the persistence of the mass. It is certain that carbon sequestration by forest masses has only recently been considered as another aim of management to be developed together with the economic factor. Former studies have shown that thinning intensification significantly increases the quantity of total biomass obtained (timber and residue biomass). However, this type of management can reduce carbon sequestration in forests [4]. For this reason, in this research an average forest management which optimizes economic (quantity of timber biomass) and environmental (CO_2 sequestration) factors has been assumed.

Supplementary Materials: Supplementary materials are available online at http://www.mdpi.com/1999-4907/9/5/253/s1. Figure S1: The target study area: province of Biscay (Spain). Table S1: Equations of forest biomass fractions expressed in kg (oven-dry-weight, (102 ± 2 °C, 24 h)), coefficient of determination (R^2), and standard error of estimate (SEE). Table S2: Expansion factors (EFs) in plots from NFI4. Figure S2: Histograms of the values of E_r. Table S3: Normality test (p values) of the values of E_r.

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