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HEATING VALUE AND ASH CONTENT OF INTENSIVELY MANAGED STANDS

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ABSTRACT

The calorimetric heating value ($q_{v(gross)}$) and ash content of bark and wood components of one to three-year-old *S.* 'Aquatica' and *S. x dasyclados* short-rotation plantations in two locations and 10 to 11-year-old dense *Betula pubescens*, *Betula pendula*, *Alnus incana*, *Salix triandra* and *Salix phylicifolia* plantations were determined. The effects of fertilisation on heating value and ash content were also studied. The wood of downy birch, silver birch and grey alder had ash content of 0.3-0.5 % and that of short-rotation willows 0.8-0.9 %. The ash content in bark was highest in short-rotation willows (2.7-3.6 %), followed by alder (2.5 %) and lowest in birch (1.5-1.6 %). The ash content of short-rotation willow shoots decreased with an increase in age from one (2.1-2.2 %) to two and three (1.8-1.9 %) years. Alder (1.0 %) and birch (0.7 %) whole trees had considerably lower ash content in their leafless above-ground biomass. Downy birch, silver birch and grey alder had 8-9 %, 11-12 %, 9-10 % and 5 % higher heating value in bark than in wood. In short-rotation willows, the heating value decreased with an increase in age. The difference between bark and wood in heating values was small. The willows had a lower heating value than birches and alder, but between-species differences were small: willows had a 2 % lower heating value than alder.

KEYWORDS: Silver birch, downy birch, grey alder, willow, fertilisation, age, bark, wood.

INTRODUCTION

The need to reduce greenhouse gas emissions is increasing the value of renewable energy obtained from forests. Wood-based fuels and recovered fuels are playing a leading role in attempts to reach European Union goals for increasing the use of renewable energy. In addition to using wood fuels derived from existing forests, the establishment and utilisation of woody biomass energy plantations are gaining new interest in many countries. Short-rotation forestry refers to the cultivation of fast-growing deciduous tree species, regenerated through sprouts, using short rotation periods of three to five years, intensive cultivation methods and dense stocking. Exotic willow species have been used widely in short-rotation experiments conducted all over the world (Ager et al. 1986, Mitchell et al. 1999). However, fertilised, densely-planted or naturally regenerated alders and birches, and native willows requiring much longer rotation than exotic willow species, could also be highly productive, especially in boreal climates (Weih 2004, Hytönen and Saarsalmi 2009, Renou-Wilson et al. 2010, Hytönen and Aro 2012). Studies have focused mainly on the establishment, nutrition and biomass production of the short-rotation crops. However, the quality of the crop is also an important factor for the user.

The properties of biomass feed stock can be determined in a number of ways depending on the end use. Fuel wood properties can be described in terms of proximate and ultimate analysis, bulk density, heating value, composition and tree species (Nurmi 1992). The calorimetric or higher heating value ($q_{v(gross)}$) is determined with a bomb calorimeter and all other heating values are derived from it. The effective, or lower heating value of oven dry biomass ($q_{v(net)}$) indicates the energy available in free combustion of oven dry biomass and is calculated as the calorimetric heating value minus the heat released by the condensation water that is created during combustion. Energy yield as measured by heating value is one of the most important quality characteristics of dedicated wood energy plantations (Kenney et al. 1990). The heating values of indigenous tree species and their components are well known. It has been shown that their heating value is affected by such factors as species, tree part (stem, branches, roots) and tree component (wood, bark, foliage) and size of trees (Nurmi 2000). However, knowledge of the properties of small-sized deciduous tree species used in short-rotation plantations is still quite limited. Short-rotation plantations are fertilised intensively. Fertilisation could affect the chemical composition of trees and the distribution of biomass in bark and wood components and thus affect heating value.

The ash content of biomass is known to vary between tree species and tree components (Hakkila and Kalaja 1983, Voipio and Laakso 1992). High ash content can decrease the heating value of biomass. In addition, high amounts of ash can also contribute to clogging of the ash handling mechanisms of plants and may mean more cleaning and maintenance required with boilers. For biomass pellets, there is a need to have a low ash content so as to meet quality standards.

Stem biomass is composed of wood and bark. The proportions of these components vary with the diameter and height of the tree (Repola 2008). Usually the majority of the stem mass is concentrated in the wood, which makes it the single most important component to consider when ash content or heating value for the whole stem is calculated (Nurmi 1992). In short-rotation biomass, the bark component is quite high, especially in one-year-old shoots. Furthermore, the high growing densities lead to small stem size which further increase bark percentage.

Based on previous knowledge, it is hypothesised that both the calorimetric heating value and ash content are higher in bark than in the wood component in all the studied tree species. It is also hypothesised that the heating value of the shoots of the genera *Salix* will decrease with increasing age. This is because the bark percentage will decrease as the stems gain volume. Furthermore, *Salix* species will have poorer fuel properties than the other genera. The aim of this study was to evaluate the calorimetric heating value and ash content of densely grown short-rotation tree species and the effects of fertilisation on the heating value.

MATERIAL AND METHDOS

Willow age and fertilisation

Two short-rotation willow fertilisation experiments were established, one at Paloneva in Ruukki (64°27¬'N, 25°26'E, *S.* 'Aquatica', clone V769) and other one at Piipsanneva, Haapavesi

(64º06'N, 25º36'E , *S. x dasyclados* Wimmer, clone P6011) with 20 cm-long cuttings at a density of 40.000 cuttings ha^{-1} on limed cut-away peatlands (Hytönen 1995). For the purposes of this study, treatments with combinations of nitrogen (100 $kg.ha^{-1}$), phosphorus (30 $kg.ha^{-1}$) and potassium (80 $kg.ha^{-1}$) were selected (0, PK, NPK). The treatments were replicated three times on plots of 56 – 80 m^2. Over three years in late August or early September, a minimum of five different-sized sprouts were sampled from each experiment plot and transferred to laboratory. Each sample tree was carefully peeled and bark and wood separated. The branches of the willow sample sprouts were also peeled and bark and wood included into corresponding compartments of the stem In the laboratory bark and wood were subsequently dried at 105ºC to a constant weight.

Tree species comparison

The biomass production of densely-planted silver birch (*Betula pendula* Roth), downy birch (*B. pubescens* Ehrh.), grey alder (*Alnus incana* (L.) Moench), *Salix triandra* (L.) and *S. phylicifolia* (L.) were monitored on a limed cut-away peatland area at Piipsanneva, Haapavesi (64º06'N, 25º36'E) on plots of 100 m^2. The planting density for birches and alders was 20.000 seedlings ha^{-1} and for willows 40.000 cuttings ha^{-1}. Two fertilisation treatments were compared (willows: two NPK fertiliser doses, birches: unfertilised control and NPK fertilisation, alder: unfertilised control and PK fertilisation) in randomized block design with two replications. The fertilisation treatments were repeated several times (Hytönen and Saarsalmi 2009).

At least five different-sized trees were sampled on each plot and cut at the age of 10 (willows) and 11 (birches, alders) years. The felled sample trees were divided into stem and branch components except for the willows, whose stem and branches were kept as one woody component. Stem and branch samples (representing the base, central and crown portions) were taken from the sample trees in the field. The birch and alder stem samples were divided in the laboratory into bark and stem wood components. Composite samples representing each sample plot were made for the heating value analyses.

Laboratory analysis

In the laboratory the samples were at 105ºC to a constant weight. The calorimetric heating value ($q_{v(gross)}$) in $J.g^{-1}$ of dry matter was determined with a bomb calorimeter (IKA C5000) using the standard SFS-EN 14918 (2010). Prior to the analysis of the heating value, the dried and milled (Retsch SM-1 mill) samples were pelletised (14 mm in diameter). The ash content of the samples was analysed by as hing the samples for eight hours at 550ºC .

The effect of fertilisation, tree component, and tree species on the heating value and ash content were studied with analysis of variance. Transformations were used to homogenise variances where necessary. The arcsine transformation was applied to variables with percentage values. Tukey's honestly significant difference test ($p < 0.05$) was used to separate the means of the treatments. The heating value and ash content of the leafless above-ground biomass of the tree species was calculated by taking the proportions of bark and wood in the whole stand biomass into account.

RESULTS

Tree components

Willow age and fertilisation

The ash content of short-rotation willow bark (2.7 - 3.5 %) was significantly higher than that of wood (0.8-1.1 %) ($F_{'Aquatica'}$ 5789.147, p = 0.000, $F_{dasyclados}$ = 2300.372, p = 0.000) (Fig. 1). *S. x dasyclados* had significantly lower ash content both in wood and bark than *S.* 'Aquatica' (Fig. 1.)

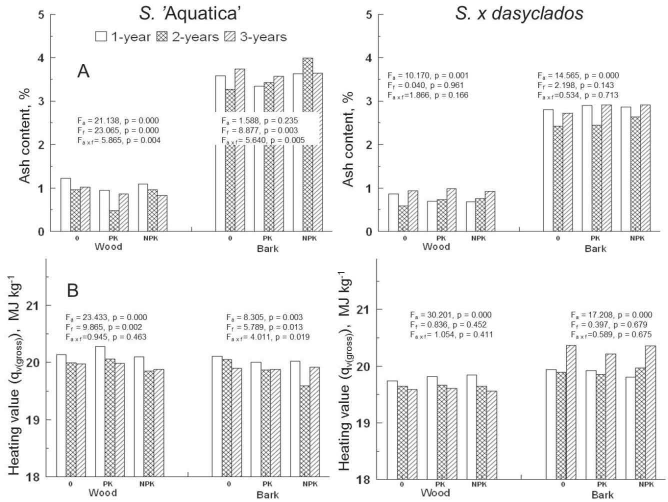

Fig. 1: Effect of fertilisation and age on the ash content (A) and on the heating value ($q_{v(gross)}$) (B) of short-rotation willow wood and bark. The ANOVA F and p values for wood and bark shown above the bars (F_a = F value for age, F_f = F value for fertilisation and F_{axf} = F value for interaction for age and fertilisation).

Age had a significant effect on the ash content of wood in both willow species and on the ash content of the bark in *S.* 'Aquatica' (Fig. 1). In *S.* 'Aquatica', one-year-old wood and in *S.* x *dasyclados* three-year-old wood had highest ash content. Fertilisation decreased S. 'Aquatica' wood ash content by 0.1 – 0.2 %-units and increased the ash content of bark by 0.2 – 0.3 %-units.

In short-rotation willow *S.* 'Aquatica', the heating value (qv(gross)) was highest in wood and in *S.* x *dasyclados* in bark (Fig. 1). The heating value of bark and wood differed from each other in both willow species ($F_{\text{'Aquatica'}}$ 15.446, p = 0.000, $F_{dasyclados}$ = 102.795, p = 0.000). The heating value of *S.* 'Aquatica' bark (19.93 MJ.kg^{-1}) was lower than that of wood (20.03 MJ.kg^{-1}) and the heating value of *S.* x *dasyclados* bark (20.04 MJ.kg^{-1}) was higher than that of wood (19.68 MJ.kg^{-1}) (Fig. 1).

The heating value generally slightly decreased with an increase in age in willows, with the exception of three-year-old *S.* x *dasyclados* bark (Fig. 1). Generally, the highest heating value was measured in one-year-old willow bark and wood. One-year-old and older wood and bark had a 0.7 – 1.4 % higher heating value than older wood and bark, with the exception of three-year-old *S.* x *dasyclados* bark. Fertilisation decreased the heating value of *S.*' Aquatica' bark and wood significantly, but it did not affect that of *S.* x *dasyclados*. The heating value of unfertilised *S.* 'Aquatica' in the wood was 0.5 % and in the bark 0.9 % higher than in the corresponding components on NPK-fertilised willows. There was also significant interaction between the heating value of bark and age.

Tree species comparison

Fertilisation and component significantly affected the ash content of 11-year-old silver birch, downy birch and grey alder (Fig. 2). Fertilisation increased ash content by units of 0.1 % in wood and branches. All the components of grey alder had higher ash content than the corresponding components in birches.

The heating value (q_v(gross)) of the 11-year-old silver birch, downy birch and grey alder trees was affected by species and component, but not by fertilisation (Fig. 2). There was also significant species and component interaction. The heating value of downy birch, silver birch and grey alder bark was 8-9 %, 11-12 % and 9-10 % higher than that of wood (Fig. 2). There were no species-significant differences in the heating value of wood. The silver birch bark had the highest heating value (21.91 MJ.kg^{-1}) and that of downy birch the lowest (21.30 MJ.kg^{-1}). The heating value of

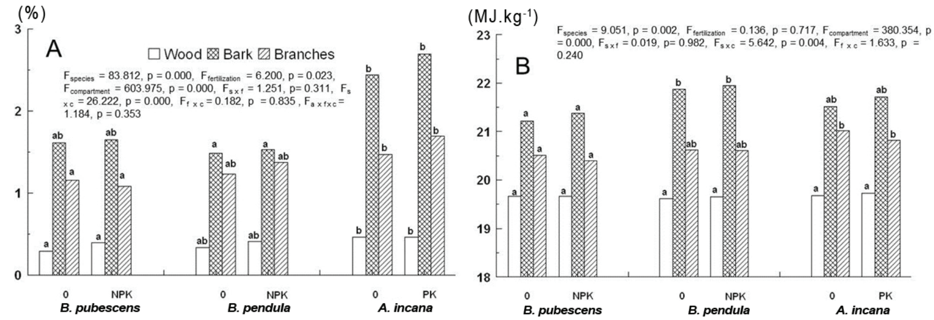

Fig. 2: Ash content (A) and heating value (q_v(gross)) (B) of unfertilised and fertilised 11-year-old silver birch, downy birch and grey alder wood, bark and branches. The same letters above the bars indicate that differences between the species in the same component are not significant according to Tukey's test at a significance level of 0.05.

branches (containing wood and bark) was in between the bark and wood figures. Grey alder had the highest heating value in branches (20.92 MJ.kg^{-1}) and downy birch the lowest (20.46 MJ.kg^{-1}) (Fig. 2).

Whole stand

Willow age and fertilisation

The stand-level ash content of the leafless above-ground biomass was calculated based on the share of the bark and wood in the biomass on the sample plots. The youngest and unfertilised short-rotation willow stands had the highest ash content (Fig. 3). The ash content of one-year-old stands was 2.1-2.2 % and that of two and three-year-old stands 1.8-1.9 %. The ash content of unfertilised S. 'Aquatica' stands was 2.1 % and fertilisation with NPK decreased ash content to 1.9 %. The bark content of the stands explained 59 % and 43 % of the variation in the whole stand ash content of *S.* 'Aquatica' and *S.* x *dasyclados*, respectively (*S.* 'Aquatica': ash content of the stand = 0.778 + 3.040 x bark %, *S.* x *dasyclados*: 0.83 + 1.857 x bark %).

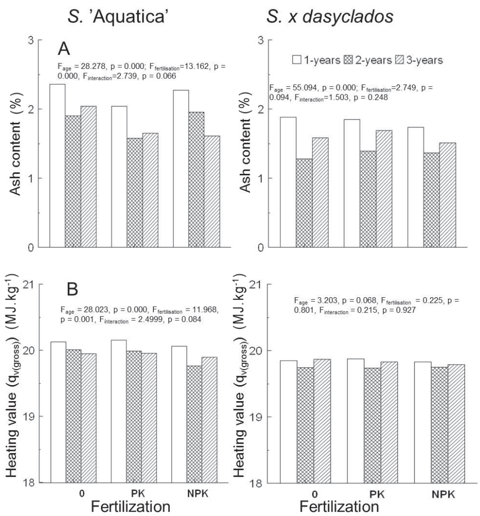

Fig. 3: Effect of fertilisation and age on the ash content A) and heating value (qv(gross)) of B) of one to three-year-old S. 'Aquatica' and S. x dasyclados stands.

The stand average q_v(gross) value of the leafless above-ground biomass of the stands was calculated from the share of the bark and wood in the biomass on the sample plots. Willow age had a significant effect on the heating value of *S.* 'Aquatica' and an almost significant effect (p=0.068) on that of *S.* x *dasyclados*. With increase in age the heating value of *S.* 'Aquatica' decreased from 20.12 MJ.kg^{-1} at the age of one to 19.92 – 19.93 MJ.kg^{-1} at the age of two to three years. The effect of age was thus 0.9 – 1.0 %. The heating value of *S* x *dasyclados* decreased less with an increase in age (0.1 – 0.5 %). Fertilisation had a significant effect on the heating value of *S.* 'Aquatica' but not on that of *S.* x *dasyclados*. The heating value of unfertilised (20.03 MJ.kg^{-1}) willows was 0.2 % higher than that of NPK-fertilised (19.91 MJ.kg^{-1}) *S.* 'Aquatica' (Fig. 3).

Tree species comparison

The ash content in the 11- (birch, alder) or 10-(willows) year-old dense stands of silver birch, downy birch and grey alder was lowest in birches (0.7-0.8 %), higher in alder (1.0 %) and highest in *S. phylicifolia* (1.3 %) (Fig. 4)

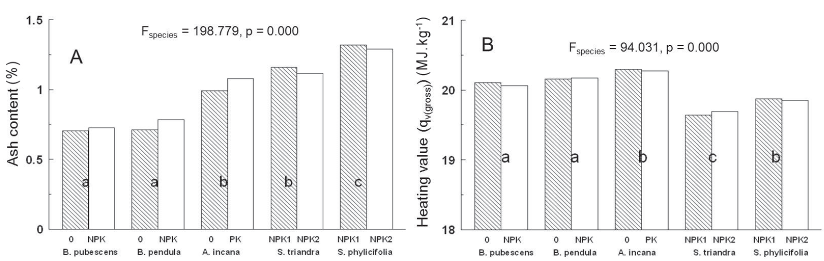

Fig. 4: Ash content A) and heating value (q_v(gross)) B) of above-ground leafless biomass of different tree species. The same letters above bars indicate means that do not differ from each other according to Tukey's test at a significance level of 0.05.

The heating value (q_v(gross)) of the above-ground biomass of the 11- (birch, alder) or 10- (willows) year-old stands differed significantly from each other (Fig. 4). The heating value was highest in grey alder (20.29 $MJ.kg^{-1}$) and lowest in *S. triandra* (19.67 $MJ.kg^{-1}$). The second native willow species *S. phylicifolia* had the second lowest heating value. The two birch species did not differ significantly in their heating values from each other (20.09 – 20.17 $MJ.kg^{-1}$). Fertilisation did not affect the heating value of these species.

DISCUSSION

Ash content of tree components

The ash content varied according to species, tree age and tree components. Wood generally had a lower ash content than bark, which is in accordance with other studies. In addition, the ash content of downy birch, silver birch and grey alder wood (0.3-0.5 %) was similar to what has been reported in other studies (0.4-0.6 %) (Hakkila and Kalaja 1983, Voipio and Laakso 1992). The ash content of short-rotation willow wood (0.8-0.9 %) was higher than in the other studied tree species. Similar (0.8-1.1 %) (Lyons et al. 1986, Senelwa and Sims 1999), but also considerably lower (0.2 %) (Dzurenda 2010a,b) and higher (1.7 %) (Lyons et al. 1986) willow wood ash contents have been reported earlier. The stem bark of the species growing in the Nordic countries has an ash content of between 2.5 – 3.5 % (Hakkila and Kalaja 1983, Voipio and Laakso 1992). The ash content of downy and silver birch bark (1.5-1.6 %) was lower than that of grey alder bark (2.5 %). The highest bark ash content was measured from short-rotation willows (2.7-3.6 %). This was similar to that reported on three to five-year-old *S. viminalis*, *S.* 'Aqautica' and *S.* x *dasyclados* bark (2.7-3.5 %) (Lyons et al. 1986, Dzurenda 2010a,b), but smaller than that measured from bark of *S. kinuyanagi* and *S. matsudana* x *alba* (4.7-5.7 %) (Senelwa and Sims 1999). Fertilisation had only a small effect on the ash content of short-rotation willow wood and bark, this being significant only for *S.* 'Aquatica'.

Ash content of whole stand

The ash content of willows decreased with an increase in age, which is in agreement with earlier studies (Szczukowski et al. 2002). The high ash content of one-year-old willows (2.1-2.2 %) decreased with an increase in age of two and three years to 1.8-1.9 %. The ash content of willow biomass seems to decrease even further with an increase in age. This was demonstrated by the native willows having a 38-69 % lower ash content at the age of 10 years compared to the one to three-year-old exotic willows. Similarly, Dzurenda et al. (2013) reported a 0.7 % ash content for five-year-old *S. viminalis*. The decrease in willow biomass ash content with an increase in age is probably mostly due to a decrease in the proportion of ash-rich bark in the biomass. Older and bigger willows have a higher proportion of their biomass in wood (Hytönen 1995), which contains less ash than bark. In comparison with willows, alder (1.0 %) and birches (0.7 %) had a much lower ash content in their leafless above-ground biomass (Fig. 5).

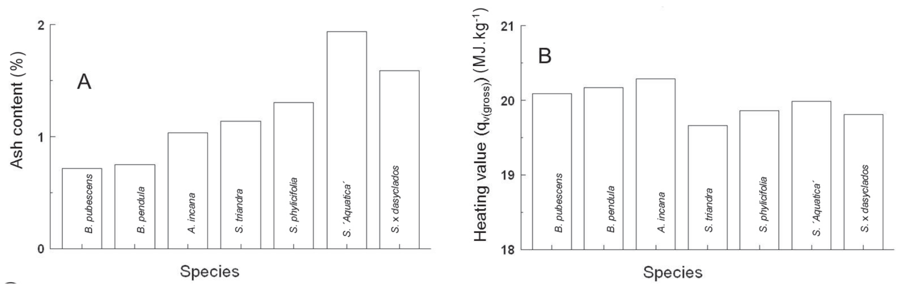

Fig. 5: Ash content (A) and heating value (B) of the studied species. Fertilisation treatments combined. Eleven-year-old birches and alder, 10-year-old S. phylicifolia and S. triandra and one to three-year-old S. 'Aquatica' and S. x dasyclados.

Heating value of tree components

The heating value q_v(gross) of bark has been reported to be higher than that of wood in many species, e.g. Scots pine, downy birch and silver birch (Nurmi 1993, 1997, 2000, Olofsson 1975). Also in this study this was true for downy birch, silver birch and grey alder, having a 8-9 %, 11-12 % and 9-10 % higher heating value respectively in bark than in wood. However, contrary to our hypothesis, in our willows the difference between the heating value of bark and wood was considerably smaller. In accordance with this study willows have been reported to have slightly higher (Lyons et al. 1986, Ager 1986, Nurmi 1995) or lower (Lyons et al. 1986, Senelwa and Sims 1999, Klašnja et al. 2002, Dzurenda 2010a) $q_{v(gross)}$ values in bark than in wood. The difference in heating value of willow bark and wood has previously been reported to be 0.3 to 1.5 % for *S. viminalis*, *S.* 'Aquatica' and *S.* x *dasyclados* (Lyons et al. 1986, Nurmi 1995, Dzurenda 2010a,b). Thus the difference between bark and wood in short-rotation willows seems to be smaller than in some other tree species. The between-species variability of heating value of the wood component was smaller than that of bark. This indicates a basic elemental similarity of wood in different species. Furthermore, this small variability in the heating value of willow components promotes the uniformity of the feed stock. This could be an important factor from a plant management point of view.

The heating value of exotic willow wood and bark components decreased slightly with age with the one-year-old willows having the highest heating value. However, even though the effect of age was significant, the difference between age groups was only 1 %. Thus a difference in age of a few years in the material will not markedly affect the fuel properties of short-rotation willows. Also, an increase in growth rate on later years of stand development will offset this miniscule reduction in higher heating value.

Heating value of the whole tree

The willows had the lowest heating value of the studied tree species (Fig. 5). Grey alder had the highest heating value and it was only slightly lower than that of birches. However, differences in the heating values of the leafless above-ground trees between the species were small. In this study, willows had a 2 % lower heating value than alder. Also, according to Nurmi (2000) the differences in heating values between native tree species are relatively small. Geyer (1981) reported a slightly higher difference of approximately 6 % in heating values of seven species of hardwoods grown in short rotation in the southern United States. In addition, small (3 %) clonal differences in the heating value between short-rotation willow clones have been reported (Ager et al. 1986). Thus it is apparent that very little variation in heating value exists among and within species of willow and poplar (Kenney et al. 1990).

Differences in the heating value of small-sized and mature trees in conifers are scarce. However, tree size can be a significant factor in many broad-leaved species. For example, mature birches have a slightly higher effective heating value than small birches (Nurmi 2000). In this study age, a variance of one to three years had only a small effect on the heating value of the leafless above-ground biomass of short-rotation willows. Both in *S.* 'Aquatica' and *S.* x *dasyclados* the heating value (qv(gross)) decreased slightly (in *S.* 'Aquatica' 0.9-1.0 % and in *S.* x *dasyclados* 0.1-0.5 %) with an increase in age. The heating values of 10-year-old *S.* x *phylicifolia* and especially that of *S. triandra* were lower than that of exotic willows. Contrasting results on the effects of age on q_v(gross) in willows have been published by Szczukowski et al. (2002) and Klašnja et al. (2002), reporting an increase with increase in age. Thus the effect of age and size is probably species-specific. The changes in the amounts of bark and wood proportions often have a significant effect. The older and bigger trees are, the smaller their bark percentage is. In dense, young short-rotation stands of Salix, the proportion of bark can be high. In this study the NPK-fertilised one-year-old shoots had a bark percentage of 46-51 % and at the age of three the bark percentage had decreased to 28-36 %.

The effect of fertilisation was studied in all the species. In downy birch, silver birch, alder, and native willows and *S.* x *dasyclados*, fertilisation did not affect heating value. Only S. 'Aquatica' fertilised trees had a significantly higher heating value, and the effect was only 0.2 %. Thus, fertilisation does not decrease energy wood heating values and can thus be safely used to increase biomass production.

According to this study, short-rotation willows are slightly inferior to the other deciduous species for fuel wood – they had the highest ash content of both wood and bark components and the lowest heating value. Since the between-species differences in heating value are small in magnitude, the choice of tree species suitable for biomass cultivation cannot be made on the basis of the heating value. Thus, factors affecting biomass yield, be they fertilisation, growing density, species or clone selection, are more important traits in determining the energy value obtained from the cultivation. However, most often moisture content is the determining factor in thermal conversion (Nurmi and Hillebrand 2007). After felling, the moisture content of trees is dependent on the post-harvest handling and storage conditions. The moisture content of biomass can be minimised by using proper material storage methods (Nurmi 1995, 2000, Jirjis 2005, Nurmi and Hillebrand 2007).

CONCLUSIONS

Bark had higher ash content than wood in all of the studied species. Birch and alder bark had higher heating value than wood, but in willows the difference between components was small. Short-rotation willows are slightly inferior to the other studied deciduous species (silver birch, downy birch, grey alder) for fuel wood – they had the highest ash content of both wood and bark components and the lowest heating value. The effect of fertilization on heating value or ash content was small. Since the between-species differences in heating value are small in magnitude, the choice of tree species suitable for biomass cultivation cannot be made on the basis of the heating value. Thus, factors affecting biomass yield, be they fertilisation, growing density, species or clone selection, are more important traits in determining the energy value obtained from the cultivation. However, it should be remembered that most often it is moisture content which is the determining factor in thermal conversion.

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