forests

Article

Assessment of Biomass Energy Potential and Forest Carbon Stocks in Biscay (Spain)

Esperanza Mateos [1,*], Florencio Garrido [2] and Leyre Ormaetxea [3]

[1] Department of Chemical and Environmental Engineering, University of the Basque Country UPV/EHU, Rafael Moreno 'Pitxitxi', n 3. 48013 Bilbao, Spain
[2] Department of Applied Mathematics, University of the Basque Country UPV/EHU, Rafael Moreno 'Pitxitxi', n 3. 48013 Bilbao, Spain; florencio.garrido@ehu.eus
[3] Department of Mathematics, Faculty of Science and Technology, University of the Basque Country UPV/EHU, Barrio Sarriena s/n, 48940 Leioa, Spain; leyre.ormaetxea@ehu.eus
* Correspondence: esperanza.mateos@ehu.eus; Tel.: +34-94-6014343; Fax: +34-94-6014300

Academic Editors: Michael Battaglia and Timothy A. Martin
Received: 25 November 2015; Accepted: 16 March 2016; Published: 29 March 2016

Abstract: The aim of this research is to identify, quantify and characterize the potential available forest biomass of *Pinus radiata* D. Don and *Eucalyptus globulus* Labill. across Biscay province in northern Spain. In order to do this, we have used information from the National Inventories of Spain to quantify the amount of carbon dioxide accumulated in the forests of Biscay by means of stratum-species-based forestry statistics. The total biomass and biomass fractions have been estimated using two different methods: allometric biomass equations (ABE) and biomass expansion factors (BEF). The second objective is to develop a methodology to quantify and produce a cartography of the prospective energy production of residual biomass from the most representative forest species of Biscay. For this purpose, we have used a Geographic Information System (GIS) computer tool. We have found that the stock of carbon accumulated in the main forest species in Biscay in 2014 amounts to 8.2 Tg (ABE) and 6.63 Tg (BEF) equivalent to 30 and 24.3 Tg of CO_2, respectively. The quantity of forestry biomass residue (FBR) obtained has been estimated as 52,214 $Mg \cdot year^{-1}$ dry matter. This amount means a prospective energy supply of 947,000 $GJ \cdot year^{-1}$.

Keywords: allometric equations; biomass expansion factors; carbon storage; forest residue

---

1. Introduction

Plant debris represents the most plentiful type of biomass on our planet. Some 10^{11} tons are produced annually in the biosphere with an energy content of about 2425×10^{18} kJ [1]. For centuries, until just before the industrial revolution, biomass was the most important energy source, and even today, it is the most widely-used fuel in underdeveloped countries. The use of biomass for energy production has created a great deal of interest recently, which is due partly 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. In Spain, the goal of the new Programme of Renewable Energies 2011–2020 [2] is to ensure that 20% of the final energy consumption in 2020 comes from renewable energies, among which forest biomass stands out. In the Autonomous Community of the Basque Country (ACBC), biomass is currently the most widely-used source of renewable energy. For example, the contribution of renewable energies to the final energy consumption of the Basque Country is 6.8%. Of this amount, 85% is biomass. According to the aims set out in the Basque government's strategy 3E-2020 [3], by 2020, 14% of the energy consumed will be based on the use of renewable sources, which include forest biomass. The use of biomass as an energy source entails a reduction in the emissions of CO_2, as it is native and renewable and is also neutral with regard to greenhouse gas emissions. The combustion of biomass releases the same amount of carbon dioxide as it absorbs in its growth. On the other hand, fossil fuels produce excess CO_2. Forest ecosystems represent one of the largest carbon reserves and sinks. It can be stated that the forests of the ACBC comply satisfactorily with their carbon sink function. The Basque Plan for the Fight against Climate Change 2008–2012 states that the forest and farming land of Biscay operated in the form of sinks in 2005 amounted to 0.6 million Mg and 297 million Mg of CO_2, respectively, while pastures and population centers constituted a source of emissions of 0.18 million Mg of CO_2 in total [4].

The energy valuation of biomass also provides other additional advantages, such as the generation of employment in rural areas and the maintenance and organization of woodlands. As a consequence, it provides ecological benefits and reduces fire hazards. The suitable exploitation of biomass may help keep and strengthen the accumulation of carbon and, at the same time, improve the forest economy [5]. One of the basic goals of forest research is the need to foresee the growth and production of woodlands and also their response to forestry actions.

Several researchers have found that the cultivation of trees in order to sequester carbon could provide a reduction in net emissions at a relatively low cost in some countries [6–8], as they may contribute to reducing 30% of the emissions of CO_2 caused by the human factor [9]. Models of growth and production are a very valuable tool for foresters and forest managers in this regard, since these would help them predict the further development of trees. These models are based on the fact that carbon forms part of the composition of the structure of all vegetation, not only in the aboveground biomass (timber, branches and leaves), but also in the underground biomass (roots). On the other hand, in the context of the Kyoto Protocol, those stored in specific ecosystems as a consequence of the different activities in the field of land use, land use change and forestry (LULUCF) are accepted as carbon sinks. This has led to a growing interest, at the international level, in securing the sustainable management of the forest and thus compensating the emissions of carbon [10–12] at a relatively low cost.

Of the main organic carbon sinks existing in terrestrial ecosystems, the organic matter in soil symbolizes the steadiest stock of carbon, with a higher residence time than the one that exists in forest biomass [13]. Even so, the accumulation of carbon in trees plays a very important role, because of the speed with which this is accumulated. Carbon sequestration has advantages with regard to its sale compared to other environmental services, such as biodiversity conservation. The reason for this is that it is easier to measure the increase and decrease in carbon storage, thereby making commercialization easier. In the same way, the estimated costs of carbon sequestration by forestry suggest that this is much less expensive than most of the other methods used to mitigate climate change. The removal and storage of excess carbon from the atmosphere in the forests is considered to be a way of mitigating global climate change [14]. Hence, the accurate estimation of biomass and the stored and sequestered carbon in the forests has acquired relevance as a result of the United Nations Framework Convention on Climate Change and the Kyoto Protocol [15].

Over recent years, several research projects on carbon estimations in forest systems have been undertaken at a global [16], national [17–19] or regional level [20–22] using data from forest inventories and models of carbon fluxes in a number of different countries. Many of these authors coincide in the weak points of the present estimations. Due to the lack of specific data in the study area, these estimations are often made using generic values of the biomass and carbon amount or equations to determine the biomass and the carbon in a specific forest ecosystem. Reducing the uncertainty in the estimations and carrying them out with a higher degree of accuracy requires specific tools to quantify the amount of carbon accumulated in the forests and the use of internationally-accepted methodologies. The estimation of the carbon stored in the forests must match the demands of the UNFCCC (United Nations Framework Convention on Climate), which allows a comparison to be made of the results obtained in a range of research papers.

The most useful means to estimate the aboveground forest biomass are the values obtained by the National Forestry Inventories. This is due to the fact that the data are usually taken with the understanding that the suitable level and the sampling method used to obtain these are statistically well designed. These forest inventories are the most suitable sources of information in order to compare the amount of forest biomass over a period of time. That is why they are sources of information used to obtain the estimations of carbon reserves and fluxes in tree biomass, as tree biomass can be changed into quantities of carbon by means of conversion factors [17].

The research undertaken in this article aims to obtain a better estimation of the sequestration of CO_2 in the forests of Biscay (Spain) using the data of the National Forestry Inventories, NFI2 [23] and NFI3 [24].

Following an examination of the estimation methodologies of forest biomass, the indirect model has been selected for this study, since it provides similar results to those obtained by the direct methods of shoringand weighing of tree fractions, and unlike these, it is a non-destructive methodology [25–27]. To that end, a quantification of tree biomass was carried out in an indirect manner using allometric equations to estimate the amount of biomass per tree and biomass expansion factors (BEF) considering a set percentage of produced biomass [28].

The value of the amount of biomass has allowed us to calculate the accumulated carbon by means of the percentage of carbon and its conversion to CO_2. By comparing the data from the inventories NFI2 and NFI3, we have estimated the annual growth of CO_2 sequestration according to both methodologies. The calculation methodology proposed comes within the framework of the prescribed guidelines and orientations on good praxis of the Intergovernmental Panel on Climate Change [1].

Secondly, this research set out to determine the amount of residual forest biomass for its energy valuation and to map the results by means of Geographic Information Systems (GIS). For the energy valuation of the biomass, the desirable result is not the existence of biomass, but the amount of annual exploitation, which in general comes from wood exploitation or from forest management. For this reason, the method used to evaluate the residues must take into account the different stages through which the complete rotation of trees and forestry mass generated at each stage developed.

2. Description of the Area of Study

2.1. Description of the Area of Study

This study was carried out in the province of Biscay, located in the north of Spain. The study covers the entire province of Biscay, located in the north of Spain (43°46′–42°42′ N, 03°45′–02°40′ W) (Figure 1). The geography of this area is basically steep and mountainous. It is crossed by deep valleys, which descend towards the sea from the mountains near the coast, and due to this fact, the slopes down which water flows to the sea are steep. It has a mesothermal, warm and wet climate, without a dry season or Atlantic climate. This oceanic climate is affected by the nearness to the sea and the orography of the area and has a considerable effect on the spread of Atlantic forest species, mainly pine trees. The area is characterized by its high rainfall, and the annual average rainfall is about 1200 mm. The monthly average temperature fluctuates between 11 °C in January and 23 °C in August.

According to the Third National Forestry Inventory [24], the present forest area in Biscay is 130,780 ha, approximately 60% of the area of this province (221,232 ha), with about 100,000 ha of planted area with eucalyptus and conifer (75% of total trees planted). The vast majority of the forestry plantations are on slopes with gradients of over 7%. Almost 50% of the plantations have gradients of between 30% and 50%. The main forestry mass of Biscay, considering the area it occupies, pertains to plantations of *Pinus radiata* D. Don (72,674 ha), *Quercus robur* L. (13,270 ha) and *Eucalyptus globulus* Labill. (10,120 ha). In this study, the mass of *Quercus robur* L. has not been considered as a potential source of residual biomass, in spite of the extent of its dispersion, due to the high market value acquired by products obtained from pruning.

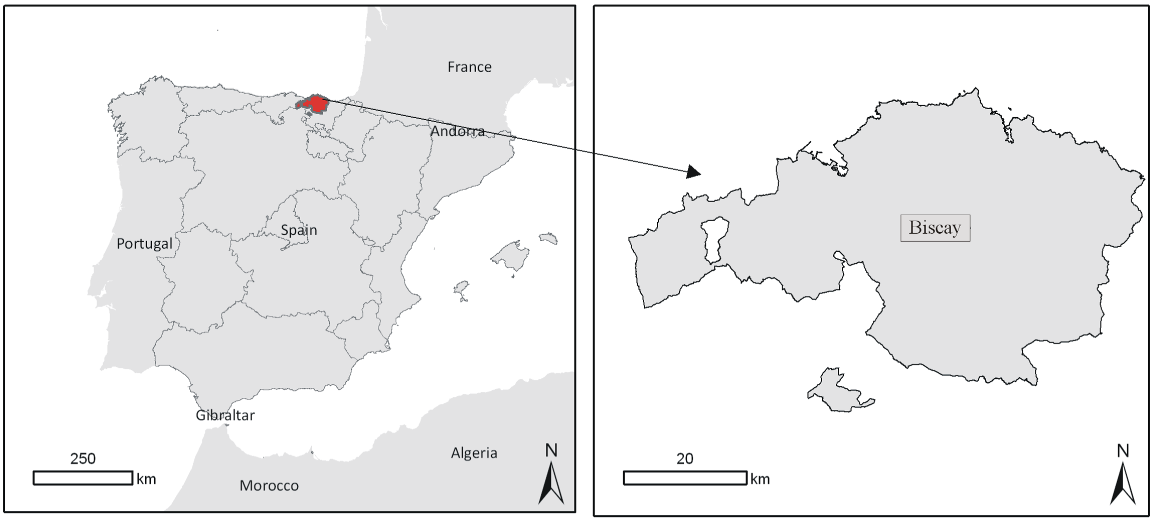

Figure 1. Territory of Biscay in Spain.

2.2. An Estimation of Forest Biomass

As stated in the previous section, the estimation of forest biomass has been undertaken using indirect methods by means of two different processes: allometric biomass equations (ABE) and biomass expansion factors (BEF). The ABE methodology is a procedure for estimating forest biomass using allometric regression equations. In them, we can use different independent variables, such as basal area, height and tree diameter at breast height (DBH), among others. We have used allometric equations with DBH as the only explicative variable, because this parameter is the one most commonly used, due to its ease of use and precision for calculating [21]. The method develops a well-known equation, which has the following analytical form:

$$W = a \times X^b \tag{1}$$

where W represents the total aboveground biomass (expressed in kg dry mass); X (cm) is the diameter at breast height (DBH), typically measured at 1.3 m of trees on the sample plots above a minimum diameter (7.5 cm); and a and b are the two specific regression parameters. The final result should be multiplied by a correction factor, obtained from the standard deviation of the estimation, in order to eliminate the bias introduced by potential transformation [29].

Biomass is estimated using appropriate allometric equations applied to the tree measurements. Previous research shows the suitability of this sort of equation in the forests of Biscay [30], having been used by several researchers to achieve suitable accuracies [17,26,31–36]. After testing different equations, those in [17] were chosen for the selected forest species (*P. radiata* and *E. globulus*), since these models have the lowest variation coefficients with respect to the data of the forestry mass in Biscay gathered in the National Forestry Inventory [24].

We have calculated the normal diameter (D_n) by species and stratum using the values of the mean basal area, which appears in The Spanish National Forest. The allometric equations used for the individual trees allowthe biomass to be calculated by species and stratum (kg·tree^{-1}). This value was then multiplied by the number of trees in that stratum to obtain the total biomass. It was later used to calculate the biomass per hectare in Biscay. Provided this inventory includes the pertinent areas and strata, the area by stratum belonging to the pre-defined region was simply selected within the ArcMap application. This led to the straightforward classification of these areas according to stratum and region, eliminating Stratum 0, which corresponded to non-forested areas (rivers, towns, roads, *etc.*).

The BEF methodology, based on the commercial volume of the trees, is an alternative method for estimating the biomass of forests. The BEF method is based on factors developed at the stand level and cannot be used for estimating the biomass of individual trees. We used the BEF proposed for Spain by Ibañez *et al*. [37], which are shown in Table 1. As with the ABE method, the diameter of all trees on the sample plots above a minimum diameter (7.5 cm) is measured. The volume of the commercial component of each tree ($\text{m}^3 \cdot \text{tree}^{-1}$) is then estimated based on locally-derived equations. BEF methods apply a single BEF ($\text{Mg} \cdot \text{m}^{-3}$) to convert commercial volume (m^3) into aboveground biomass (Mg). The biomass is then added for all trees in a stand and expressed as biomass per unit area ($\text{Mg} \cdot \text{ha}^{-1}$). Eventually, the area occupied by each region and stratum was obtained from the Forest Inventories and the corresponding map within the ArcMap application.

Table 1. Source of the applied allometric equations for calculating aboveground tree biomass (kg) source [17] and biomass expansion factors (BEF) ($\text{Mg} \cdot \text{m}^{-3}$) [37].

Species	**Equations**	**BEF**
P. radiata	$W = e^{\frac{0.193270^2}{2}} e^{-2.61093} D_n^{2.48739}$	0.44
E. globulus	$W = e^{\frac{0.157850^2}{2}} e^{-1.33002} D_n^{2.19404}$	0.81

The wood densities were obtained from the forests located in the north of the Iberian Peninsula [38]. The expansion factors of biomass were obtained from the studied region [37]. These values have been validated intentionally by the Action Cost E21, as it refers specifically to the forest species of the Spanish territory. The expansion factor values of the roots, obtained from the data given by [17], allows us to calculate underground biomass.

2.3. Annual Biomass Increment

The annual growth of biomass has been estimated in two different ways. The first one is the introduction of diametrical growth in the models. The second one is the comparison of inventories NFI3 and NFI2. Expression Equation 2 yields the annual biomass increment (ΔW_i) in kg year^{-1}, D_n being the normal diameter in cm and ΔI_n the annual increment in the diameter (also expressed in $\text{cm} \cdot \text{year}^{-1}$).

$$\Delta W_i = f(D_n + \Delta I_n) - f(D_n) \tag{2}$$

The normal diameter for each species and stratum was calculated using data available in Table 301 of NFI3. Calculations in such increments for *P. radiata* and *E. globulus* were done using an Excel spreadsheet program. An extrapolation of the data obtained allows us to obtain the estimation of the annual biomass increment in $\text{Mg} \cdot \text{tree}^{-1}$ for each forest species and stratum. Finally, the combination of those annual biomass increments with the forestry density ($\text{trees} \cdot \text{ha}^{-1}$), available at the IFN3 of the province of Biscay, yielded the biomass estimated in $\text{Mg} \cdot \text{ha}^{-1}$. The information corresponding to the province of Biscay, contained in the National Inventories, was used to determine the area (ha) occupied by the stratum that will generate that biomass with the support of the GIS. The results of the biomass of *P. radiata* fractions are listed in Table 2.

The weight of biomass of each fraction for 2006, the date of the NFI3, was obtained from the data of the number of trees of each species and the diametrical class given by the Forestry Inventory and the models of biomass estimation. The annual growth in biomass helps us to obtain the biomass stock for 2014.

Table 2. Annual increments of aboveground (AB), underground (UB) and fractions of biomass expressed in kg tree^{-1} year^{-1} for *P. radiata* and diametric class (DC).

DC (cm)	Branches < 2 cm	Branches 2–7 cm	Branches > 7 cm	Needles	AB	UB
10	2.02	0.77	0.00	0.79	6.76	2.75
15	4.13	1.06	0.58	1.81	11.04	3.83
20	6.84	1.28	1.65	3.28	15.12	4.68
25	10.13	1.48	3.72	5.18	19.19	5.42
30	13.96	1.69	7.23	7.54	23.78	6.24
35	18.31	1.98	12.69	10.36	29.81	7.34
40	23.16	2.22	20.66	13.64	35.39	8.24
45	28.49	2.41	31.74	17.38	40.46	8.98
50	34.29	2.77	46.62	21.59	48.82	10.37
55	40.55	3.23	66.01	26.26	59.33	12.10
60	47.25	4.01	90.68	31.42	76.50	15.05
65	54.39	4.74	121.44	37.04	93.70	17.82
70	61.97	3.93	159.14	43.14	80.33	14.83

2.4. Carbon and CO_2 Stock Determination

In order to estimate the carbon stock stored in the forests, only the carbon stored in the main forest species is taken into account, as previous research reveals that carbon stored in the undergrowth herbaceous strata and the dead organic matter is much lower than the tree biomass [22,39]. There are different devices to calculate the carbon stored in the Spanish forestry systems [40]. In this research, the carbon stock and the variations in this stock were calculated using the carbon reserves variation method, described by the Intergovernmental Panel on Climate Change, and on the orientations on good praxis in the change in the use of the ground and forest area [1].

According to this method, all of the biomass data obtained in field measurements must be expressed on an oven-dry basis. It must also be converted to carbon by means of multiplying the oven-dry matter values by the carbon fraction of dry biomass (CF).

Several studies indicate that the carbon percentage in wood is similar in all tree species, as well as in the same tree in its diverse elements (trunk, branches, leaves, *etc.*) [17]. In this research, the following values have been used for the CF: 0.50 for *P. radiata* [41] and 0.4735 for *E. globulus* [37]. The weight of the equivalent CO_2 is obtained multiplying the quantity of carbon by 3.67, which is the proportion between the molecular weight of CO_2 and the carbon atomic weight.

2.5. Estimation of Residual Forest Biomass for Energy Use

The methodology used to determine the annual amount of residual forest biomass (RFB) in Biscay, expressed in Mg ha^{-1} of dry weight, involves determining two factors:

1. The forestry residue per unit of surface and time, which comes from a forestry mass (Mg ha^{-1} year^{-1}), an area in a forest where a treatment is performed, according to the species and the forestry treatment to which each mass has been subjected.
2. The area (ha) taken by the forestry mass that is going to produce this residue.

In this research, we have not attempted to estimate the total non-wood biomass existing in the forest, but that biomass obtained after the forest exploitation and that has little or no commercial use. Therefore, this mass may be considered the "final residue", that is to say, the residue that can only be used as an energy source and that can be used for energy uses due to its beneficial characteristics as a fuel [42–44]. The most widespread forestry model in Biscay is based on the intensive exploitation of fast-growing forestry species. In this research, it has been considered that forestry treatment occurs every 10 years (Table 3).

Table 3. Forest biomass-generating silvicultural operations.

Forest species	Stand age (years)	Forest operation	Biomass residues
P. radiata	0–10	Brush cleanings	Small diameter trees DBH $<$ 7 cm (the whole trees are used as energy sources) Small branches and shrubs
	10–20	Thinnings	Tops, branches and leaves
	20–30	Final cuttings	Tops and branches
E. globulus	10	Final cuttings	Tops and branches

The residual biomass has been estimated from the information obtained from the Forestry Inventory [24], which provides quantitative data about the wooded area, describing it by strata or homogeneous areas of timberline. The strata are defined and classified according to species, state of the mass of the principal species and canopy cover fraction (CCF (%)). The last concept represents the percentage of land covered by the horizontal projection of vegetation. In Biscay, the NFI3 states 12 strata (Table 4).

Table 4. Basic features of the strata from the National Forestry Inventory, NFI3, of Biscay. CCF, canopy cover fraction.

Stratum	Dominant Forest Grouping	Mass State	CCF (%)
1	*P. radiata*	Sawtimber, poles	$\geq$70
2	*P. radiata*	Sawtimber, poles	5–69
3	*P. radiata*	Saplings, seedlings	40–100
4	*P. radiata* and *P. nigra* with *Q. robur, C. sativa* and Brook trees	Saplings, seedlings	5–39
5	*Lawsoniana Chamaecyparis Pseudotsuga menziesii* and *Larix* spp.	All	5–100
6	*Pinus pinaster* and *Pinus nigra*	Sawtimber, poles	5–100
7	*Q. robur* and *Q. robur* with *Casativa, C. nut, A. unedo* or with *P. radiata*	All	5–100
8	*Q. ilex* and *Q. ilex* with *Quercus faginea*, *Arbutus unedo* or with *Q. robur*	All	5–100
9	*Eucalyptus* spp.	Sawtimber, poles	5–100
10	*Eucalyptus* spp. and *Eucalyptus* spp. with *P. radiata*	Saplings, seedlings	5–100
11	*F. sylvatica*, *F. sylvatica* with *Betula* spp., *Castanea sativa* with *Q. robur*	All	5–100
12	Brook trees	All	5–100

Once the forestry masses had been classified by strata, the forestry treatments, which must be undertaken in each stratum for 10 years, were identified. To do this, previous studies performed by the Regional Government of Castilla y León, 1989, were considered. For each sampled and documented tree in the parcels inventoried in the NFI3 in Biscay, the residual forest biomass Er ($\mathrm{Mg{\cdot}ha^{-1}{\cdot}year^{-1}}$) of *P. radiata* and *E. globulus*, which was obtained after the forestry treatments in the strata where both species are predominant, was estimated. Strata 1, 2 and 3, in which *P. radiata* appears as the predominant species, were selected. As far as *E. globulus* is concerned, Stratum 9, whose mass state (sawtimber, poles) advises a final clearing or cut, was selected. The state of eucalyptus masses in Stratum 10 (saplings, seedlings) does not currently add, in a meaningful way, any residual biomass. This residue was determined by using allometric equations (Table 5).

Table 5. Estimating equations of residual forest biomass.

Species	F.operation	Equations	References
P. radiata	Brush, cleanings	$W_{PME} = e^{0.193270^2} D_n^{273489}$	[17]
	Thinnings and final cuttings	$\ln \mathrm{W_{PMA}} = -2.47 + 1.95 \ln \mathrm{D_n}$	[14]
E. globulus	Final cuttings	$W = 0.1785 D_n^{1.7564} / 2.110$	[34]

Figure 2 shows the investigation method used in this project, which is based on the method proposed by [45] and [27].

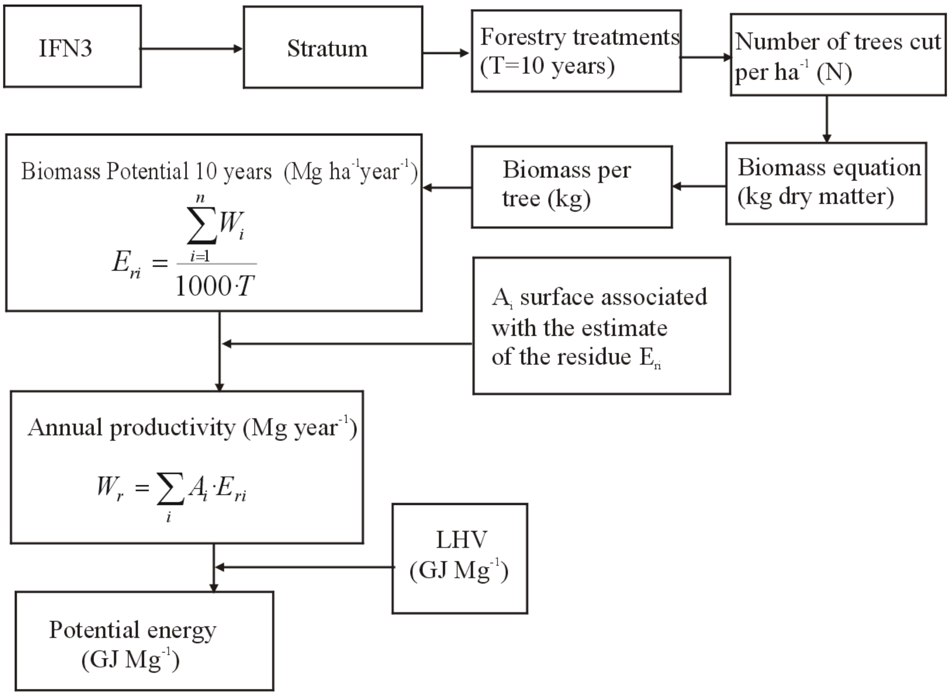

Figure 2. Schematic diagram of the method followed to determine the biomass energy.

According to this methodology, the amount of annual forest biomass residue W_r (Mg·ha^{-1}) capable of being used for energy purposes has been estimated by the use of the area of the resulting sites and the estimators of woodland residue:

$$W_r = \sum_i A_i E_{ri} \tag{3}$$

Once the estimator of forest residue (E_{ri}) had been estimated (Mg·ha^{-1}·year^{-1}), the following step consisted of determining the surface from the NFI3 to which each estimator of residue obtained can be applied. As the data used are sampling data, the value of the estimator is unknown at any point other than the sampling plot. To overcome this, Thiessen's polygons from the sampling points were used in order to allocate the value of the residue estimator to an influential area of the tree stratum. According to several authors [27,45], this way of allocating values to the residue estimator to the rest of the non-sampled surface is the most adequate.

Geographic Information Systems (GIS) are useful tools for understanding the geographic context of a wide range of issues pertinent to bioenergy, especially energy demand and biomass supplies. The program package ArcInfo v.10 was used in the present study. ArcInfo tools are structured in three applications whose combined use allows access to all of the package's functionality: ArcMap, ArcCatalog and ArcToolbox.

2.6. Energy Potential Derived from Residual Biomass

Firstly, we calculate the quantity of forest residue generated by the main forest species of Biscay. We do this in the strata in which those species are predominant. After this has been done, the potential energy that could be achieved with those residues is estimated, taking into account their sustainable exploitation. The potential energy of the residues P is a function of the lower heating value (LHV). The LHV was calculated using the higher heating value (HHV) on a dry basis, *i.e.*, 0% moisture content obtained experimentally in the laboratory. Being a solid lignocellulosic biofuel, the methodology proposed by Marcos [46] was used. The available potential energy was calculated combining the results of the calorific value with the amount of residual biomass generated by the forestry exploitation.

$$P = \sum_i A_i \, E_{ri} \, \text{LHV} \tag{4}$$

where P represents the potential energy (GJ·year^{-1}) and LHV the lower heating value (GJ·Mg^{-1}).

3. Results and Discussion

3.1. Biomass and Carbon Stock Estimates

Table 6 shows the results of biomass calculations in 2006 (NFI3) and 2014 and the annual increment of aboveground, underground and total biomass according to the allometric biomass equations (ABE) and biomass expansion factors (BEF).

Table 6. Aboveground biomass (Tg), total biomass and accumulated equivalent CO_2 (Tg) in Biscay.

	Allometric Biomass Equations			**Biomass Expansion factors**		
	Total aboveground biomass	**Total biomass**	**Total CO_2**	**Total aboveground biomass**	**Total biomass**	**Total CO_2**
2006	9.004	12.504	22.807	10.642	13.790	25.154
Annual growth	0.319	0.498	0.908	0.088	0.121	0.195
2014	11.553	16.488	30.074	11.343	14.754	26.712

The aboveground biomass calculated by allometric equations was smaller in 2006 than that calculated by BEF, but the annual increment obtained was higher using the equation method than that of BEF (Table 6). The studies undertaken by different researchers are contradictory, e.g., Gil *et al.* for example [21] and Jalkanen *et al.* [47] estimate a higher amount of biomass by using equations. On the contrary, other researchers, such as [48], obtained higher values of aboveground biomass using BEF than those estimated by equations. According to several researchers [1,17,21], the use of allometric equations is a more accurate method of estimation compared to BEF. This is due to the fact that those equations have been validated by means of representative samples of each tree species in parcels sharing similar characteristics to the study area. We agree with this argument and estimate, therefore, that the total biomass amount existing in Biscay that comes from *P. radiata* and *E. globulus* in 2014 is 16.488 Tg of dry matter, representing a stock of 30.074 Tg of CO_2. Using the equation method, the biomass of the different parts of the tree (timber, branches of different size, leaves, *etc.*) was estimated. To do that, the equations in [17] were used for the two main species in Biscay (*P. radiata* and *E. globulus*). The results are shown in Table 7.

The amount of timber biomass estimated in 2014 is 9.658 Tg d.m., which represents about 84% of the estimated aboveground biomass 11.553 Tg of dry matter. Consequently, the final result of non-timber aboveground is 1.896 Tg.

Taking into account that a forestry treatment is undertaken every 10 years and that the sustainable management of the forest is about 50% of the non-timber biomass, this would mean that 0.948 Tg of forestry residue could be exploited as an energy source.

It has been estimated that the total biomass stored in Biscay's forests due to the main species amounts to 16.488 Tg of dry matter, which involves a sequestration of about 30 Tg of CO_2 with an annual growth of 2.2 Tg·year^{-1} (see Section 2.4).

Table 7. Estimating biomass (Tg d.m.), Δ annual biomass (Tg d.m. year^{-1}), Δ annual withdrawals (Tg d.m. year^{-1}) and CO_2 stock (Tg) of *P.radiata* and *E. globulus*.

	Timber Biomass	Non-Timber Biomass	Aboveground Biomass	Underground Biomass	Total Biomass
Biomass (2006)	7.519	1.485	9.004	3.500	12.504
Δ annual biomass	0.648	0.125	0.773	0.435	1.208
Δ annual withdrawals	0.411	0.079	0.490	0.276	0.765
Biomass (2014)	9.658	1.896	11.553	4.935	16.488
Accumulated CO_2 (2006)	13.714	2.708	16.422	6.384	22.807
Annual accumulated Δ CO_2	1.183	0.227	1.410	0.793	2.203
Accumulated CO_2 (2014)	17.722	3.479	21.200	9.056	30.255

3.2. Residual Biomass

Table 8 shows the results of biomass calculations for the main forest species in Biscay. From these, 52,214 Mg·year^{-1} dry matter and 74,591 Mg·year^{-1} wet matter of residual total biomass have been estimated. This yields an equivalent energy potential of 947,000 GJ·year^{-1}. Most of this residue derives from the *P. radiata*, due to the predominance of this species in Biscay. This effect is the most outstanding in Stratum 1 (Figure 3), where the highest quantity of residual biomass is 39.796 Mg·year^{-1} of dry matter and 56.741 Mg·year^{-1} of wet matter. The residual biomass obtained in stratum 3 is 3.243 Mg·year^{-1} of dry matter and 4.618 Mg·year^{-1} of wet matter (Figure 4).

Table 8. Lower heating value (LHV), residual biomass production of dry matter and actual available energy potential in Biscay.

Biomass Residues	LHV (GJ·Mg $^{-1}$)	Usable (ha)	Biomass Residues (Mg·year^{-1})	Potential Energy (GJ·year^{-1})
P. radiata	12.67	63,181	44,689	808,871
E. globulus	12.85	9183	7524.5	138,129
Total	25.52	72,364	52,213.5	947,000

The residues coming from *E. globulus* are in the ninth stratum, generating 7525 Mg year^{-1} of dry matter and 10,750 Mg year^{-1} wet matter. The estimators of the residue obtained for *P. radiata* fluctuate between 0.43 and 0.89 Mg ha^{-1} year^{-1} of dry matter and between 0.61 and 1.28 Mg ha^{-1} year^{-1} of wet matter (Figure 5). With respect to *E. globulus*, the residue estimators obtained values from 1.11 to 1.29 Mg ha^{-1} year^{-1} dry matter and from 1.59 to 1.84 Mg ha^{-1} year^{-1} wet matter. Other researchers have also studied these species: Dominguez *et al.* [49] estimated 1.3 Mg ha^{-1} year^{-1} of wet matter residual biomass in *P. radiata* in Navarra (Spain), and [27] found values of estimated residual biomass of between 0.97 and 2.020 Mg ha^{-1} year^{-1} (wet matter) in *E. globulus* plantations in Huelva (Spain).

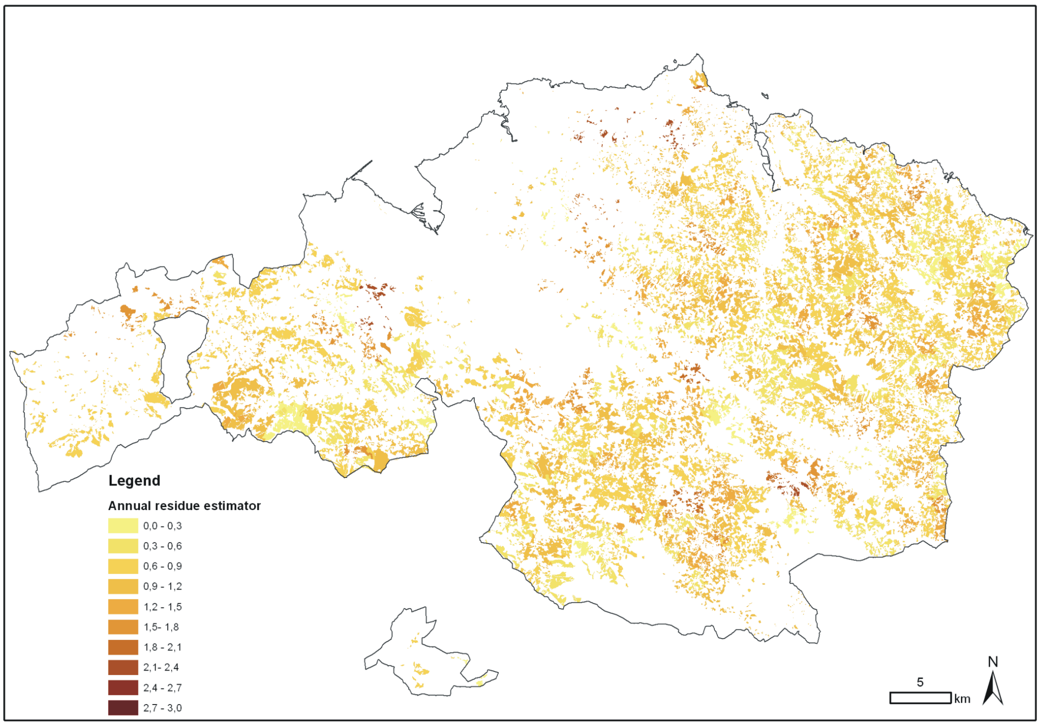

Figure 3. Map of residue estimator E_r (Mg·ha^{-1}·year^{-1}) of Stratum 1.

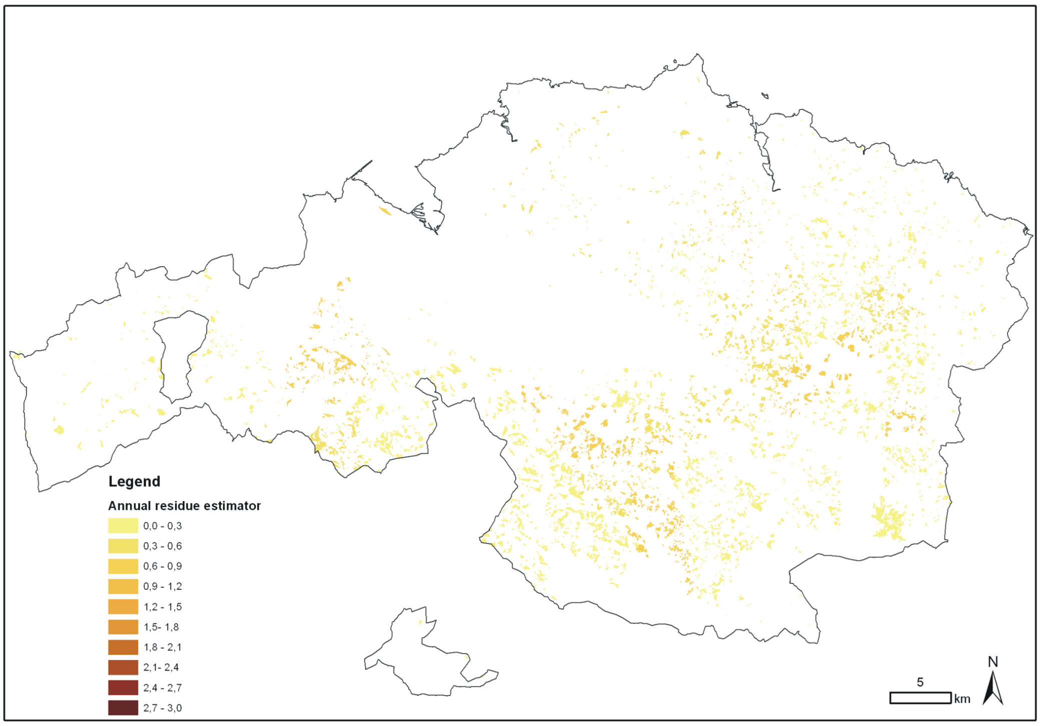

Figure 4. Map of residue estimator E_r (Mg·ha^{-1}·year^{-1}) of Stratum 3.

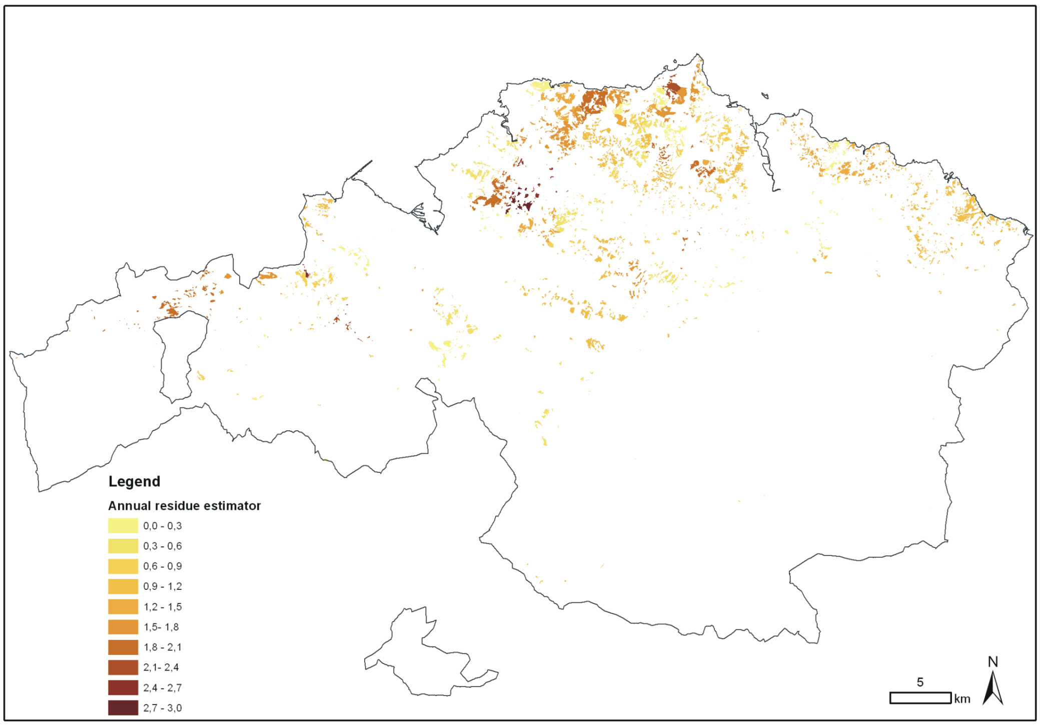

Figure 5. Map of residue estimator E_r (Mg·ha^{-1}·year^{-1}) of Stratum 9.

4. Conclusions

Finally, based on the results shown in the above figures, the following assertions can be made: A high percentage of the land of Biscay is used for forestry, generating every year 52,214 Mg of dry matter, the energy use of which is very interesting from an environmental point of view. This amount of residue accounts for barely 16.38% of Biscay's annual growth of forest biomass, estimated at 318,741 Mg d.m. year^{-1} in 2006 using the allometric equations method (ABE). These data show the possibility of increasing the use of forest biomass according to a sustainable exploitation of the forest.

The main advantages obtained in the event of carrying out the actions defined in this project can be summarized as follows:

- There is an increase in the use of forest biomass as an energy source instead of fossil fuels, which involves first-rate environmental advantages, such as a reduction in sulfur emissions and particles and minimum emissions of polluting agents.
- GIS is a powerful tool of great use for evaluating forest biomass resources, since it efficiently combines both cartographic data and information from different databases that facilitate the work of mapping the results.
- Through the use of forest biomass, an important reduction is expected in forest fires, which at this time are a cause for concern in the study area.
- Using residual forest biomass as an energy source provides employment and creates new business opportunities in rural communities.
- Biomass fuels reduce the dependence on fossil fuels and increase levels of energy self-sufficiency.

Acknowledgments: This work has been supported by the Office of Research of the University of the Basque Country grant by Project NUPV08/22, by Project SAI10/147-SPE10UN90and by Project NUPV10/10. The authors acknowledge gratefully the technical and personalsupport provided by José Miguel Edeso, Aitor Bastarrica and Leyre Torre for drawing the figures.

Author Contributions: Esperanza Mateos developed the conceptual ideas, designed the study, conducted the data analysis in field experiments and wrote the paper. Florencio Garrido and Leyre Ormaetxea developed the conceptual ideas and designed the study.

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

References

1. Intergovernmental Panel on Climate Change (IPCC). *Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories. Programme. Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2003.
2. Gobierno de España Plan Nacional de Energías Renovables de España 2011–2020. Available online: http://www.minetur.gob.es/energia/desarrollo/EnergiaRenovable/Paginas/paner.aspx (accessed on 23 February 2015).
3. Ente Vasco de la Energía (EVE). Estrategia Energética de Euskadi. Available online: http://www.eve.es/EVE/media/EVE/pdf/ Estrategia_Energetica_Vasca2020.pdf (accessed on 12 January 2015).
4. IHOBE. Inventario de Carbono Orgánico en Suelos y Biomasa de la Comunidad Autónoma del País Vasco. Available online: http://www.ingurumena.ejgv.euskadi.eus/r4911293/es/contenidos/inventario/ carbono_organico/es_pub/adjuntos/carbono_organico.pdf (accessed on 10 January 2015).
5. González, J.B.; Garcí a de la Fuente, L.; García, M.A.A. Condicionantes Económicos del Aprovechamiento de Biomasa Forestal con Fines Energéticos. Una Revisión de las Estimaciones Para el Norte de España. Available online: http://www.revista-eea.net/documentos/31109.pdf (accessed on 12 May 2014).
6. Keles, S.; Baskent, E. Modelling and analyzing timber production and carbon sequestration values of forest ecosystems: A case study. *Polish J. Environ. Stud.* **2007**, *16*, 473–479.
7. Newell, R.; Stavins, R. Climate change and forest sinks: Factors affecting the cost of carbon sequestration. *J. Environ. Econ. Manag.* **2000**, *40*, 211–235.
8. Xu, W.; Yin, Y.; Zhou, S. Social and economic impacts of carbon sequestration and land use change on peasant households in rural China: A case study of Liping, Guizhou province. *J. Environ. Manag.* **2007**, *85*, 736–745.
9. Canadell, J.; Raupach, M. Managing forests for climate change mitigation. *Science* **2008**, *320*, 1456–1457.
10. Caparrós, A.; Ovando, P.; Oviedo, J.; Campos, P. Accounting for carbon in avoided degradation and reforestation programs in Mediterranean forest. *Environ. Dev. Econ.* **2011**, *16*, 405–428.
11. Finkral, A.; Evans, A. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *For. Ecol. Manag.* **2008**, *255*, 2743–2750.
12. Neilson, E.; MacLean, D.; Arp, P.; Meng, F.; Bourque, C.; Bhatti, J. Modeling carbon sequestration with CO_2 fix and a timber supply model for use in forest management planning. *Can. J. Soil Sci.* **2006**, *86*, 219–233.
13. Camps, M.; de Arano, I.M.; Mendarte, S.; Aizpurua, A.; Pinto, M. Pautas para inducir una acumulación adicional de carbono orgánico en biomasa forestal y en suelos agrícolas, piscícolas y forestales en la Comunidad Autónoma del País Vasco. *Edafologia* **2004**, *11*, 171–196.
14. Merino, A.; Rey, C.; Brañas, J.; Rodriguez, R. Biomasa arbórea y acumulación de nutrientes en plantaciones de *Pinus radiata*. *Investig. Agrar. Sist. Recur. For.* **2003**, *12*, 85–98.
15. Santamarta, J. Las Energías renovables son el futuro. *World Watch* **2004**, *22*, 34–40.
16. Pan, Y.; Birdsey, R.; Fang, J.; Houghton, R.; Kauppi, P.; Kurz, W.; Phillips, O.; Shvidenko, A.; Lewis, S.; Canadell, J.; *et al.* A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993.
17. Montero, G.; Ruiz-Peinado, R.; Muñoz, M. *Producción de Biomasa Y Fijación de CO_2 en los Montes Españoles*; Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria: Madrid, Spain, 2005.
18. Vayreda, J.; Gracia, M.; Canadell, J.; Retana, J. Spatial patterns and predictors of forests carbon stocks in Western Mediterranean. *Ecosystems* **2012**, *15*, 1258–1270.
19. Woodbury, P.; Smith, J.; Heath, L. Carbon sequestration in the U.S. forest sector from 1990 to 2010. *For. Ecol. Manag.* **2007**, *241*, 14–27.
20. Balboa-Murias, M.; Rojo, A.; Alvarez, J.; Merino, A. Carbon and nutrient stocks in mature *Quercus robur* L. stands in NW Spain. *Ann. For. Sci.* **2006**, *63*, 557–565.
21. Gil, M.; Blanco, D.; Carballo, M.; Calvo, L. Carbon stock estimates for forests in the Castilla y León region, Spain. A GIS based method for evaluating spatial distribution of residual biomass for bio-energy. *Biomass Bioenergy* **2011**, *35*, 243–252.

22. Zhang, J.; Ge, Y.; Chang, J.; Jiang, B.; Jiang, H.; Peng, C.; Zhu, J.; Yuan, W.; Qi, L.; Yu, S. Carbon storage by ecological service forests in Zhejiang Province, subtropical China. *For. Ecol. Manag.* **2007**, *245*, 64–75.
23. Ministerio de Agricultura, Alimentación y Medio Ambiente. *National Forestry Inventory 1997–2006*; Department of Environment, Basque Government: Vitoria-Gasteiz, Spain, 2006; pp. 1–410.
24. Third National Forestry Inventory. Available online: http://www.nasdap.ejgv.euskadi.eus/informacion/inventarios-forestales/r50-7212/es/ (accessed on 23 March 2014).
25. Esteban, L.; Pérez, P.; Ciria, P.; Carrasco, J. *Evaluación de los Recursos de Biomasa Forestal en la Provincia de Soria. Análisis de Alternativas Para su Aprovechamiento Energético*; CIEMAT: Madrid, Spain, 2004; pp. 1–109.
26. Parresol, B. Assessing tree and stand biomass: A review with examples and critical comparisons. *For. Sci.* **1999**, *45*, 573–593.
27. Zabalo, A. Modelo de Estimación del Potencial Energético de la Biomasa de Origen Forestal en la Provincia de Huelva. Ph.D. Thesis, Universidad de Huelva, Huelva, Spain, 2006.
28. Lehtonen, A.; Makipaa, R.; Heikkinen, J.; Sievanen, R.; Liski, J. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *For. Ecol. Manag.* **2004**, *188*, 211–224.
29. Sprugel, D. Correcting for bias in log-transformed allometric equations. *Ecology* **1983**, *64*, 209–210.
30. Mateos, E.; Edeso, F.; Bastarrika, A.; Torre, L. Estimación de la biomasa residual procedente de la gestión forestal en Bizkaia. *Lurralde Investig. Espac.* **2012**, *35*, 13–30.
31. Araujo, T.; Higuchi, N.; Andrade, J. Comparison of formulae for biomass content determination in a tropical rain forest site in the state of Pará, Brazil. *For. Ecol. Manag.* **1999**, *117*, 43–52.
32. Esteban, L.; García, R.; Ciria, P.; Carrasco, J. *Costs in Spain and Southern EU Countries. Clean Hydrogen-Rich Synthesis Gas Report, Chrisgras Fuels from Biomass*; Colección Documentos CIEMAT; CIEMAT: Madrid, Spain, 2009.
33. Keller, M.; Palace, M.; Hurtt, G. Biomass estimation in the Tapajos National Forest, Brazil: Examination of sampling and allometric uncertainties. *For. Ecol. Manag.* **2001**, *154*, 371–382.
34. Silva, R.; Tavares, M.; Pascoa, F. Residual Biomass of Forest Stands—*Pinus pinaster* Ait. and *Eucalyptus globulus* Labill. In Proceedings of 10th World Forestry Congress, Paris, France, 17–26 September, 1991; FAO: Paris, France, 1991.
35. Ter-Mikaelian, M.; Korzukhin, M. Biomass equations for sixty-five North American tree species. *For. Ecol. Manag.* **1997**, *97*, 1–24.
36. Zianis, D.; Mencuccini, M. On simplifying algometric analyses of forest biomass. *For. Ecol. Manag.* **2004**, *187*, 311–332.
37. Ibáñez, J.; Vayreda, J.; Gracia, C. Metodología complementaria al inventario forestal nacional en cataluya. In *El Inventario Forestal Nacional: Elemento Clave Para la Gestión Forestal Sostenible*; Fundación General de la Universidad de Valladolid: Valladolid, Spain, 2002; pp. 66–77.
38. CPF. *Centre de la Propietat Forestal L'inventari Forestal: Annexe Indicadors Dendrométrics En: Manual de Redacción de Plans técnics de gestió i Millota Forestal (PTGMF) Plans Simples de Gestió Forestal (PSGF)*; Instruccions de Redacció i L'inventari Forestal; Generalitat de Catalunya: Barcelona, Spain, 2004; pp. 211–314.
39. Chen, X.; Zhang, X.; Zhang, Y.; Wan, C. Carbon sequestration potential of the stands under the Grain for Green Program in Yunnan Province. *China For. Ecol. Manag.* **2009**, *258*, 199–206.
40. Sánchez-Peña, G.; de Viciana, J.S.-V. Proceso de contabilización de los sumideros de CO_2 en los sistemas forestales españoles. *Cuadernos de la Sociedad Española de Ciencias Forestales*, **2001**, *12*, 29–33.
41. Kollmann, F. *Tecnología de la Madera y sus Aplicaciones*; Ministerio de Agricultura: Madrid, Spain, 1959; Volume 1, pp. 1–665.
42. Martín, A.G.; Cabello, F.P.; de la Riva Fernández, J. Evaluación de los recursos de biomasa residual forestal mediante imágenes del satellite Landsat y SIG. *GeoFocus* **2006**, *6*, 205–230.
43. Instituto para la Diversificacion y Ahorro de la Energía (IDAE). *Plan de Fomento de las Energías Renovables en España*; IDAE: Madrid, Spain, 1999.
44. Velázquez, B. Situación de los sistemas de aprovechamiento de los residuos forestales para su utilización energética. *Ecosistemas* **2006**, *15*, 77–86.
45. Gutiérrez Puebla, J.; Gould, M. *SIG: Sistemas de Información Geográfica*; Sintesis: Madrid, Spain, 1994.
46. Marcos, F. *Biocombustibles sólidos de Origen Forestal*; Aenor: Madrid, Spain, 2001; pp. 1–299.

47. Jalkanen, A.; Mäkipää, R.; Ståhl, G.; Lehtonen, A.; Petersson, H. Estimation of the biomass stock of trees in Sweden: Comparison of biomass equations and age-dependent biomass expansion factors. *Ann. For. Sci.* **2005**, *62*, 845–851.
48. Solla-Gullón, F.; Santalla, M.; Rodríguez-Soalleiro, R.; Merino, A. Nutritional status and growth of a young Pseudotsuga menziesii plantation in a temperate region after application of wood-bark ash. *For. Ecol. Manag.* **2006**, *237*, 312–321.
49. Dominguez, J.; Ciria, P.; Esteban, L.; Sánchez, D.; Lasry, P. Evaluación de la biomasa potencial como recurso energético en la región de Navarra. *GeoFocus* **2003**, *3*, 1–10.