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The effective heating values of the above and below ground biomass components of mature Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), downy birch (*Betula pubescens*), silver birch (*Betula pendula*), grey alder (*Alnus incana*), black alder (*Alnus glutinosa*) and trembling aspen (*Populus tremula*) were studied. Each sample tree was divided into wood, bark and foliage components. Bomb calorimetry was used to determine the calorimetric heating values.

The species is a significant factor in the heating value of individual tree components. The heating value of the wood proper is highest in conifers. Broad-leaved species have a higher heating value of bark than conifers. The species factor diminishes when the weighted heating value of crown, whole stems or stump-root-system are considered. The crown material has a higher heating value per unit weight in comparison with fuelwood from small-sized stems or wholetrees. The additional advantages of coniferous crown material are that it is a non-industrial biomass resource and is readily available. The variability of both the chemical composition and the heating value is small in any given tree component of any species. However, lignin, carbohydrate and extractive content were found to vary from one part of the tree to another and to correlate with the heating value.

Keywords biomass, heating value, logging residue, lignin, carbohydrates, extractives, hydrogen, carbon
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Contents

Symbols

MC	= moisture content on green weight bases (%)
P	= probability
$q_v(gross)$	= calorimetric heating value
$q_v(net)$	= effective heating value of oven dry biomass or net calorific value or, lower heating value of oven dry biomass
$q_v(moist)$	= effective heating value of biomass with moisture
RMS	= residual mean square
r	= correlation coefficient
β	= regression coefficient, slope
ESOS	= extractives soluble in organic solvents
dbh	= diameter at breast height

1 Introduction

In Finland the share of woodbased fuels of the total energy consumption is some 15 %. This is the highest in all industrialized countries. This figure includes black liquor and other industrial wood wastes. According to the 8th national forest inventory the average annual volume increment of stemwood during 1986–94 was 77.1 Mm³/a (Metsätilastollinen vuosikirja 1995). The total growth of the above ground woody biomass, branches and foliage included is some 110 Mm³/a. Of this volume 29 Mm³/a is logging residue and small-sized trees (Hakkila and Fredriksson 1996).

Possible but rather restricted areas of utilization for this reserve are pulp and paper products, panel products, chemicals and fodder. However, due to the low quality of this non-commercial wood the most likely form of utilization is fuelwood. Age long traditions in this field have led to the high level of technical know-how in both harvesting and combustion. Unfortunately the oil price is a dictating factor for the expansion of fuelwood utilization. Because of the difficulties wood has had in competition with other energy sources there has been a need to expand our knowledge of this renewable energy source.

This report is the second part of a study on the heating values of woody biomass native to Finland. The first part dealt with the above ground biomass of small-sized trees, and the results have been reported by Nurmi (1993). In that study the heating values of wood, inner and outer bark, and foliage components of small-size trees of seven species were studied. Significant differences were found between species within each tree component. However, the differences between species for weighted stem, crown and whole-tree biomass are very small. The weighted heating value of the crown mass is slightly higher than that of the stem in all species. The heating value of stem, crown and whole-tree material was found to be 1–2 % higher in the northern part of the country.

The effective heating value of wood was found to correlate best with the lignin content, inner bark with carbohydrate, and outer bark with carbohydrates and the extractives soluble in alcalic solvents. It was also suggested that the determination of the heating value might be used as an indicator of the cellulose content of coniferous wood.

This second part will concentrate on the heating values of mature trees. The main emphasis is given to the crown mass, because it is the most significant part of the above ground biomass with no industrial use. Some 24 Mm³ of crown mass are estimated to be left in the forest in conjunction with the harvesting of industrial wood. It is our largest unused biomass reserve today. However, when considering the utilization of residue material one has to remember the possible environmental consequences. It has been estimated that the nutritional status of the site, baring capacity, rockiness and the small size of final cuttings will limit the amount of harvestable residue. In addition the prerequisite of mechanized harvesting does in practice limit residue harvesting to regeneration cuttings. All this will limit the available quantity to some 8.6 Mm³ of foliage free biomass (Hakkila and Fredriksson 1996).

Although stem wood from the regeneration cuttings (i.e. Scots pine, Norway spruce and silver birch) can not be considered as fuelwood by any means, it was also included in the study to compare the data with the results on small-sized trees (Nurmi 1993) and to see if the tree size affects heating value.

1.1 The Aim

The first aim of this study is to determine the heating values of tree components of the major tree species in Finland, and secondly how heating values relate to wood chemistry. On the basis of information from the small-sized trees the following is hypothesized: the species is a significant factor on the heating value of individual tree components.

Each tree component (wood, inner bark, outer bark) originates from different mother cells. This is reflected in the carbohydrate-lignin-extractive ratios as their sum is always a unity. As a result, differences in heating values between components may exist. When lignin, carbohydrate and extractive content alternatively are used as a dependent variable and heating value as an independent variable in simple linear regressions, it is hypothesized that the population regression coefficient, ie. the slope, is not zero ($\beta \neq 0$). Heating values of mature trees are compared with the heating values of small-sized trees presented in the earlier study (Nurmi 1993). Tree size is hypothesized to have an effect on the heating value.

The third aim is to give practical information on the energy content of both above and below ground biomass of mature trees at different moisture contents for the evaluation and pricing of fuelwood. The emphasis of this aim is on the crown biomass of spruce and pine as they are the most readily available forest biomass for fuelwood at the moment.

Acknowledgements. The author acknowledges Heikki Leppänen for the selection of sample tree stands, Markku Parhiala for field work, Arto Ketola and Seppo Vihanta for help in the statistical analysis, Keijo Polet for the computer graphics, and Raili Voipio for the chemical analysis. Thanks are due to Professor Pentti Hakkila and Ass. Professor Raida Jirjis for reading the manuscript, and to Dr. Jyrki Hytönen for fruitful discussions and being an example. Elva Nurmi edited the language of the text. Finally, special thanks to Reetta Kolppanen for doing all the hard work in the laboratory alone.

2 Material and Methods

2.1 Selection and Handling of Sample Trees

The study was carried out at the Kannus Research Station. All the study material was collected in Central Ostrobothnia where the station is located. The geographical location and the site factor were not taken into consideration as the resources to accomplish the study were limited. Nonetheless, it has been earlier shown by Nurmi (1993) that geographical location has a significant effect on the heating value of some tree components of small-sized trees. However, the fact that the vast majority of regeneration cuttings do take place in the southern part of the country justifies the decision to exclude the northern part of the country. As far as the site factor is concerned, significant differences were found between mineral and organic soils on the outer bark components of the small-sized trees (Nurmi 1993). But as outer bark composes only about 3 % of the dry stem mass it was considered justifiable not to include the site factor in the study.

The locations of sampling sites and the sample tree data are seen in Table 1. Two sample trees of each of the seven species – Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), downy birch (*Betula pubescens*), silver birch (*Betula pendula*), grey alder (*Alnus incana*), black alder (*Alnus glutinosa*) and trembling aspen (*Populus tremula*) were selected from mineral soils for the analysis of heating value. The chemical analysis was done on pine, spruce and the two birch species.

The individual sample trees were selected on the basis of visual observation by trying to choose the most typical individuals from the stand. No random sampling was used. Trees were felled and delimbed. All the delimbed branches were cut into branch sections according to diameter: < 5, 5–25,

Table 1. Sample tree data.

Species	Sample tree	dbh, cm	Stump diameter, cm	Height, m	Municipality
P. sylvestris	1	28.3	35.0	20.0	Kälviä
	2	37.7	41.9	20.6	Kälviä
P. abies	1	32.5	35.9	19.5	Kälviä
	2	39.0	45.2	22.0	Kälviä
B. pubescens	1	26.2	35.0	19.8	Kälviä
	2	30.9	45.1	19.0	Kälviä
B. pendula	1	22.0	34.5	28.7	Kälviä
	2	25.7	37.7	19.8	Kälviä
A. incana	1	23.2	30.1	16.3	Kälviä
	2	19.6	24.0	15.8	Kälviä
A. glutinosa	1	23.2	35.2	16.6	Oravainen
	2	26.6	35.3	17.0	Bodö
P. tremula	1	25.8	29.0	18.0	Kälviä
	2	23.6	29.8	19.0	Kälviä

25–50 and > 50 mm. Samples were taken for the determination of heating value, chemical composition and moisture content. Dead branches were excluded.

The stump-root systems were dug out of the ground with an excavator. They were washed with a pressure hose to get rid of soil prior to dividing them into roots and stump. In this context stump is considered as the continuation of the stem below the crosscut and containing the underground portion as well. Roots were sorted and sampled according to the diameter into classes of 5–25, 25–50, 50–100 and 100–200 mm. The diameter was measured in vertical direction as described by Hakkila (1975). Stumps were sampled by extracting a sample from the midpoint between the crosscut and the lowest point of the underground projection of the main stem.

Sample discs were sawn off each stem for the determination of heating value and proportion of wood, inner bark and outer bark at relative heights of 10, 30, 50, 80 and 90 %. Samples for the determination of chemical composition were taken at 20 and 80 % relative heights. These heights had been found practical and sufficient in an earlier study by Voipio and Laakso (1992). The samples were attained with a chainsaw without bar oil, a bow saw and clippers, and placed in plastic bags for storage in a freezer.

The above ground biomass of each sample tree was also weighed. The stems were weighed by first bucking them at the center between sampling points, i.e. at 20, 40, 65 and 85 % of the relative height. This was done to determine the stem mass that each calorimetric sample represented and to calculate the weighted mean heating values. Similarly all the branches were cut and separated according to the diameter and each class was weighed. The stump-root systems were not weighed as some of the root mass was lost during the excavation. Instead calculations are based on Hakkila's (1975) results.

2.2 Preparation of Samples

The laboratory handling of the samples included separation of tree components, drying and milling of the components, pressing the powdered samples into pellets, combustion of the samples in an oxygen bomb calorimeter and extraction of the chemical components.

From the practical point of view there is no interest to separate the two bark components. However, from the scientific standpoint previous information on the fuel properties of the two bark components of tree species native to Finland is limited. To provide more basic information wood, inner bark and outer bark were separated from each of the stem samples, i.e. discs and whole branches over 5 mm in diameter. Root bark and bark on the branches less than 5 mm in diameter was separated as one component. Carefulness in separation was of prime importance and the foundation in gaining reliable data. Species with distinct outer bark were relatively easy to handle. They included pine, spruce, downy birch, and silver birch. With grey alder, black alder and trembling aspen, however, the separation was extremely tedious. After separation the samples were dried to constant weight at 102 °C and weighed to determine the proportion of each component at each sample point.

The milling of each entire component, e.g. whole discs in the case of the wood component, was done with a Retsch SM-1 cutting mill. Stainless steel bottom sieves with 0.5, 1 and 10 mm perforations were used. The sieve with the largest openings was used for primary reduction of the sample followed by milling through either one or both of the finest sieves depending on the consistency of the material. To avoid contaminating the samples with the remnants of the previous samples the mill was always thoroughly cleaned using a vacuum cleaner, pressurized air and brushes.

During bomb calorimetry analysis some fuels may splatter around the bomb if they are burned in powder form. To avoid this problem the samples were pelletized with a custom made MKH press manufactured by Keski-Suomen Teräsrakenne Oy. A mould of 14 mm in diameter was used. An attempt was made to make approximately 1 gram samples as the recommended samples size range for the calorimeter is 0.8–1.3 grams. Five pellets were commonly made from each component.

After pelletizing, the remainder of the sample and the pellets were allowed to come to equilibrium moisture content with the surrounding atmosphere over several days. Many laboratories keep

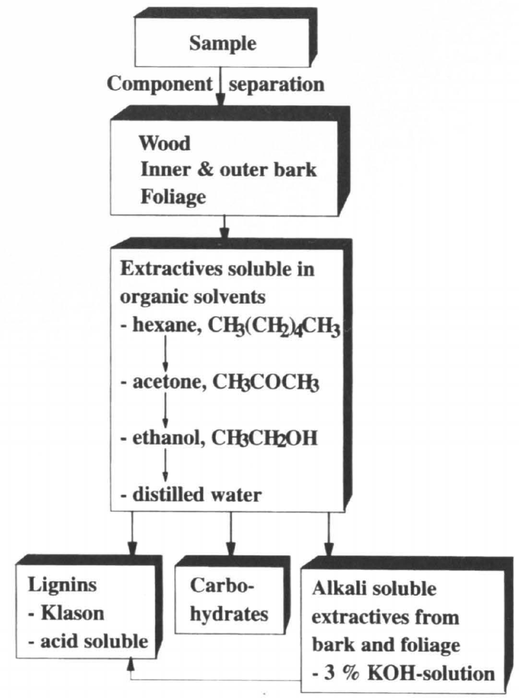

Fig. 1. Order of chemical analysis of the whole-tree components.

their oven-dried samples in a desiccator. However, this method was not used because of the large number of samples and the rapid absorption of moisture into the sample between removing the samples from the desiccator and combustion. It was found much more convenient and secure to determine the moisture content of the sample from the powdered sample with a Mettler PM100 balance equipped with a Mettler LP16 infrared drying unit which gives the moisture content to the nearest 1/100 %. The sample size varied between 0.7–1.2 grams and the selected temperature was 105 °C. In the calibration of the dryer it was discovered that a drying time of 3.5 to 4.5 minutes was sufficient to bring the sample to a constant weight. Three determinations were made per sample and the average was used to calculate the calorific heating value. The range of moisture contents for the whole study material was 1.5–8.0 %. The samples were periodically cross-checked by drying them in a conventional convection oven.

The extraction of chemical components of pine, spruce and birch species was done at the Finnish Forest Research Institute laboratory in Vantaa. The lignin, carbohydrate and extractive contents were determined in wood and bark components of stem, branches and roots as shown in Fig. 1.

It should be noted that the extractive composition is given as a percentage of the dry mass of the sample, whereas total lignin (Klason + acid soluble lignin) and carbohydrates were determined from the extractive free sample. This means that if the percentage figures are added up the sum will exceed 100 % per sample. The chemical composition of each biomass component is given by species in Appendix 1. A more detailed description of the procedures used is given by Voipio and Laakso (1992).

2.3 Determination of the Calorimetric and Effective Heating Values

Three different measures of energy content appear in literature: calorimetric heating value ($q_v(gross)$), effective heating value of oven dry biomass ($q_v(net)$), also called net calorific value or lower heating value of oven dry biomass, and effective heating value of biomass with moisture ($q_v(moist)$). Calorimetric heating value is determined in a bomb calorimeter and all other heating values are derived from it. Calorimetric heating value includes the heat of condensation from water created during the combustion of the sample. In free combustion this water escapes with flue gases resulting in a loss of energy. The amount of water is directly proportional to the amount of hydrogen in the combustible matter. To calculate the energy available in the free combustion of oven dry biomass, i.e. effective heating value, one has to know the hydrogen content. The hydrogen analysis was done for all the tree components of each species at the Finnish Forest Research Institute's Central laboratory at Vantaa with a Leco CHN -analyzer. The results are shown in Appendix 2.

All the results in this study are given as effective heating values of oven dry biomass ($q_v(net)$). It is simply the calorimetric value ($q_v(gross)$) minus the heat released by the condensation water that is created during combustion. The following formula is used for the calculation:

$$q_v(net) = q_v(gross) - 2.45 \times 0.09H_2 = q_v(gross) - 0.22H_2 \quad (1)$$

where
2.45 MJ/kg = the latent heat of vaporization of water at 20 °C.
0.09 = a factor that expresses that one part of hydrogen and eight parts of oxygen form nine parts of water
H_2 = the hydrogen content of oven dry biomass (%).

In practice, however, biofuels always contain some moisture which has to be evaporated in the first stage of combustion. The energy needed for evaporation comes from the burning fuel lowering the amount of usable energy. This is called the effective heating value of moist biomass which is proportionate to the fuel moisture content and can be expressed on both dry and wet weight basis. The latter has been used more commonly by the fuelwood trade.

$$q_v(moist_{dr}) = q_v(net) - 2.45 \times \frac{MC}{100 - MC} \quad (2)$$

$$q_v(moist_{wt}) = \frac{q_v(net) \times (100 - MC) - 2.45 \times MC}{100} \quad (3)$$

where
$q_v(moist_{dr})$ = effective heating value of biomass with moisture (MJ/kg of dry biomass)
$q_v(moist_{wt})$ = effective heating value of biomass with moisture (MJ/kg of wet biomass)
MC = the moisture content on green weight basis (%)

Leco AC-300, a microprocessor-based isothermal-jacket bomb calorimeter, was used to determine the calorimetric heating values. It includes a master cabinet for loading the bomb and the housing of electronics; a control console for operations and data editing; LB-80 analytical balance; and a vessel compartment.

The complete description of the calorimetric analysis is given by Nurmi (1993, p. 10). Hence only the outline of the analysis is given here. The pelletized and weighed sample is combusted in a pressurized combustion chamber of the calorimeter. The heating value is calculated on the bases of the temperature profile of the water jacket. The moisture content of the sample is entered and the calorimeter calculates the calorimetric value for an oven dry sample. The calorimetric values are then converted to effective heating values on dry basis using Formula 1. Nitrogen and sulphur contents were not analyzed as wood contains them in such minute quantities that they can be omitted when calculating heating values. A benzoic acid standard was used to calibrate the system. A total of 950 determinations were made from the 14 sample trees.

To test the effect of tree species on the heating value of a given tree component the sample tree data was pooled. The number of samples per tree component varied from 2 in the case of stumpwood to 10 in the case of stemwood and bark. The analysis of variance and Duncan's multiple range tests were used. Due to the low number of stumpwood samples good judgement has to be used when reffering to this data. Furthermore analysis of variance with repeated measures was used to test the significance of relative stem height, branch and root diameter on the heating value.

The regression analysis on chemical composition was done separately for wood and the two bark components. Lignin, carbohydrates, extractives soluble in organic solvents and hot water (ESOS), and alkali soluble extractives were used as dependent variables and matched with the corresponding heating values. There is one exception to the rule and that is the chemical composition at 20 % relative height. Unfortunately the sampling heights for chemical and calorimetric analysis are not the same at the base of the stem. Hence, it was decided to use the average $q_v(net)$ value from 10 and 30 % relative heights to match with the chemical composition from 20 % height.

It is realized by the author that the data presented in this study is made up of a small number of sample trees. For this reason stemwood-stembark and stem-crown proportions were quoted from larger biomass studies to calculate the weighted heating values of crown, stem, whole-tree and stump-root biomass. The proportions and the references used are listed in the Appendix 3. In some cases no previous information was available for a given component. In that case the data collected in this study was used. Also, the data on the inner-outer bark ratio is an outcome of this study.

3 Results and Discussion

3.1 Heating Value of Wood Components

The heating value of any fuel is dependent on its chemical composition. Biofuels are made of three basic elements: carbon, oxygen and hydrogen. They usually make up 95 % of the dry matter. When carbon and hydrogen are combusted they generate heat. The higher their share of the combusted material, the higher the heat output. Oxygen has a contrary effect because it is already present in abundant quantities in the air. Wood and bark matter are made of cellulose, hemicellulose, lignin and a number of extracts, i.e. resins, terpines and waxes. Cellulose and its monosaccharide sugars are lower in carbon and hydrogen than the other chemical compounds making it lower in thermal energy in comparision with lignin (Kollmann 1951).

The analysis of variance and Duncan's multiple range test were carried out to test if species is a factor that has a significant affect on the $q_v(net)$ of any given tree part. The test statistics support the hypothesis that heating value should not be the same for all species (Table 2). Pine has the highest $q_v(net)$ (19.532 MJ/kg) and spruce the second highest (19.163 MJ/kg) of all stemwoods. This is primarily caused by the higher lignin content and secondly by a slightly higher ESOS content. The case is much the same as with small-sized trees (Nurmi 1993). When comparing the heating values of the stemwood of small-sized and mature trees significant differences were found in alders, aspen and silver birch (Table 3). In Fig. 2a we see that the heating value of stemwood is independent of the relative stem height.

Branch, stump and root wood components were also submitted to Duncan's multiple range test. The results of Table 2 support the hypothesis of all species not having the same $q_v(net)$. In the case of branch wood, conifers have significantly higher heating values than broad-leaved species. This could be due to the compression wood which is formed in the lower side of coniferous branches. This wood is characterized by increased lignin content and hence by a higher $q_v(net)$. The difference between pine and spruce branch wood to the advantage of pine is not quite clear in the face of the evidence. However, it does seem that the difference is caused by the greater quantity of ESOS present in pine branch wood (Appendix 1). Fig.

Table 2. Effective heating values in dry basis (MJ/kg) and test statistics for wood components.

Tree part	Species							F-ratio
	P. sylvestris	*P. abies*	*B. pubescens*	*B. pendula*	*A. incana*	*A. glutinosa*	*P. tremula*	
Stem	19.532^{a}_{a}	19.163^{b}_{a}	18.571^{c}_{a}	18.417^{d}_{a}	18.761^{e}_{a}	18.497^{cd}_{a}	18.430^{f}_{a}	78.76***
Branches	19.989^{a}_{b}	19.300^{b}_{a}	18.644^{ce}_{a}	18.568^{c}_{a}	18.875^{d}_{a}	18.508^{c}_{a}	18.812^{de}_{b}	52.54***
Stumps	22.362^{a}_{c}	19.175^{b}_{a}	18.613^{b}_{a}	18.500^{b}_{a}	19.271^{b}_{b}	18.909^{b}_{b}	18.319^{b}_{a}	21.61***
Roots	19.324^{a}_{a}	19.334^{a}_{a}	18.596^{b}_{a}	18.503^{b}_{a}	18.828^{c}_{b}	18.979^{c}_{b}	18.298^{d}_{a}	46.24***
F-ratio	49.22**	1.76	0.09	0.72	3.30*	43.45***	39.53***	

The figures indicated with a different upper index in horizontal direction and lower index in vertical direction differ from each other at 5 % significance level.

Table 3. Effect of tree size on the heating values of stem and branch wood.

Tree component	Tree size	Species						
		Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*
Stem	Large	19.532	19.163	18.571	18.417	18.761	18.497	18.430
	Small	19.308	19.048	18.617	18.611	18.670	18.883	18.668
	F-ratio	1.62	5.73	1.87	7.53*	14.16**	139.57***	60.36***
Branches	Large	19.989	19.300	18.644	18.568	18.875	18.508	18.812
	Small	19.895	19.704	18.766	18.729	18.985	18.637	18.776
	F-ratio	0.24	11.68**	1.57	5.21*	0.34	1.36	0.41

2b shows that excluding black alder the branch diameter is not a significant factor. However, one should be careful with the interpretation of the results as they are made of only two samples per diameter class.

Where the $q_v(net)$ of stumpwood is concerned, pine has a significantly higher value from all the other species (Table 2). This difference is caused by the high content of ESOS. Pine stumpwood contains some 18–20 % of these extractives whereas spruce and birches contain only 3–6 %. When all the other species average about 19 MJ/kg, pine is 17 % higher at 22.4 MJ/kg, which puts it in advantage over all other species.

Species is also a significant factor in rootwood heating value. However, no significant differences were found within the genera *Betula* and *Alnus*. Conifers show the highest $q_v(net)$ which could be caused by the relatively high levels of lignin. There is no significant difference between the two coniferous genera in $q_v(net)$ (Table 2). As with the branch wood the heating value of root wood does not seem to be effected by the root diameter (Fig. 2c).

It was also tested whether heating value changes from one part of the tree to another. This was done separately for each species. It was found out that the $q_v(net)$ of spruce, downy and silver birch wood did not show significant differences within the tree (Table 2). However, the two alder species and aspen did. Aspen branches were significantly higher in $q_v(net)$ than the rest of the tree. Alders on the other hand had higher heating values in the stump-root system. The effect of the tree part is most significant in pine. Stump and branch wood are significantly higher in $q_v(net)$ than stem- and rootwood. The reasons behind this significance are traced back to the chemical structure as discussed above.

The relationship between the heating value and the chemical composition of wood is demonstrated in simple linear regression equations in Appendix 4. Only those cases are listed where the probability of $\beta = 0$ is less than 5 %. It was found that single tree components do not provide good correlation due to the low degree of variation both in the independent and dependent variables. This means that the chemical composition of any single component may not be predicted by the heating value. Hence, the pooling of different combinations of tree components was tried. This means that what really was tested was the variability between the tree components.

Of all the regressions those with pine stumps included had the lowest probabilities. This is caused by the high extractive content leading to a high $q_v(net)$ and is seen as a positive slope of the equation. On the other hand stumpwood is low in lignin and hence, the slopes of regressions predicting lignin content are negative. Spruce wood, however, is so uniform in terms of lignin content that it can not be significantly predicted with any combination of tree parts.

Heating value does not correlate to a high degree with carbohydrate content of either conifer species. Not even when data from different wood components are pooled. Earlier it has been suggested by Nurmi (1993) that on the basis of data on small-sized trees it might be possible to predict carbohydrate content by determining the heating value of wood. However, the data on mature trees does not give a very convincing evidence of this relationship.

The lignin content of downy birch could be predicted with a number of combinations of tree parts, but carbohydrate and ESOS content did not correlate with heating value at all. The lignin content of silver birch correlated with heating value only when both stem and branch wood data were included in the analysis, whereas the content of ESOS correlated with heating value in many combinations of tree part (Appendix 4).

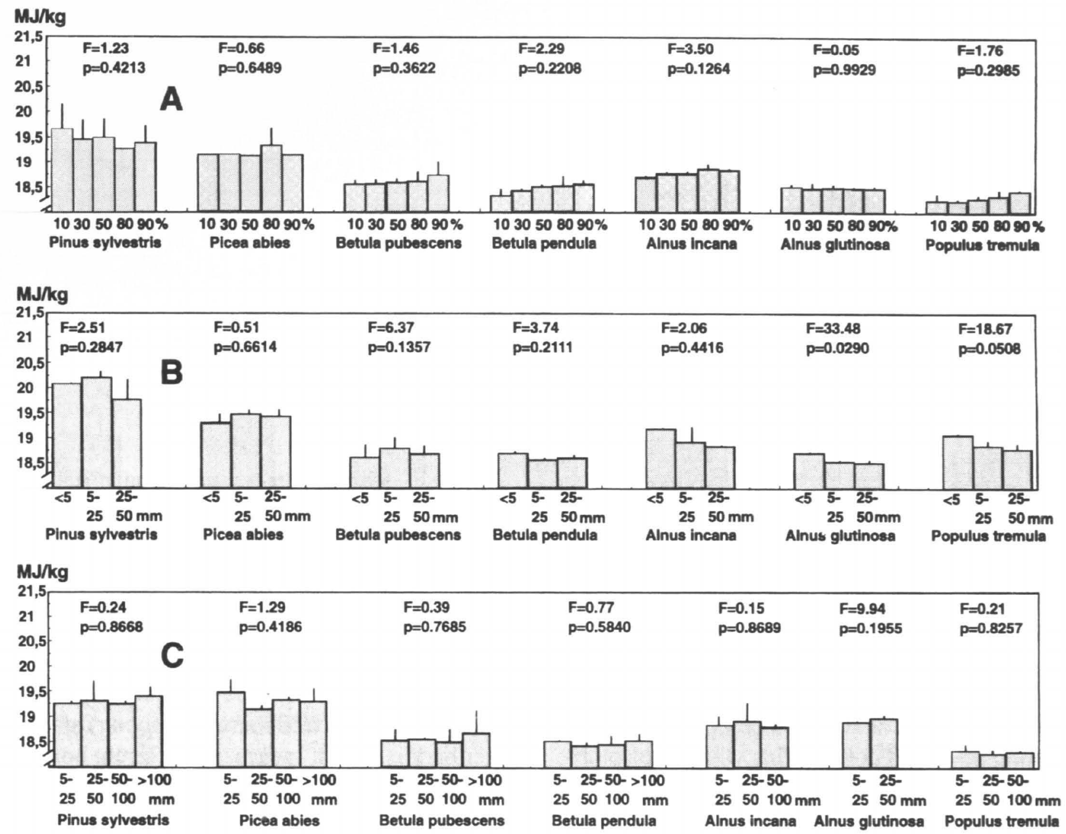

Fig. 2. Effective heating values (MJ/kg) of wood by species: (A) on the stemwood at different relative stem heights, (B) the branch wood in different diameter classes and (C) the root wood in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

3.2 Heating Value of Bark Components

3.2.1 Inner Bark

In the forest industry inner and outer bark are handled as one component. In this study, however, bark is divided into inner and outer bark. This is done to provide basic information on the chemical composition and heating value of these two bark components of different physiological origins. Depending on the species they make up 7–16 % of the dry stem mass (Appendix 3). On average 50–75 % of the bark component is inner bark. In comparison with wood, bark is more complex in chemical structure. It contains compounds that are present in wood in only minor

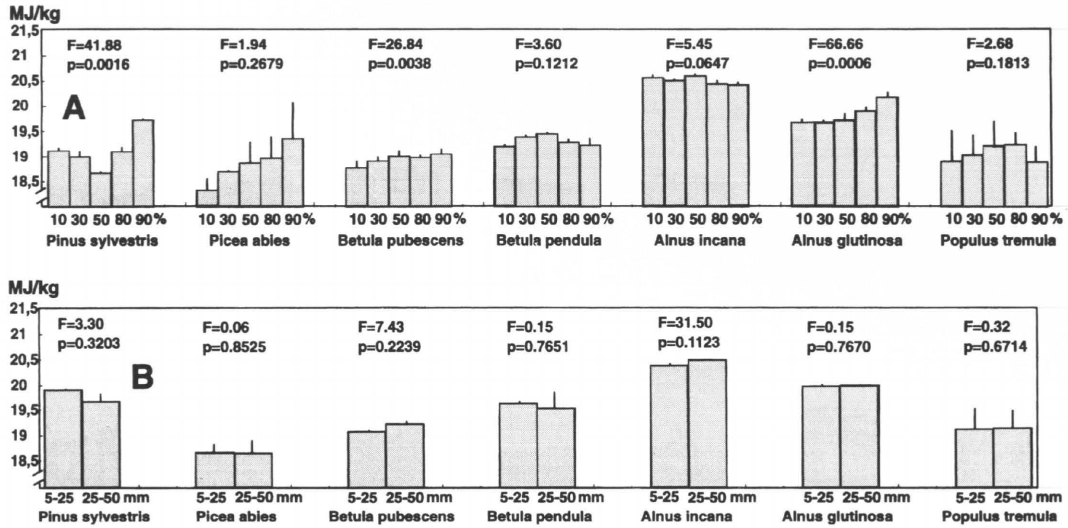

Fig. 3. Effective heating values (MJ/kg) of inner bark by species: (A) on the stem at different relative stem heights, (B) on the branch in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

quantities or not at all. Such compounds include fenolic acids and polyestolids which are soluble only in alkaline solvents.

The effect of relative stem height on heating value is shown by species in Fig. 3a. The $q_v(net)$ of inner bark of some species demonstrates more sensitivity to the stem height than wood. The relative stem height is a significant factor on the heating value of pine, downy birch and black alder. Similar phenomena was observed with small-sized trees (Nurmi 1993). The test statistics support the hypothesis which assumes that $q_v(net)$ should not be the same in all species (Table 4).

When the effect of tree size on the $q_v(net)$ of stem inner bark is tested, spruce, silver birch, both alders and aspen demonstrated significant differences (Table 5). Most commonly the mature trees had higher heating values.

The $q_v(net)$ of branch inner bark was determined only on those branches over 5 mm in diameter. There is about the same amount of variability between species in branch inner bark as in stem inner bark (Table 4). When tree size is tested we find statistically significant differences only in alders and downy birch (Table 5). With alders it is for the advantage of mature trees and with downy birch for the advantage of the small-sized trees. The branch diameter has no effect on the $q_v(net)$ (Fig. 3b).

Conifers and broad-leaved species are distinctly different in chemical composition. Coniferous inner bark contains low quantities of lignin, whereas in broad-leaved species the concentration is threefold. Conifers on the other hand have twice as high concentrations of ESOS than the broad-leaved species (Appendix 1).

Pine inner bark is very uniform in chemical composition and heating value. Hence, no correlation was found between these two variables. Individual components of spruce and birch species do not show significant correlation either. However, when data from stem and branches is pooled these species do show correlation with some combination of heating value and a chemical composition. In birch species the significant correlation is found with carbohydrates, and in spruce with the ESOS (Appendix 4). It should be noted that this significance is strictly caused by the differences between and not within tree components.

Table 4. Effective heating values in dry basis (MJ/kg) and test statistict for inner bark.

Tree part	Species							F-ratio
	P. sylvestris	*P. abies*	*B. pubescens*	*B. pendula*	*A. incana*	*A. glutinosa*	*P. tremula*	
Stem	18.976^{ab}_{a}	18.619^{a}_{a}	18.869^{a}_{a}	18.318^{b}_{a}	20.541^{c}_{a}	19.726^{d}_{a}	19.204^{ab}_{a}	43.63***
Branches	19.277^{a}_{a}	17.866^{b}_{b}	18.494^{c}_{b}	19.073^{a}_{b}	20.111^{d}_{b}	19.548^{e}_{a}	18.459^{c}_{b}	53.83***
F-ratio	0.85	14.62**	45.87***	4.89*	72.35***	8.21*	7.36*	

The figures indicated with a different upper index in horizontal direction and lower index in vertical direction differ from each other at 5 % significance level.

Table 5. Effect of tree size on the heating value of stem and branch inner bark.

Tree component	Tree size	Species						
		Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*
Stem	Large	18.976	18.619	18.869	19.318	20.541	19.726	19.204
	Small	18.758	17.844	18.965	18.846	20.141	19.262	18.049
	F-ratio	1.71	31.9***	0.30	51.22***	40.11***	45.04***	39.16***
Branches	Large	19.277	17.866	18.494	19.073	20.111	19.548	18.459
	Small	19.441	18.481	18.985	18.763	19.491	19.413	17.822
	F-ratio	3.80	5.12	10.87*	1.57	68.41**	97.65***	4.18

3.2.2 Outer Bark

Outer bark is a less important fuel than wood or even inner bark when evaluated in terms of quantity. In those included in this study it made up only 3 % of the oven dry stem mass. However, outer bark presents more variability between species in terms of chemical structure and heating value than wood or inner bark. In general the coniferous outer bark has distinctly lower heating values than the broad-leaved species. This is because coniferous outer bark is rich in carbohydrates but low in extractives (Appendix 1).

Although the $q_v(net)$ seems to be effected by the relative stem height this factor seems to be a more significant one only with the conifers and alders (Fig. 4). With these species the trend of heating value along the stem is much like those of the small-sized trees (Nurmi 1993). Table 6 shows the difference between species to be as much as 11 MJ/kg. This is much higher than with wood and inner bark components, but it is about the same as that which was observed with the small-sized trees (Nurmi 1993). The test statistics of analysis of variance shows species to be a highly significant factor.

The highest heating values are found in the birch species (Fig. 4). This is caused by the high extractive concentration, mainly betulin (ESOS) and suberin (alkali soluble). According to Ekman (1983) birch outer bark contains 315 g of triterpenoids per kilogramme of bark and betulinol accounts for 77 % percent of that amount. The amount of suberin is 322 g/kg. In addition it should also be noted that the low ash content of birch bark contributes to the high heating value (Voipio and Laakso 1992) . As with the small-sized trees there is no statistical difference in the heating value of the two birch species (Table 6).

The next highest heating values are found in grey alder followed by black alder. The $q_v(net)$ of mature grey alder peaks at the center of the stem as did the $q_v(net)$ of small-sized ones (Nurmi 1993). The effect of tree size on the heating value is very

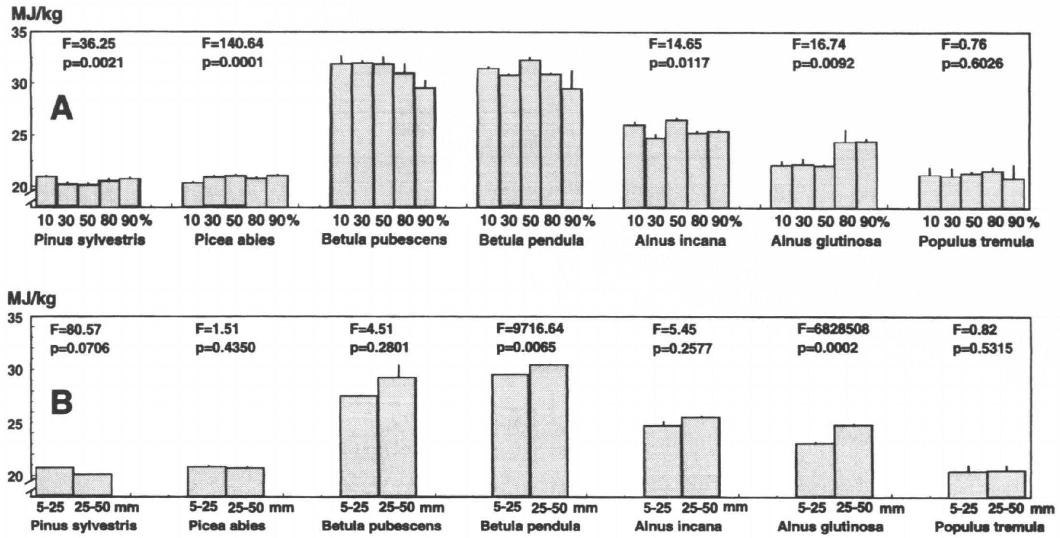

Fig. 4. Effective heating values (MJ/kg) of outer bark by species: (A) on the stem at different relative stem heights and (B) on the branch in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

Table 6. Effective heating values (MJ/kg) and test statistics for outer bark.

Tree part	Species							F-ratio
	P. sylvestris	*P. abies*	*B. pubescens*	*B. pendula*	*A. incana*	*A. glutinosa*	*P. tremula*	
Stem	20.558^{a}_{a}	20.721^{a}_{a}	31.859^{b}_{a}	31.322^{b}_{a}	25.677^{c}_{a}	22.452^{d}_{a}	21.401^{a}_{a}	288.55***
Branches	20.363^{a}_{a}	20.771^{a}_{a}	28.527^{b}_{b}	29.870^{c}_{a}	25.149^{d}_{a}	23.924^{d}_{a}	20.482^{a}_{a}	53.83***
F-ratio	0.94	0.17	18.26***	4.11	1.2	3.11	3.89	

The figures indicated with a different upper index in horizontal direction and lower index in vertival direction differ from each other at 5 % significance level.

Table 7. Effect of tree size on the heating value of stem and branch outer bark.

Tree component	Tree size	Species						
		Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*
Stem	Large	20.558	20.721	31.859	31.322	25.677	22.452	21.401
	Small	20.309	20.542	31.433	32.045	28.900	23.286	21.202
	F-ratio	0.02	0.15	0.46	2.80	110.70***	1.13	0.33
Branches	Large	20.363	20.771	28.527	29.870	25.149	23.924	20.482
	Small	21.166	20.691	27.580	28.548	26.758	25.901	21.886
	F-ratio	3.10	0.46	5.87*	2.94	17.31**	2.02	13.49*

Table 8. Effective heating values (MJ/kg) and test statistics for bark on branches less than 5 mm in diameter, root bark and foliage.

Tree component	Species							F-ratio
	Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*	
Bark on branches < 5 mm in diameter	21.387a	20.266bc	20.576c	20.133bc	21.845a	21.755a	19.687b	15.42**
Root bark	20.427a	19.549b	19.652b	20.179a	20.362a	19.611b	19.593b	5.72***
Foliage	21.038a	19.188b	19.357b	19.757ab	20.367ab	19.784ab	19.852ab	2.82

Means indicated with the same letter in horizontal direction do not differ from each other at 5 % significance level.

significant. The difference in $q_v(net)$ is as much as 3.3 MJ/kg in favour of the small-sized trees. This is the only case where the stem outer bark is significantly effected by stem size (Table 7).

The sensitivity of black alder heating value to the stem height is statistically significant, but it is much less pronounced than on small-sized black alder stems (Nurmi 1993). Although the chemical compositions of large diameter alders were not determined we know from the data on small-sized trees that this is the result of the increase in extractive content from the base to the top of the tree.

The heating values of the outer bark of branches over 5 mm in diameter are very similar to the stem material. In Table 6 we can see that the only significant difference between stem and branch material was found in downy birch. This suggests that the chemical composition should be rather uniform throughout the trees. Also the branch diameter is an insignificant factor with most species silver birch and black alder being the only exceptions (Fig. 4).

The chemical composition of pine and spruce stem bark did not correlate with the $q_v(net)$ in any combination of tree parts, not even when the stem and branch data were pooled. On the other hand downy birch stem bark demonstrated correlation with ESOS (p = 0.01) and lignin (p = 0.05). Similarly correlation in silver birch stem bark was found between carbohydrates and $q_v(net)$. Additionally, in the case of downy birch the combined $q_v(net)$ data on stem and branches correlates with carbohydrates and ESOS. Both correlations were caused by the differences in heating value and chemical composition between the two tree components (Appendix 4).

3.2.3 Bark on Small Branches

Half of the dry mass of small branches less than 5 mm in diameter is bark. This bark contains both inner and outer bark. Hence, the $q_v(net)$ falls in between the heating values of the two bark components of larger branch diameters. This is also supported to some extent by the analysis on chemical composition (Appendix 1). Pine is an exception to the rule as its $q_v(net)$ is higher than the value of either inner or outer bark values of the larger branches. The same was observed with small-sized pine trees (Nurmi 1993). The only two indications why this should be is that pine bark on small diameter branches is rather high in ESOS (Appendix 1) and low in ash content (Voipio and Laakso 1992). The magnitude of heating values and the test statistics are shown in Table 8.

3.2.4 Root Bark

In comparison with stem and branch bark, root bark is higher in lignin but lower in carbohydrates and extractives (Appendix 1). The heating value of coniferous bark is higher on roots than on stems, the case being the opposite with the

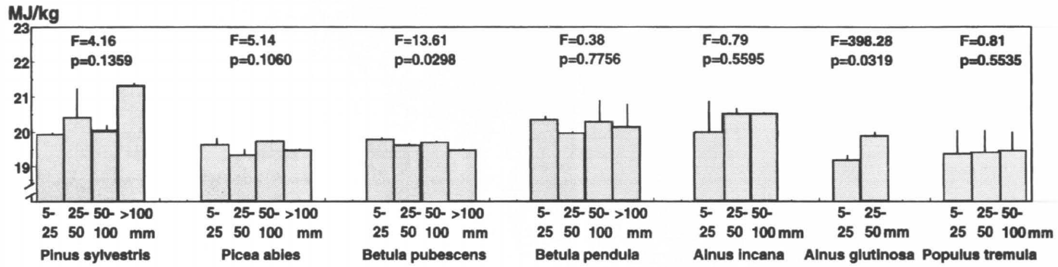

Fig. 5. Effective heating values (MJ/kg) of root bark by species in different diameter classes. The statistical significance of diameter class shown above.

broad-leaved species. Although there is less variability among root bark than among stem bark, the species is still a significant factor (Table 8). On the other hand root diameter is not a significant factor, the exceptions being downy bich and black alder (Fig. 5).

3.3 Foliage

The significance of tree species on the $q_v(net)$ of foliage is low. Pine is the only one to be significantly different from the other species (Table 8). It is known from literature that pine needles have a much lower ash content than the foliage of other species (Hakkila and Kalaja 1983, Voipio and Laakso 1992). This a more convincing reason for the difference than the one given by the combustible chemical components of this study. Making decisions on the bases of lignin, carbohydrate or extractive composition involves quite a deal of uncertainty as the analysis of variance for the pooled data gives low probability values. The lignin content of pine is lower and carbohydrate content higher than in other species. Based on previous knowledge on the $q_v(net)$ of carbohydrates and lignin the opposite outcome should be more likely. Olofsson (1975) reports similar values for the pine foliage but his figures for spruce are 0.8 MJ/kg higher than the values reported in this study. A difference of the same magnitude was also observed for the spruce foliage of small-sized trees (Nurmi 1993). When comparing the $q_v(net)$ of the foliage of mature trees with that of small-sized trees the species are roughly in the same order of magnitude.

3.4 Weighted Heating Value of the Above and Below Ground Biomass

3.4.1 Crown and Logging Residue

The crown is formed by branches including wood, bark and foliage. Bark accounts for roughly one third of the live branch mass without foliage. This enhances the heating value of crown biomass as the heating value of bark is higher than that of wood (Tables 9 and 10). Foliage is another major component of the live crown. This is especially true in conifer stands. It accounts for 25.7 % of mature pine and 37.6 % of spruce crowns (Hakkila 1991).

Pine has the highest and aspen the lowest foliage free crown heating value. Other species were intermediate. The foliage-bearing crown material of pine is as much as 1 MJ/kg higher in heating values than spruce (Table 10). This is explained by the difference in the $q_v(net)$ of foliage which is 1.85 MJ/kg higher in pine. Olofsson (1975) reported 0.2–0.4 MJ/kg higher figures for foliage-bearing conifer branches than those determined in this study. This difference could be caused by the difference in the research methods used. In Olofsson's study heating values were determined from an intermixed branch sample of wood, bark and foliage. In this study, however, heating values were separately determined for each component and the weighted heating value for the branch mass was calculated.

From the standpoint of fuelwood procurement the crown mass should receive much attention as it accounts for as much as 85–90 % of spruce logging residue. Of all the forest biomass reserves it

Table 9. Effective heating values (MJ/kg) of wood, bark and foliage components of branches over and under 5 mm.

Species	Wood			Bark				Foliage	Crown without foliage
	> 5 mm	< 5 mm	Total branch	Inner	Outer	< 5 mm	All bark		
P. sylvestris	20.01	19.96	19.99	19.28	20.36	21.39	20.30	21.04	20.09
P. abies	19.36	19.23	19.30	17.87	20.77	20.27	19.60	19.19	19.41
B. pubescens	18.68	18.57	18.64	18.49	28.53	20.58	21.03	19.36	19.33
B. pendula	18.53	18.65	18.57	19.07	29.87	20.13	21.78	19.76	19.61
A. incana	18.83	19.11	18.88	20.11	25.15	21.85	21.69	20.54	19.74
A. glutinosa	18.48	18.66	18.51	19.55	23.92	21.76	21.29	19.78	19.47
P. tremula	18.76	19.00	18.81	18.46	20.48	19.69	19.20	19.02	18.96

Table 10. Effective heating values (MJ/kg) of the crown components.

Component	Species						
	P. sylvestris	*P. abies*	*B. pubescens*	*B. pendula*	*A. incana*	*A. glutinosa*	*P. tremula*
Bark	20.30	19.60	21.03	21.42	21.69	21.25	19.20
Wood	19.99	19.30	18.64	18.57	18.87	18.51	18.81
Crown without foliage	20.09	19.41	19.33	19.61	19.74	19.47	18.96
Foliage	21.04	19.19	19.36	19.76	20.37	19.78	19.85
Crown with foliage	20.33	19.33	..	..	..	..	..

is this residue from regeneration cuttings which is most readily available for energy production. Annually about 29 Mm^3 of this material is created by wood harvesting of which 8.6 Mm^3 is considered harvestable (Hakkila and Fredriksson 1996). In comparison with the harvesting of small-sized trees from over-stocked stands residue from clearcuts can be handled as a mass item with conventional forest machines. This has at least two advantages. The cost of fuel per produced megawatt hour is lower and the regeneration of the forest becomes easier when the residue is removed. As a result residue from clearcuts is considered a more attractive source of fuelwood than small-sized trees.

Residue harvesting involves some storage and seasoning of the fuel stock. As a result varying amounts of foliage will fall off. From the ecological standpoint this may be beneficial if seasoning takes place on a clear cutting area and not at the landing. Table 10 contains figures for foliage free crown. In the case of conifers it also gives heating values with foliage intact. This is because the most sophisticated combustion plants are able to consume wet material and still utilize the energy in the exhaust steam through a condensation process. It also makes sense from the harvesting point of view to harvest the crown material with foliage as it significantly increases harvesting yield and productivity.

In addition to the crown, the harvesting residue also contains the top section of the stem. The proportion of the top section in the residue is dependent on the top diameter of the merchantable stem. This diameter on the other hand depends on a given wood market situation. For spruce, however, Nurmi (1997) has measured the proportion of the residual stem section of spruce crowns. This proportion has a negative correlation coefficient with stem volume. The residual stem section of a 500 liter stem accounted for 11.5 % of the total residual dry mass. The weighted $q_v(net)$ for spruce har-

Table 11. Effective heating values (MJ/kg) of stump and root components.

Species	Root wood	Root bark	Whole roots	Stump	Stump-root system
P. sylvestris	19.32	20.43	19.51	22.36	21.02
P. abies	19.33	19.55	19.38	19.18	19.32
B. pubescens	18.60	19.65	18.84	18.61	..
B. pendula	18.50	20.18	18.97	18.50	..
A. incana	18.83	20.38	19.28	19.27	..
A. glutinosa	18.98	19.66	19.17	18.91	..
P. tremula	18.30	19.73	18.78	18.32	..

Table 12. Effective heating values (MJ/kg) of oven dry stem components.

Species	Wood	Bark			Weighted stem mean
		Inner	Outer	All bark	
P. sylvestris	19.53	18.98	20.56	19.77	19.55
P. abies	19.16	18.62	20.72	19.11	19.16
B. pubescens	18.57	18.87	31.86	22.47	19.06
B. pendula	18.42	19.32	31.32	22.08	18.96
A. incana	18.76	20.54	25.68	21.15	19.14
A. glutinosa	18.50	19.73	22.45	21.31	18.90
P. tremula	18.43	19.20	21.40	19.87	18.62

vesting residue is 19.316 MJ/kg. This is slightly less than the heating value of spruce crown material. However, the difference is so small that any difference in moisture content will rule out this difference.

3.4.2 Stump-Root System

According to Hakkila (1989) the stump-root system is defined as "all below- and above-ground wood and bark mass of a tree below the stump cross-section". Putting the economical considerations aside, pine and spruce are the only species to provide plentiful raw material for harvesting stump-root systems. The average heating values of stump-root system of these two species are reported in Table 11. The stump and root proportions in the complete stump-root system are based on Hakkila's (1975) results. Much of the mass of the pine stump-root system is concentrated on the stump component. Hence, the $q_v(net)$ is as high as 21.023 MJ/kg. Unlike pine the majority of spruce stump-root mass is in the root component. This, however, has very little effect on the weighted heating value (19.316 MJ/kg) as the heating values of stumps and roots are not so different. The proportion of stump-root system of the merchantable stem volume is about 22–24 % in both species (Hakkila 1972). Hence, pine does appear as a more atractive alternative for fuelwood harvesting than spruce. However, this difference in heating value for the benefit of pine may well be compensated for by the higher harvesting productivity of spruce harvesting. On one hand this is due to the more superficial root system of spruce. On the other hand the greater number of small diameter roots makes it more difficult and time consuming to clean pine roots (Hakkila et.al. 1974).

3.4.3 Stems

The proportions of wood, inner bark and outer bark components vary with the relative stem height and age of the tree (Taras 1978, Hakkila et al. 1975). The majority of stem mass is concentrated in the wood proper (Appendix 3). This makes it the single most important component to consider when a heating value for the whole stem is calculated.

Table 12 shows that in all species the heating value of outer bark is higher than the heating value of wood or inner bark. Although outer bark is higher in heating value than the other two components there is only a small amount of it. Hence, it makes a lesser contribution to the average heating value of stem biomass than inner bark. For example the high $q_v(net)$ of the birch outer bark has relatively little effect on the weighted $q_v(net)$ of stem biomass. This is also supported by Sandala et. al. (1981) who reported on the heating values of three broad-leaved species from the northeastern United States. Furthermore, the heating value of combined inner and outer bark is higher than that of wood for all species except for spruce. The same fact has been observed on small-sized trees (Nurmi 1993). Musselman and Hocker (1981) and Singh and Kostecky (1986) found that North American species in the genera *Pinus*, *Picea*, *Betula* and *Populus* had higher heating values in bark as well. Olofsson (1975) has also reported pine, birch and spruce bark to be higher in heating value than wood.

3.5 Heating Value of Biomass with Moisture

In spite of the large differences in proportions and $q_v(net)$ of tree components the differences between species actually turn out to be small for crown, whole stem or stump-root material. This has also been shown earlier by Olofsson (1975) and Nurmi (1993). From the practical point of view moisture content is a much more significant factor. This is because the moisture in wood needs to be evaporated and the energy required to evaporate it comes from the fuel itself. This means that the higher the moisture content, the less energy is yielded by the fuel. All types of fuelwood always contain some moisture. How high the biomass moisture content is depends on the harvesting schedule, i.e. when fuelwood is harvested; how, when and in what form it is stored; what time of the year it is comminuted. Only those modern heating plants capable of retrieving the heat of condensation from the flue gasses may overlook the moisture content to some extent.

For the reader's convenience the effective heating values of crown, stem, whole-tree as well as stump-root biomass are presented in Table 13 on dry weight basis and in Table 14 on wet weight basis. The latter table is a more convenient one for heating plant staff and the procurement organizations in everyday use as this form of expression is more common to the trade. Those interested in other moisture contents should refer to the Formulas (2) and (3) in Chapter 2.3.

Table 13. Effective heating values of mature whole-tree biomass (MJ/kg of dry biomass) as a function of moisture content.

Tree part	Species	Moisture content, %						
		0	10	20	30	40	50	60
Crown	*P. sylvestris*	20.09	19.81	19.47	19.03	18.45	17.63	16.41
	P. abies	19.41	19.14	18.80	18.36	17.78	16.96	15.73
	B. pubescens	19.33	19.06	18.72	18.28	17.69	16.88	15.65
	B. pendula	19.61	19.34	19.00	18.56	17.98	17.16	15.94
	A. incana	19.74	19.47	19.13	18.69	18.11	17.29	16.07
	A. glutinosa	19.47	19.19	18.85	18.42	17.83	17.02	15.79
	P. tremula	18.96	18.69	18.35	17.91	17.32	16.51	15.28
Stem	*P. sylvestris*	19.55	19.28	18.94	18.51	17.92	17.11	15.88
	P. abies	19.16	18.95	18.61	18.17	17.59	16.77	15.54
	B. pubescens	19.06	18.78	18.44	18.01	17.42	16.61	15.38
	B. pendula	18.96	18.69	18.35	17.91	17.33	16.51	15.29
	A. incana	19.14	18.87	18.53	18.09	17.51	16.69	15.46
	A. glutinosa	18.90	18.6	18.28	17.85	17.26	16.45	15.22
	P. tremula	18.62	18.34	18.00	17.56	16.98	16.16	14.94
Whole-tree	*P. sylvestris*	19.63	19.37	19.03	18.59	18.01	17.19	15.96
	P. abies	19.24	19.01	18.67	18.23	17.65	16.83	15.61
	B. pubescens	19.09	18.82	18.48	18.04	17.46	16.64	15.42
	B. pendula	19.05	18.78	18.44	18.00	17.42	16.60	15.38
	A. incana	19.22	18.96	18.62	18.18	17.59	16.78	15.55
	A. glutinosa	19.00	18.73	18.39	17.95	17.37	16.55	15.32
	P. tremula	18.66	18.38	18.04	17.60	17.02	16.20	14.98
Stump/root system	*P. sylvestris*	21.02	20.75	20.41	19.97	19.39	18.57	17.35
	P. abies	19.32	19.04	18.70	18.27	17.68	16.87	15.64

Table 14. Effective heating values of mature whole-tree biomass (MJ/kg of wet biomass) as a function of moisture content.

Tree part	Species	Moisture content, %						
		0	10	20	30	40	50	60
Crown	*P.sylvestris*	20.09	17.84	15.58	13.33	11.07	8.82	6.57
	P. abies	19.41	17.22	15.04	12.85	10.67	8.48	6.29
	B. pubescens	19.33	17.15	14.97	12.80	10.62	8.44	6.26
	B. pendula	19.61	17.40	15.20	12.99	10.79	8.58	6.37
	A. incana	19.74	17.52	15.30	13.08	10.86	8.65	6.43
	A. glutinosa	19.47	17.28	15.09	12.89	10.70	8.51	6.32
	P. tremula	18.96	16.82	14.68	12.54	10.40	8.26	6.11
Stem	*P. sylvestris*	19.55	17.35	15.15	12.95	10.75	8.55	6.35
	P. abies	19.16	17.00	14.84	12.68	10.52	8.36	6.19
	B. pubescens	19.06	16.91	14.76	12.61	10.46	8.31	6.15
	B. pendula	18.96	16.82	14.68	12.54	10.40	8.26	6.11
	A. incana	19.14	16.98	14.82	12.66	10.50	8.35	6.19
	A. glutinosa	18.90	16.77	14.63	12.50	10.36	8.23	6.09
	P. tremula	18.62	16.51	14.41	12.30	10.19	8.09	5.98
Whole-tree	*P.sylvestris*	19.63	17.42	15.21	13.01	10.80	8.59	6.38
	P. abies	19.24	17.07	14.90	12.73	10.56	8.40	6.23
	B. pubescens	19.09	16.94	14.78	12.63	10.47	8.32	6.17
	B. pendula	19.05	16.90	14.75	12.60	10.45	8.30	6.15
	A. incana	19.22	17.05	14.89	12.72	10.55	8.39	6.22
	A. glutinosa	19.00	16.86	14.71	12.57	10.42	8.28	6.13
	P. tremula	18.66	16.55	14.44	12.33	10.22	8.11	5.99
Stump/root system	*P. sylvestris*	21.02	18.67	16.33	13.98	11.63	9.29	6.94
	P. abies	19.32	17.14	14.97	12.79	10.61	8.44	6.26

4 Conclusions

The number of sample trees was small. However, the number of samples per each sample tree was a minimum of 32 not including the three repetitions of each sample. This number of samples is sufficient to give a reliable knowledge on how the heating value varies within the tree. However, the data was not sufficient to make solid conclusions on the species factor on every single tree component.

The species is a significant factor in the heating value of individual tree components. This is in accordance with the earlier study on small-sized trees. The heating value of the wood proper is highest in conifers. This is true with stem, branch and root components. Similarly broad-leaved species have a higher $q_v(net)$ of combined inner and outer bark than conifers. The species factor, however, becomes minor when whole stems or branches are considered. Pine, however, stands out as an exception to the rule as its crown and stump material contain more energy than the same tree parts of other species.

What is interesting from the utilization point of view is that the crown mass of mature trees in comparison with small-sized stems and whole-trees has a higher heating value per unit weight. Additionally, crown material is plentiful in the form of logging residue and can easily be harvested due to its nature. Harvesting this material, however, requires the right harvesting methods (Nurmi 1994, Elonen and Korpilahti 1996). When they are mastered, the harvesting of logging residue has a considerable advantage over the harvesting of small-sized trees for energy. In addition, this is a resource that does not have any industrial use.

The stumps and roots are similarly unsuitable as industrial raw material. Although large volumes of stumps and roots are available on clearcut areas and could provide a source of fuelwood, their harvesting is much more problematic than that of the above ground residue. This brings up the concern over the harvesting cost. The material also contains significant quantities of mineral soil and stones which could damage comminution and combustion equipment.

The variability in chemical composition is small in a given tree component of a given species. Significant correlations between chemical composition and $q_v(net)$ of wood or bark components are found only when the analysis is done by pooling the data on tree components. This means that the variability is actually caused by the differences between tree parts and not within them. Hence, it is concluded that the heating value is a poor indicator of chemical composition within any given part of the tree.

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Total of 25 references

Appendix 1. Chemical composition of biomass components by species. The asterisk (*) indicates combined inner and outer bark on all roots and branches < 5 mm in diameter.

Component	Species	Stem heights, %		Branches, mm				Stump	Roots, mm			Foliage
		20	80	< 5	5–25	25–50	> 50		5–50	50–100	100–200	
Lignin, % of dry weight												
Wood	*P. sylvestris*	26.5	27.3	29.9	32.1	29.5	31.7	24.0	28.4	27.0	26.9	..
	P. abies	27.5	28.3	31.0	30.9	31.5	..	28.7	28.8	28.2	28.0	..
	B. pubescens	19.9	20.3	19.3	20.0	21.3	..	19.5	22.2	21.2	21.5	..
	B. pendula	19.4	19.9	22.2	20.0	20.3	..	8.6	20.9	21.5	19.7	..
Inner bark	*P. sylvestris*	14.5	13.6	21.5*	13.9	12.1	9.9	..	42.3*	41.5*	43.3*	..
	P. abies	9.6	10.1	32.2*	5.3	9.9	..	..	33.0*	33.6*	30.9*	..
	B. pubescens	31.3	36.3	32.7*	26.6	28.6	..	..	38.9*	44.0*	42.8*	..
	B. pendula	33.0	33.1	31.7*	28.5	29.5	..	..	44.3*	44.8*	43.5*	..
Outer bark	*P. sylvestris*	31.7	25.3	..	27.8	30.5	21.5	..	..	..	..	12.2
	P. abies	23.7	28.5	..	26.6	38.3	..	..	..	..	..	16.5
	B. pubescens	38.7	46.0	..	45.1	46.3	..	..	..	..	..	28.9
	B. pendula	33.5	28.1	..	38.9	29.9	..	..	..	..	..	24.7
Carbohydrates, % of dry weight												
Wood	*P. sylvestris*	74.4	71.9	61.8	61.3	65.4	67.3	74.4	72.1	75.1	74.6	..
	P. abies	73.8	73.5	61.0	64.2	63.2	..	73.5	68.7	70.4	71.7	..
	B. pubescens	68.6	67.8	63.8	68.3	72.4	..	67.5	69.7	70.0	70.7	..
	B. pendula	74.3	71.0	64.0	66.8	66.8	..	35.2	68.1	68.9	72.3	..
Inner bark	*P. sylvestris*	61.6	70.5	50.7*	64.2	64.6	65.4	..	32.2*	33.0*	32.1*	..
	P. abies	69.7	68.0	44.2*	64.0	55.9	..	..	40.5*	43.0*	43.1*	..
	B. pubescens	51.5	54.9	26.5*	48.6	47.8	..	..	32.3*	28.8*	28.5*	..
	B. pendula	49.3	49.5	25.7*	47.3	44.9	..	..	21.7*	24.5*	23.5*	..
Outer bark	*P. sylvestris*	41.8	55.5	..	50.3	44.5	54.9	..	..	..	..	66.9
	P. abies	48.1	44.0	..	35.7	36.8	..	..	..	..	..	51.7
	B. pubescens	6.8	5.4	..	9.6	9.0	..	..	..	..	..	30.9
	B. pendula	7.4	6.2	..	7.9	6.7	..	..	..	..	..	40.0
Extractives soluble in organic solvents and hot water (ESOS), % of dry weight												
Wood	*P. sylvestris*	6.0	7.6	12.8	8.6	5.0	7.2	18.7	6.4	6.8	6.0	..
	P. abies	3.7	3.8	8.5	6.3	5.8	..	3.6	6.3	7.2	6.1	..
	B. pubescens	3.7	4.9	9.2	6.5	6.1	..	5.8	8.4	8.7	6.8	..
	B. pendula	2.4	4.1	9.1	6.0	5.2	..	3.6	6.6	5.7	5.0	..
Inner bark	*P. sylvestris*	32.6	32.7	30.6*	28.1	29.9	35.0	..	18.8*	21.7*	20.0*	..
	P. abies	39.2	39.4	17.8*	31.7	35.3	..	..	25.2*	22.6*	26.5*	..
	B. pubescens	16.4	23.0	19.1*	19.2	15.5	..	..	19.4*	18.7*	20.0*	..
	B. pendula	17.8	14.3	17.2*	23.2	18.6	..	..	17.9*	21.6*	22.9*	..
Outer bark	*P. sylvestris*	26.1	22.3	..	20.2	17.9	12.4	..	..	..	..	38.6
	P. abies	33.6	24.8	..	25.2	17.4	..	..	..	..	..	37.8
	B. pubescens	33.3	30.3	..	17.6	22.8	..	..	..	..	..	32.4
	B. pendula	34.4	34.9	..	27.9	30.7	..	..	..	..	..	28.8
Alkali soluble extractives, % of dry weight												
Inner bark	*P. sylvestris*	15.4	15.7	24.1*	14.2	19.7	9.7	..	9.4*	10.9*	10.5*	..
	P. abies	17.2	19.1	26.8*	19.4	24.7	..	..	17.6*	13.6*	15.2*	..
	B. pubescens	10.2	8.9	38.8*	21.5	16.9	..	..	19.4*	24.3*	21.1*	..
	B. pendula	16.0	14.4	40.8*	21.0	14.9	..	..	10.4*	15.3*	10.7*	..
Outer bark	*P. sylvestris*	12.8	20.1	..	22.1	27.4	12.0	..	..	..	..	16.9
	P. abies	14.7	24.6	..	29.0	30.5	..	..	..	..	..	16.8
	B. pubescens	54.1	61.4	..	59.9	59.7	..	..	..	..	..	29.6
	B. pendula	55.3	58.6	..	61.6	61.4	..	..	..	..	..	23.2

Appendix 2. Elemental composition of tree components.

Element/ Species	Wood				Inner bark		Outer bark		All bark		Foliage
	Stem	Branches	Stump	Roots	Stem	Branches > 5mm	Stem	Branches > 5mm	Branches < 5mm	Roots	
Carbon, % of dry weight											
P. sylvestris	52.70	55.59	58.49	54.08	51.86	52.32	54.88	54.72	55.07	55.59	50.49
P. abies	51.48	52.84	52.69	54.08	52.04	48.84	55.54	55.90	54.95	52.32	51.50
B. pubescens	51.68	52.68	51.52	52.67	51.08	51.68	72.77	70.62	54.88	53.28	51.50
B. pendula	51.92	52.37	51.2	51.52	52.44	52.46	72.24	70.24	53.02	54.94	51.00
A. incana	52.72	51.61	51.78	52.24	54.61	54.14	65.07	60.71	55.31	55.11	52.60
A. glutinosa	51.78	51.54	49.02	50.94	53.08	53.33	59.07	60.71	56.34	53.96	50.69
P. tremula	51.86	51.50	51.44	50.70	51.86	50.99	55.70	52.85	52.43	54.19	51.40
Hydrogen, % of dry weight											
P. sylvestris	6.46	6.39	7.07	6.38	5.81	5.60	5.52	5.66	5.77	4.89	6.37
P. abies	6.32	6.52	6.25	6.36	5.79	5.39	5.66	5.46	5.64	5.32	5.78
B. pubescens	6.28	6.38	6.32	6.22	5.63	5.77	9.21	8.93	6.24	5.19	5.84
B. pendula	6.21	6.45	6.15	6.31	5.81	5.79	9.24	9.00	5.87	5.28	6.13
A. incana	6.34	6.33	6.16	6.26	6.07	5.88	7.49	7.08	6.13	5.73	5.89
A. glutinosa	6.23	6.35	6.07	6.15	5.72	5.77	6.03	7.13	6.34	5.52	5.94
P. tremula	6.32	6.28	6.18	6.17	5.88	5.80	6.44	6.33	5.80	5.41	5.90
Nitrogen, % of dry weight											
P. sylvestris	0.07	0.08	0.05	0.08	0.54	0.53	0.25	0.25	0.73	0.37	1.07
P. abies	0.04	0.09	0.08	0.12	0.61	0.39	0.39	0.4	0.53	0.41	0.89
B. pubescens	0.07	0.17	0.08	0.24	0.38	0.39	0.32	0.32	0.65	0.49	1.99
B. pendula	0.04	0.16	0.07	0.17	0.38	0.51	0.33	0.38	0.82	0.61	1.61
A. incana	0.18	0.21	0.22	0.28	0.75	0.91	0.99	1.22	1.45	1.22	3.21
A. glutinosa	0.2	0.33	0.24	0.53	1.17	1.19	0.98	1.14	1.44	1.3	2.7
P. tremula	0.02	0.14	0.13	0.37	1.13	0.91	0.49	0.46	0.75	1.21	1.95

Appendix 3. Stem, crown and whole-tree composition by species. The division of stem and branch biomass into wood and bark, and the division of whole-tree into crown and stem are based on referenced biomass studies.

Stem composition, %

Species	Bark division*		Stem division		References
	Inner	Outer	Wood	Bark	
P. sylvestris	49.4	50.6	92.7	7.3	Hakkila 1967
P. abies	77.4	22.6	90.8	9.2	Hakkila 1967
B. pubescens	72.7	27.3	87.6	12.4	Data collected in this study
B. pendula	76.9	23.1	85.1	14.9	Data collected in this study
A. incana	87.5	12.5	84.3	15.7	Data collected in this study
A. glutinosa	41.9	58.1	85.6	16.6	Björklund 1984
P. tremula	70.3	29.7	88.0	13.3	Kärkkäinen 1980

Crown composition, %

Species	Branches > 5 mm				Branches < 5 mm		Total branch	
	Bark		Branch					
	Inner	Outer	Wood	Bark	Wood	Bark	Wood	Bark
P. sylvestris	74.9	25.1	81.8	18.2	49.7	50.3	68.7	31.3
P. abies	61.5	38.5	79.4	20.6	48.9	51.1	64.6	35.4
B. pubescens	71.8	28.2	78.1	21.9	58.2	41.8	71.3	28.7
B. pendula	71.8	28.2	75.0	25.0	53.2	46.8	67.6	32.4
A. incana	68.7	31.3	73.0	27.0	50.3	49.7	69.0	31.0
A. glutinosa	63.7	36.3	69.2	30.8	49.2	50.8	65.6	34.4
P. tremula	65.5	30.5	69.2	30.8	37.6	62.4	62.5	37.5

Whole-tree composition, %

Species	Branches*		Whole-tree		References
	> 5 mm	< 5 mm	Crown	Stem	
P. sylvestris	59.4	40.6	15.9	84.1	Hakkila 1991
P. abies	51.6	48.4	33.9	66.1	Hakkila 1991
B. pubescens	65.9	34.1	13.4	86.6	Hakkila 1991
B. pendula	65.9	34.1	13.4	86.6	Hakkila 1991
A. incana	82.6	17.4	14.5	85.5	Data collected in this study
A. glutinosa	82.1	17.9	17.9	82.1	Björklund 1984
P. tremula	78.9	21.1	11.2	88.8	Kärkkäinen 1980

Stump/root composition, %

Species	Roots		Stump/root system		References
	Bark	Wood	Roots	Stump	
P. sylvestris	10.3	89.7	47	53	Hakkila 1975
P. abies	12.5	87.5	68	32	Hakkila 1975

* Data collected in this study

Appendix 4. Chemical composition of wood and bark as a function of heating value (X). The parts of the trees included in the analysis are listed in the fifth column of the table.

Wood component	Species	Dependent variable, Y	Equation	Tree parts included in the regression	RMS	r	p
Wood	*P. sylvestris*	lignin	50.04 – 1.17X	stump + roots	0.49	–0.93	<0.001
			46.33 – 1.00X	stem + stump	0.15	–0.98	<0.001
			48.57 – 1.10X	stem + stump + roots	0.42	–0.91	<0.001
			–33.03 + 3.14X	stem + branches + roots	2.89	0.61	0.009
		carbohydrates	228.46 – 8.10X	stem + branches + roots	23.45	–0.58	0.015
		ESOS	–65.98 + 3.76X	stem + stump	5.06	0.95	0.004
			–69.89 + 3.94X	stump + roots	1.95	0.97	<0.001
			–63.34 + 3.63X	stem + branches + stump	7.36	0.85	<0.001
			–68.23 + 3.86X	stem + stump + roots	0.95	0.95	<0.001
			–65.68 + 3.74X	stem + branches + stump + roots	5.03	0.86	0.001
	P. abies	carbohydrates	353.52 – 14.58X	stem + roots	11.35	–0.69	0.03
		ESOS	–107.23 + 5.82X	stem + stump + roots	2.48	0.62	0.03
	B. pubescens	lignin	–261.77 + 15.14X	stem + branches	2.86	0.82	0.04
			–139.98 + 8.66X	stem + roots	3.72	0.70	0.02
			–276.34 + 15.91X	stem + stump + branches	3.45	0.78	0.003
			–145.87 + 8.96X	stem + stump + roots	4.79	0.63	0.03
			–161.26 + 9.77X	stem + stump + branches + roots	4.02	0.67	0.002
	B. pendula	lignin	–247.93 + 14.48X	stem + branches	4.06	0.65	0.04
			–265.52 + 15.41X	stem + stump + branches	4.22	0.65	0.03
		ESOS	–265.67 + 14.63X	stem + branches	4.10	0.65	0.04
			–273.22 + 15.03X	stem + stump + branches	3.76	0.66	0.03
			–215.20 + 11.91X	stem + branches + roots	3.25	0.59	0.02
			–221.60 + 12.25X	stem + stump + branches + roots	3.15	0.60	0.01
Inner bark	*P. abies*	ESOS	–85.98 + 6.69X	stem + branches	10.83	0.77	0.026
	B. pubescens	carbohydrates	–153.78 + 10.94X	stem + branches	3.54	0.84	0.009
	B. pendula	lignin	130.72 – 5.35X	branches	0.04	–0.99	0.006
		carbohydrates	–157.86 + 10.73X	stem + branches	1.52	0.90	0.002
Outer bark	*B. pubescens*	lignin	257.69 – 6.85X	stem	5.41	–0.95	0.05
		carbohydrates	32.88 – 0.84X	stem + branches	1.07	–0.86	0.007
		ESOS	–87.70 + 3.80X	stem	0.30	0.99	0.01
			–95.19 + 4.05X	stem + branches	18.42	0.89	0.003
	B. pendula	carbohydrates	–213.76 + 7.12X	stem	0.07	0.98	0.02

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