ONLINE ISSN 2069-7430
ISSN-L 1841-4737

PRO LIGNO
www.proligno.ro

Vol. 11 N° 4 2015
pp. 663-672

WEIGHT CHARACTERISTICS OF LOGGING RESIDUES OF FIR AND BEECH AS AN ENERGY SOURCE

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Abstract

In Greece, logging residues are left on the forest after wood harvest. In the light of the increasing energy needs and unemployment, particularly in rural areas, utilization of forest residues for energy is becoming important. In this research weight of logging residue were estimated in two uneven aged and selectively harvested forest stands of fir and beech in northwest Greece. The oven dry weight of logging residues (WLR) depended strongly on species and site quality. It was (22.4) t/ha and 6,33 t/ha in site quality II and IV of a fir forest and 12.46 t/ha and 9.26 t/ha in site quality II and III of a beech forest, respectively. The percentage weight of the residues on the total biomass harvested amounted to about 25 - 30 % in fir and 18 - 20 % in beech. The separation of logging residues into various fractions (branches > 5 cm in diameter, branches ≥ 2 ≤ 5 cm , branches < 2 cm with needles or foliage, stump, tops, bark) showed that branches with diameter > 5 cm had the higher weight percentage (%) in both species and in all site qualities. The relative amount of the thicker branches (branches > 5 cm in diameter, branches ≥ 2 ≤ 5 cm) was higher in the better quality sites in both species. The sum weight of branches without needless or leaves (WB) was 11.24 % and 13.19 % in fir site quality II and IV, and 14.20 % and 8.68 % in beech site quality II and III, respectively. Linear regression analysis helped to develop several models that relate the total oven dry weight of residues or the amount of their various fractions to diameter at breast height (BH) and/or the height of the tree. With the current situation and current management plan for the regions where this project was implemented we could estimate logging residues per unit area. Finally we could have the total amount of logging residues in total for the forest and proceed for a further econometechnical analysis for exploitation of logging residues.

Key words: *biomass energy; weight of logging residues; wood residues; estimation models; uneven aged forests; selective cutting.*

INTRODUCTION

The projected depletion of fossil fuels and particularly the growing concern for the impact of CO2 emissions on climate change have focused global attention on biomass, especially on forest biomass for energy production (European Commission 2005, Smeets and Faaij 2007, Ladanai and Vinterbäck 2009, Becker *et al*. 2011). Forest biomass has the potential to be one of the most convenient energy sources in the future as it was in the past (Ladanai and Vinterbäck 2009). In recent years, the use of residues that remain in the forests after logging has attracted great interest as an energy source (Gan and Smith 2006, 2007, Nurmi 2007, Hu and Heitman 2008, Malinen *et al*. 2010, Lehtikangas 2011).

Logging residues from final harvest are expected to play a pivotal role in meeting renewable energy goals in many countries (Perlack *et al*. 2005). In addition, utilization of logging residues as a forest biomass could create business opportunities and employments in local populations, generate profit from residual material and provide energy self-sufficiency for rural communities. (Eker *et al*. 2009). Leaving logging residues in the forest, fuel material density and risk of fire in the forest base increase and the problem of bark beetle damage and rejuvenation obstacles can emerge (Spinelli *et al.* 2007). On the other hand, the literature on removal of logging residues from the forest and their exploitation also addresses various environmental and ecological issues and puts some constrains (Abas *et al*. 2011, Hesselink 2010, Wall and Hytönen 2011). The removal of this biomass results in removal of nutrients and if it is practiced for long time it will have an impact on nutrient cycle and impoverish the growing environment of the forest. However, this effect is influenced by the forest species, the rotation time, site quality, the overall management of the forest ecosystem and the form of residue removed. For example foliage and small branches are particularly rich in nutrients and their removal should be avoided (Abbas *et al*. 2011).

In the past the logging residues were not exploited mainly because their harvest and transport was technically difficult and uneconomic. Currently new harvesting technologies and transportation systems have been developed and in conjunction with the increase in petroleum prices enable their extraction from the forest (Kauriinoja 2010, Svanaes and Jungmeier 2010, Bergseng *et al*. 2013, Philippou 2014). Also, new and more efficient technologies enable conversion of biomass into energy in small units (mainly gasification) or conversion into compressed forms (wood pellets) that can be installed in or near the forests (Kauriinoja, 2010). These further limit transportation costs and give opportunities for local employment and rural development.

The interest in utilizing logging residues for energy has driven many efforts to estimate their availability in various forest ecosystems in different countries (Rørstad *et al*. 2010, Eker, 2011, Peltola *et al*. 2011, Scarlat *et al.* 2011, Eisenbies *et al*. 2011, Haughlin *et al.* 2012, Bergseng *et al*. 2013, Bouriaud *et al*. 2013, Tavankar and Eynollahi 2014). Estimates of potential available residues require knowing what percentage of total harvested tree volume can be expected to be left on site as logging residues following harvesting (residue yield rate or ρ) and the proportion of logging residues which is recoverable (current recovery rate or η) (Gan and Smith 2006). The amount of logging residues yielded from harvested timber depends on tree species and form, stand quality, management methods and utilization limits. Current recovery rates are affected by available technology, costs, environmental constraints and other factors (Jurevics, 2010). Researchers typically use sampling and regression models that relate some combination of easily measurable properties of a tree, such as diameter, height, and stem form, to estimate volume or biomass. The biomass estimates for branches, needles and stump and root system are usually based on the statistics regarding timber used for commercial purposes or the total volume of stem. Their volumes are derived from the dimensions of stem wood by applying biomass models (Muukkonen and Mäkipää, 2006, Peltola *et al*. 2011). These biomass models are based on tree allometry which allows predicting the other biomass compartments of a tree with the measured diameter and/or height information. Only in a few studies (Bouriaud *et al*, 2013, Tavankar and Eynollahi, 2014) actual sampling of cut trees and direct measurement and weighing of the logging residues were used to estimate logging residues.

In Greece, logging residues are left on the forest after wood harvest. Occasionally some of the larger residue wood is removed as firewood for domestic consumption. In light of the increasing energy needs and the increasing unemployment, particularly in rural areas, utilization of forest residues in Greece using small gasification units or/and small pellet manufacturing machines is becoming challenging. Wood pellets are an upgraded solid fuel with small size and high specific gravity that allow easy storage and automatic feeding, high energy density, high energy recovery and minimal particulate emissions during combustion. Their production is technologically simple and it can be done even in small mobile facilities in or near the forests (Philippou 2014).

OBJECTIVE

The objective of the present work was: a. to estimate the amount of dry weight of the various fractions consisting the logging residues of Fir and Beech left after selective cutting in two uneven aged forests, b. to estimate their percentage (%) on the total biomass of the harvested trees and c. to develop regression models for estimating weight of the various types of logging residues using diameter at BH and/or height of trees. This work is a part of a broader project[1] aiming at exploiting the

[1] Utilization of forest biomass (logging residues) for production of refined solid biomass fuels. Impact on forest ecosystem ". Financed by the GREEN FUND, Ministry of Environment, Energy and Climatic Change, Greece.

characteristics of logging residues of various species as an energy source, their suitability for pellet production and also at assessing the effect of their removal on forest floor nutrient capital.

MATERIAL AND METHODS

Sampling

The study was performed in uneven aged stands: 1. of fir (*Abies boriisi)* in the Aristotle University forest in Pertouli, and 2. of beech *(Fagus silvatica)* in the forest region of Aridea of northwest Greece. Harvesting of wood in these forests is done by selective cutting and by the cut-to-length methods. Logging operation is generally performed by using ground based skidding system. Fuel/pulp wood is extracted by loading on mules. For the estimation of the residues left after logging in this forest, we proceeded as follow: From the management plan of the forests and the programmed clusters to be harvested in 2014 we selected 4 fir stands (2 of site quality II and 2 of site quality IV) and 4 beech stands (2 of site quality II and 2 of site quality III). The area of the stands was 0.5 ha for fir and 0.4 ha for beech. The slope of the stands ranged between 10 and 20 %. Following the management plan, we marked the mature trees in each stand and we measured for their diameter at BH. The trees were felled using a chain saw, debranced and topped at merchantable height. The stem was cut in sawlogs in lengths of 6 to 8 m long and in fire/pulp wood of 120 cm long. Sawlogs of fir were debarked in situ. Sawlogs of beech remained with the bark. Also in Beech there was no distinct top and all crown material was cut and separated in the tree class sizes of branches. The length of each log and of the top was measured and summarized as the length (or height) of each stem. The branches and the unmerchantable tops were further cut at the stamp area into: (i) branches having diameter > 5 cm, (ii) branches having diameter between 2 and < 5 cm and (iii) the smaller branches with the needles. The various types of residues were separated (Figure 1) and weighted with a mobile (bucher's) balance. The above ground stump was measured for its volume (height above ground and av. diameter). The average diameters and length of sawlogs and fire/pulp wood of each tree were taken to determine their volume. Representative specimens were taken from all parts of the tree and put into plastic bags for moisture content determination

Fig. 1.
Logging residues of Fir trees: a. branches of < 2 cm in diameter with the needles, b. branches of >2- <5 cm in diameter, c. branches of > 5 cm in diameter. d. tops, e. stump and f. bark

From the above data the green and ovendry volume of round wood (sawlogs and fire/pulp wood) was calculated and their ovendry weight was estimated using the average density and volumetric shrinkage of fir and beech which were found in other studies (Pasialis and Tsoumis 1983). The ovendry weight of all types of residues and their percentage (%) of total biomass (WTB) and of total residues (WLR) were determined per cut tree, summarized and averaged for each site quality.

Statistical analysis

Given the absence of adequate equations for estimating tree biomass in general in Greece and equations for logging residues in particular regression analysis was used to find any relations between diameter and/or height of the trees with the oven dry weight of residues. Linear and nonlinear regression models (Table 2) were fitted to the data to model biomass WLR (Weigh of Logging Residues), WBNT (Weight of Branches, Needles and Tops) and WB (sum Weight of Branches of >2-<5 cm and >5 cm) for Fir and biomass WLR, WBL (Weight of Branches and Leaves) and WB for Beech.

Table 2

Regression models tested

Linear models with d	*Linear models with an interaction of d and h:*
$Y=b_0 + b_1 d$ (1)	$Y=b_0 + b_1 dh$ (7)
$Y=b_0 + b_1 d^2$ (2)	$Y=b_0 + b_1 d^2h$ (8)
$Y=b_0 + b_1 d + b_2d^2$ (3)	***Nonlinear regression models***
$Y=b_0 + b_1 h$ (4)	$Y=b_0 d^{b1} + b_4$ (9)
$Y=b_0 + b_1 h^2$ (5)	$Y=b_0 (d^2h)^{b2} + b_4$ (10)
$Y=b_0 + b_1 h + b_2h^2$ (6)	$Y=b_0 d^2h^{b3} + b_4$ (11)
b_0, … b_4 are the estimates for the regression coefficients, d diameter at breast height in cm, h total tree height in m and Y the response variable as it was stated before.	

Models (1) and (8) were proposed by Harrison et al. (2009) and (9), (10) and (11) by Bouriaud *et al.* (2013). The log transformations of models (1), (2), (7) and (8) were also fitted to the data. Models that their coefficients were significant were evaluated and compared using the coefficient of Determination (R-Squared), mean squared error (MSE) and the Akaike information criterion (AIC). Analysis for the regression residuals was conducted and tested for nonlinearity, normality with Lilliefors (Kolmogorov-Smirnov) normality test and heteroscedasticity with non-constant variance test (ncv.test) from R package (car) and from the plot of the residuals vs. fitted values. Statistical Analysis was conducted using R Programming Language.

RESULTS AND DISCUSSION

Logging residues biomass measurement

The results of the various measurements of biomass recovered from the harvested trees in the selected from the managerial plan stands of fir and beech are given in Table 1. The oven dry weight of the total biomass (WTB) and of the total logging residues (WLR) of the harvested trees, expressed as t/ha, varied between species and quality sites. It was higher in Fir than in Beech and higher in the better site quality. The WLR in Fir was 22.4 and 6.33 t/ha in quality site II and IV and in Beech 12.46 t/ha and 9.26 t/ha in quality site II and III, respectively. The average WLR per tree in Fir site II and IV was 373 kg and 211 kg, and in Beech 248 kg and 168 kg, respectively, as a result of the dimensions of the mature trees in each species and site. Tree dimensions were bigger in fir than in Beech in both quality sites. However, in Beech even though the difference in the average tree dimensions between quality site II and III were small (about 5 %) the amount of logging residues per tree was about 50% higher in site II. We could not find in the literature any research results on estimations of logging residues in selective cutting fir forests. Bouriaud *et al* (2013) estimated the WLR of mature trees with an average 40 cm diameter to be over 156 kg/tree based on nonlinear models and stock volume tables of a Beech forest. His estimations also showed that WLR/ha varied strongly according to the productivity class, but all estimates proved to be quite substantial ranging from 14 to 42 t /ha for beech stands at harvest age.

The (WLR) expressed as percentage (%) of the weight (WTB) of the harvested trees was much higher in fir than in beech. In fir this percentage was higher in site quality IV (30.8 %) than in II (25.8 %) while in beech the opposite was observed (site II 19.8 % , site III 17.2 %). The small percentage of WLR in site III of beech explains the above mentioned small amount of residues per tree in this quality site.

ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 11 N° 4 2015
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Table 1

Measurements of logging residues

Characteristics	Fir		Beech	
	Site Qual. II	Site Qual. IV	Site Qual. II	Site Qual. III
Total biomass (WTB) t/ha	86.83	20.57	62.84	53.89
Total residues (WLR) t/ha	22.4	6.33	12.46	9.26
LRW as (%) of WTB	25 8	30 8	19.83	17.19
Branches > 5 cm (%)	8	6.76	11.74	8.29
Branches ≥ 2 ≤ 5 cm (%)	3.24	6.43	2.38	3.19
Branches < 2 cm + needles (%)	5.42	5.75	3.57	3.22
Stump (%)	3. 65	5. 50	2. 13	2. 49
Bark (%)	5. 36	5. 65	-	-
Average tree diameter BH (cm)	59 (±9.6)	46 (±11.67)	40 (±8.7)	38 (±9.5)
Average tree height (m)	26 (±2.85)	19 (±5.08)	10.45 (±4.5)	9.95 (±2.28)
No of trees	30	15	20	22
WLR/tree (kg)	373	211	249	168
Range of WLR/tree (kg)	175-594	57-374	116-484	59-214

The separation of logging residues into the various fractions and expressing their weight as % of the total tree biomass (WTB) showed that branches with diameter > 5 cm had the higher weight percentage (%) in both species and in all site qualities. The relative amount of the thicker branches was higher in the better quality sites in both species. The sum weight of branches without needless or leaves (WB) was 11.24 % and 13.19 % in fir site quality II and IV, and 14.20 % and 8.68 % in Beech site quality II and III, respectively. The percentage of the small branches (diameter < 2 cm) with the needles or leaves were on the average about 5.6 % in fir and 3.3 % in beech The percentage of the above ground stump weight was much higher in fir than in beech. It was interesting to find that the bark remaining in the fir forest after debarking the sawlogs was more than 5 % (sawlogs o.d. weight amounted about 62 % and 57 % of the WTB in site quality II and IV, respectively). Beech logs were not debarked in the forest.

The woody biomass of branches and stump and probably bark could be valuable materials for pellet production. Their exploitation by the farmers using small mobile pellet production machinery could open new working positions near the forests and/or increase their income. The suitability of these materials as raw material for pellet production constitutes another research topic of our project. All logging residues could be used for heat and electricity cogeneration in small gasification units (Philippou 2014). However, small material less than 2 cm in diameter with the foliage is of crucial concern in managing residues. A high proportion of the nutrient content of trees is in the needles or leaves and fine twigs (Abbas *et al*. 2011, Wall and Hytönen 2011). A parallel research of our project aims at estimating the effect of removing the various fractions of logging residues from fir and beech forest on the nutrition balance of soil.

Model development

All regression models were fitted to the data and for the nonlinear models non-significant effects for the coefficients were captured so the models were rejected for all cases in fir. The results for the linear regression models for the both qualitie sites separate and in total are presented in Table 2 for fir and in Table 3 for beech. Only the best model that was selected in every occasion is shown along with the R Squared, MSE, AIC and the mean of the predicted biomass. In all models there was a consistency among all criteria. Log transformation models didn't perform better in any case.

Ncv test for heteroscedasticity in all cases showed that there isn't evidence for a non-constant variance of the residuals. That conclusion can be made also from the plots of the residuals vs. fitted values for all the models. In the same plots there is randomness which is the desirable image. Figure 2 (A(ii),B(ii)) and Figure 3 (A(ii), B(ii)) comprehend these plots for WLR of Fir for Sites Quality II and IV and of Beech for Sites Quality II and III. For the cases not shown the graphic display for the residuals is similar.

Table 2

Linear models with the best fit, R Squared, MSE, AIC and mean of predicted biomass for the two sites quality and in total for Fir

Site Quality	Model	R squared	MSE	AIC	Mean Predicted Biomass
Fir II	WLR= -45,5935-0,2681dh	0,7632	3318,461	334,354	373,474 kg
	WBNT=81,4704+0,0017d^2h	0,7201	1539,960	311,322	242,982 kg
	WB= -495415+5,1274d	0,5659	1812,613	321,212	152, 464kg
Fir IV	WLR= 43,690+0,003549d^2h	0,9341	690,033	146,619	211,589 kg
	WBNT= 2,57457+0,14768dh	0,8350	659,554	145,942	135,032 kg
	WB=0,74472+0,09205dh	0,797	330,188	135,563	86,519 kg
Fir Both sites	WLR=-31,42231+0,2594dh	0,8616	2582,296	487,256	319,512 kg
	WBNT=-12,45306+0,16221dh	0,8282	1303,86	456,493	206,998 kg
	WB= 26,29+0,0013d^2h	0,6813	1368,002	458,654	130,482 kg

Models sellected for logging residues of fir in all cases has a good fit as is implied from the value of R- Squared and the value from mean predicted biomass which is close to real value from the sample WLR/tree shown in Table 1. In graphic display of the fit Figure 2 (A(i),B(i)) the goodness of fit is confirmed.

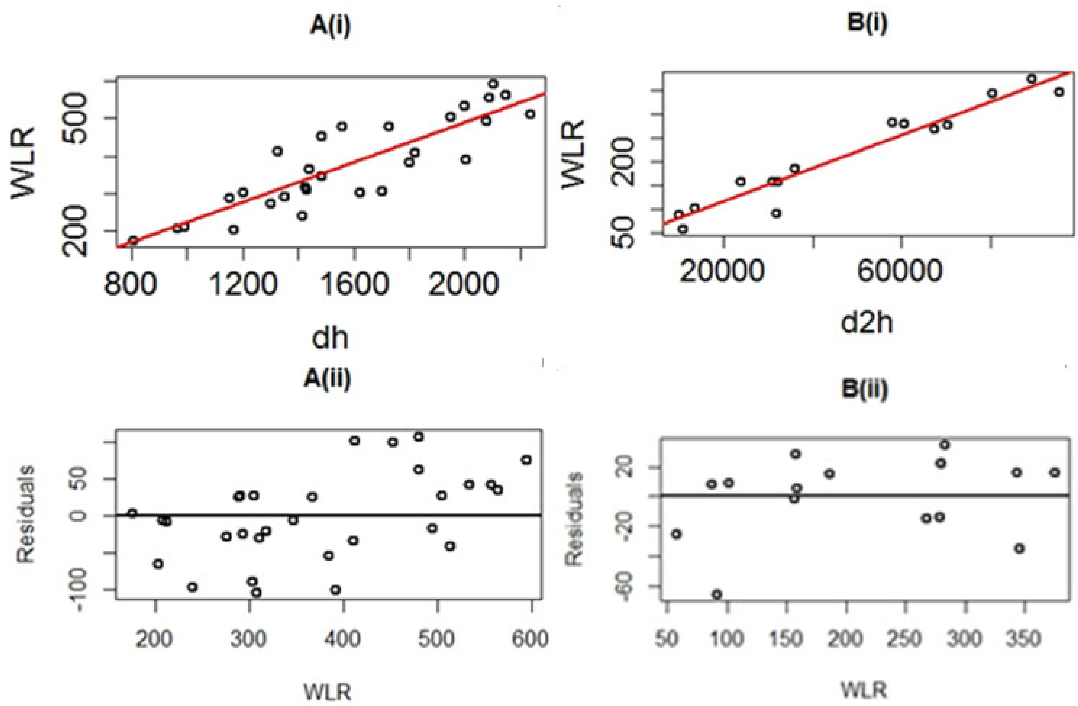

Fig. 2.

Selected models for (WLR) of fir for site quality II (A) and for site quality IV (B). Regression line on the plot of response with independent variable (A(i), B(i)) and residuals plots vs. fitted values (A(ii), B(ii))

Results for beech are presented in Table 3. Regarding nonlinear models and cases in site III and both sites, nonlinear model (10) was significant but AIC was bigger from AIC in linear models so it isn't shown in the results. For the other models results are similar. In site II biomass is more associated with d than h. R Squared, mean predicted biomass and plots in Figure 3 (A(i),B(i)) shows that there is a good fit of the models in the two sites separate. For models in both sites smaller values for R squared are reported and since nonlinear model (10) was significant this and other nonlinear models could be considered and further investigated.

Table 3

Linear models with the best fit, R Squared, MSE, AIC and mean of predicted biomass for the two sites quality and in total for beech

Site Quality	Model	R squared	MSE	AIC	Mean Predicted Biomass
Beech II	WLR= -122.937+9.338d	0.7975	1590.449	210.193	249.189 kg
	WBL= -132.230+8.899d	0.7871	1538.502	209.529	222.389 kg
	WB= -99.7384+6.0561d	0.7865	943.484	199.749	177.461 kg
Beech III	WLR= 132.4+0.0021d^2h	0.8195	117.196	173.234	168.443 kg
	WBL= 1207,+0.0014d^2h	0.6991	96.420	168.945	144.079 kg
	WB= 73729+1.013d	0.5237	81.690	165.298	112.490 kg
Beech Both sites	WLR=115.9471+0.2145dh	0.5522	2555.116	454.717	206.894 kg
	WBL=98.9971+0.1943dh	0.5031	2553.528	454.691	181.370 kg
	WB= 77.89453 + 0.1546dh	0.5039	1610.785	435.339	143.429 kg

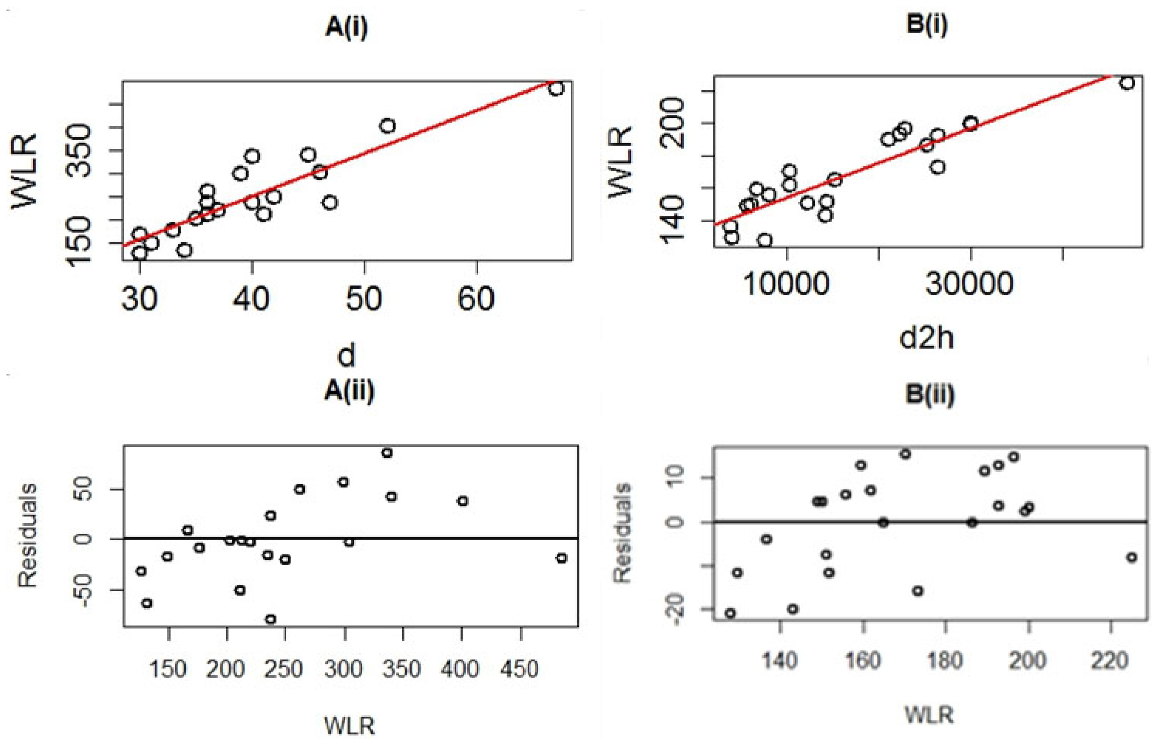

Fig. 3.
Selected models for weight of total residue biomass (WLR) of beech for site quality II* (A) *and for Site Quality III* (B)*. Regression line on the plot of response with independent variable (A(i), B(i)) and residuals plots vs. fitted values A(ii), B(ii))

Models that had the best fit and finally chosen could be used in the same species and similar sites quality to predict the biomass for the log residues of the trees measuring only the independent variables required for every model respectively. With the current situation and current management plan for the regions where this project was implemented we could estimate logging residues per unit area. And finally we could have the total amount of logging residues in total for the forest and proceed for a further economotechnical analysis for economic exploitation of logging residues.

CONCLUSIONS

Commercial high forests in Greece are limited, and the country imports about 3/4 of its needs in wood products and even more in energy. Utilization of the residues left in the forest after harvesting need to be to examined as an supplemental energy source and income revenue for the population leaving near the forests. Before assessing the feasibility of residue utilization for energy or other products, it is important to know the available quantities, the characteristics and the availability of the residues. The results of this work showed that the oven dry weight of logging residues depended strongly on species and site quality. It was 22.4 t/ha and 6.33 t/ha in site quality II and IV of a Fir forest and 12.46 t/ha and 9.26 t/ha in site quality II and III of a Beech forest, respectively. The weight of the residues amounted to about 25 - 30 % in Fir and 18 - 20 % in Beech of the total biomass of the harvested trees in forests of the nothwest area of Greece. The amount of logging residues on a particular harvest area appears to be related to logging intensity, site quality and productivity, size and number of felled trees per ha.

The separation of logging residues into various fractions (branches > 5 cm in diameter, branches ≥ 2- ≤ 5 cm, branches < 2 cm with needles or foliage, stump, tops, bark) showed that branches with diameter > 5 cm had the higher weight percentage (%) in both species and in all site qualities. The relative amount of the thicker branches (branches > 5 cm in diameter, branches ≥ 2- ≤ 5 cm) was higher in the better quality sites in both species. The sum weight of branches without needless or leaves (WB) was 11.24 % and 13.19 % in fir site quality II and IV, and 14.20 % and 8,68 % in beech site quality II and III, respectively. This woody fraction of the residues appears to have better possibilities for exploitation.

Linear regression analysis helped to develop several models that relate the total oven dry weight of residues or the amount of their various fractions (such as branches + top foliage or woody part of the branches) to diameter at BH and/or the height of the tree.Even though the size of the sample (number and area of each plot of harvesting) was rather small, reliable models with good fit where developed for Fir and Beech, for each site quality of each species and for each fraction of the residues. With the current situation and current management plan for the regions where this project was implemented we could estimate logging residues per unit area. Finally we could have the total amount of logging residues in total for the forest and proceed for a further economotechnical analysis for exploitation of logging residues.

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