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ORIGINAL PAPER

Assessment of load and quality of logging residues from clear-felling areas in Järvselja: a case study from Southeast Estonia

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Abstract

The properties of biomass-based fuel and combustion tests showed that logging residues are promising renewable energy sources. The data used in this study were collected from four clear-felling areas in Järvselja Training and Experimental Forest Centre, Southeast Estonia in 2013–2014. Logging was carried out by harvesters in Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* [L.] Karst.), silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* L. Gaertn.) dominated stands with a small admixture of other tree species according to the cut-to-length method and logging residues were placed in heaps. The aim of this research is to assess different characteristics of logging residues (quantity, moisture content, energetic potential, ash content and amount) in clear-felling areas. The highest load of slash was measured on the birch dominated study site, where the dry weight of the logging residues was 29 t ha^{-1}. Only the branch fraction moisture content on the black alder dominated site (35.4%) was clearly different from respective values on other sites (21.6–25.4%). The highest calorific value of the residues was assessed with the residues from the birch dominated site, where in moist sample it was 365 GJ ha^{-1} and in dry matter 585 GJ ha^{-1}. The heating value of the fresh residues is highest in coniferous trees. The highest ash content in branch segments was registered for the black alder dominated site. Järvselja data indicate higher quality in conifer dominated sites, yet a higher load of logging residues in broadleaf dominated stands.

Key words: bioenergy; biomass of forest residues; energetic potential; moisture content; ash content

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1. Introduction

Public demand for ecosystem services is limiting a more extensive use of forests although wood consumption is increasing globally. Intensive forest management and deployment of underutilized resources (e.g. stumps and logging residues) on clear-felling sites are expected to ease the contradicting needs. The utilization of logging residues can improve also the economics of forest management as there are now available, efficient technologies for collecting residues from logging areas. At the same time, a market is slowly developing for logging residues, since geographically scattered local power plants have a higher demand for solid biofuels, including wood chips from logging residues. Substitution of fossil fuels by forest biomass as a CO$_2$-neutral energy source is a common policy target in many countries, including Northern Europe (Olsson et al. 1996; Stupak et al. 2007; Routa et al. 2012; Rytter et al. 2016).

Around two thirds of current renewable energy is produced mainly from solid biomass (90.8 Mtoe; mega tonne of oil equivalent is a unit of energy defined as the amount of energy released by burning one tonne of crude oil) followed by liquid (14.4 Mtoe) and gaseous (13.5 Mtoe) biomass sources (Sustainable and optimal... 2017). Switching to renewable energy sources has been quite successful in Estonia, e.g. the share of electricity generated from solid renewable sources in total electricity consumption has been increasing from 6% in 2009 to 18% in 2017 (Statistical Yearbook of... 2017). The share of energy produced from wood constituted 50% of electricity and 75% of heat energy production from renewable sources in 2016 (Statistical Yearbook of... 2017). However, logging residues from forest management operations should be considered and used more widely for energy production in Estonia (Muiste et al. 2004; Muiste & Kakko 2004; Uri et al. 2015). Analyses in the past and the potential for the future indicate that the availability of suitable wood for energy production in Estonia is several times higher than current consumption (Hepner et al. 2010).

There are different technologies available for efficient harvesting of forest biomass. The whole-tree harvesting technology can have short and long-term negative impacts on forest ecosystems (Mälkönen 1976; Egnell

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& Leijon 1997; Jacobson et al. 2000; Helmisaari et al. 2011; Wall 2012; Persson 2017). Intensive harvesting of forest biomass (utilization of whole-tree biomass, logging residues, stumps and roots, etc.) increases the mineralization of organic material and the removal of nutrients from the ecosystem compared to the traditional stem-wood harvesting (Møller 2000; Olsson et al. 2000; Palviainen 2005; Raulund-Rasmussen et al. 2008; Saarsalmi et al. 2010). If nutrient-rich parts of trees (needles, branches) are also harvested from the forest ecosystem, nutrient loss is considerably amplified. There is also a significant risk of changes in soil chemical properties (acidification, leaching out of nutrients, etc.) upon intensive harvesting of forest biomass in conifer stands (Staaf & Olsson 1991; Saarsalmi et al. 2010; de Jong et al. 2017). The exchangeable aluminium content increased and the calcium/aluminium ratio was significantly lower on the whole-tree harvesting sites than in the conventional harvesting area (Saarsalmi et al. 2010). The removal of macro- and microelements during intensive biomass harvesting should be compensated for on acid soils; the return of wood ash might prevent deficiency (Raulund-Rasmussen et al. 2008).

The aim of the current study is to assess different characteristics of logging residues (quantity, moisture content, energetic potential, ash content and amount) on clear-felling areas in Järvselja (Southeast Estonia).

2. Material and methods

The data used in this study was collected from four clear-felling areas in Järvselja Training and Experimental Forest Centre, Southeast Estonia (Table 1). Before clear-felling, the study sites were Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* [L.] Karst.), silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* L. Gaertn.) dominated stands with a small admixture of other tree species (Table 2). Admixture species included Norway spruce, silver birch and small-leaved linden (*Tilia cordata* Mill.) on the sites. Logging was carried out on all study sites in 2013–2014 by harvesters according to the cut-to-length method and logging residues were placed in heaps. In the clear-felling areas all the trees were harvested, except the retention trees (up to 5% of stand volume). The heaps included treetops, branches and unconditional logs, and they covered 15–35% of the logging area on different sites. The maximum height of heaps was 0.6 m.

All study sites were measured and samples collected in the late autumn of 2014 as logging residues were left to dry during the summer at the sites. This method provides logging residues with low amounts of needles and leaves, as requested by the energy-converting industry (Nilsson et al. 2013). At each study site, all heaps were mapped and logging residue plots (LRP) were distributed evenly on the heaps. Five LRPs were established at sites A, C and D (on each site), and three LRPs at site B. The length of an LRP was 10 m and the width was the actual width of the heap. After the establishment of an LRP, the branches without foliage and billets were torn apart, separately piled and weighed. The samples of branches and billets were taken from each LRP for laboratory tests in November 2014 (birch, pine, spruce) and in April 2015 (alnus).

Laboratory tests were carried out at the laboratories of the Estonian University of Life Sciences where the moisture content, calorific value and ash content of the samples were determined according to standards (CEN/TS 14774 2004; CEN/TS 14775 2004; CEN/TS 14918 2005).

Table 1. Basic information on the study sites. Site types are according to Lõhmus (2004).

Study site	Area ha	Site type	Coordinates	Elevation [m a.s.l.]	Logging time
A	1.92	Myrtillus	58°15’38” N, 27°19’32” E	41	Feb 2014
B	0.30	Oxalis-Myrtillus	58°17’12” N, 27°17’52” E	34	Apr 2013
C	0.67	Aegopodium	58°18’12” N, 27°18’08” E	32	Dec 2013
D	3.42	Eutrophic fen	58°17’31” N, 27°21’04” E	33	Oct 2014

Table 2. Tree stand characteristics before clear-felling.

Study site	Tree species	A [years]	N [trees ha^{-1}]	H [m]	$D_{1.3}$ [cm]	G [m^2 ha^{-1}]	V [m^3 ha^{-1}]
A	Scots pine	120	531	25	25	26.0	296
	Norway spruce	120	4	26	26	0.2	3
	Norway spruce	40	303	7	5	0.7	3
	Silver birch	30	50	6	6	0.1	1
	All species		888			27.0	303
B	Norway spruce	75	252	27	33	21.6	277
	Scots pine	75	35	28	30	2.5	31
	All species		287			24.1	308
C	Silver birch	60	618	27	24	28.0	343
	Norway spruce	40	260	10	12	2.9	18
	Small-leaved linden	40	27	13	12	0.3	2
	All species		905			31.2	363
D	Black alder	70	461	23	23	19.2	197
	Silver birch	70	163	23	22	6.2	66
	Norway spruce	40	89	9	10	0.7	4
	All species		713			26.1	267

A – age, N – stem number, $D_{1.3}$ – diameter at breast height, H – height, G – basal area, V – stem volume.

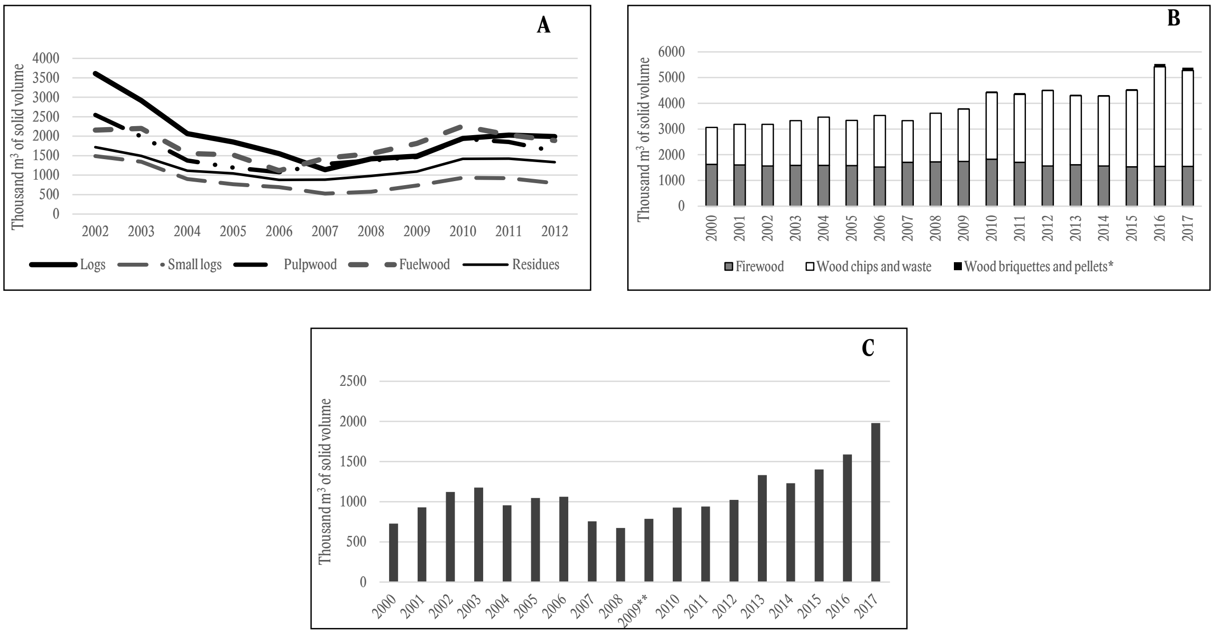

Fig. 1. Fellings by assortments (A), gross inland consumption (B) and export (C) of wood fuels in 2000–2017 in Estonia (Yearbook Forest 2013, 2014; Statistical Yearbook of... 2017).* 1,000 tons; ** accounting of assortments has changed since 2009.

Over the last five years, wood pellets have become an important fuel on the Estonian energy market (Fig. 1). In 2010–2015 the consuption of pellets has increased more than seven times. The increasing of regeneration fellings proportion during last years is promising for using residues (Fig. 1).

Statistical analysis was implemented using Statistica 10.0 software. Analysis of variance (ANOVA, Tukey's test and Tukey's Unequal N test) was used to test the equality of the means on the study sites.

3. Results

3.1. Quantity, moisture content, energetic potential and ash content of logging residues

The highest load of slash was measured at the birch dominated study site (C) in Järvselja Training and Experimental Forest Centre, where the dry weight of the logging residues was 29 t ha^{-1} (Table 3). Based on the load, the next site was Scots pine dominated site (A) where 25 t ha^{-1} (Table 3) of logging residues were measured. The spruce dominated site (B) and black alder dominated site (D) yielded with an almost comparable load, 12 t ha^{-1} and 16 t ha^{-1} of logging residues, respectively (Table 3). The weight consisted of an approximately double amount of residues from billets in comparison to branches in the case of pine and alder study sites; for birch an opposite result was observed (Fig. 2). The dry weight of birch branches differed statistically significantly ($p < 0.05$) in comparison to branches from the alder dominated site (Fig. 2).

Analyses indicate that the moisture content of residues on different sites with different dominating tree species is different (Table 3). The moisture content of alder site branches was statistically significantly higher ($p < 0.05$) in comparison to the moisture content of spruce and birch branches (Fig. 2). In general, no statistically significant difference was measured in the moisture content between the sites or between different fractions on the same site (Fig. 2). Only the branch fraction moisture content on the black alder dominated site (35.4%) was clearly different from respective values on other sites (21.6–25.4%), being 1.6 times higher (Fig. 2).

The calorific value of the residues was expressed as the calorific value of dry matter per kilogram and hectare and calorific value of moist samples (Table 3; Fig. 3). The highest value was assessed with the residues from the birch dominated site where in moist sample it was 365 GJ ha^{-1} and in dry matter 585 GJ ha^{-1} (Table 3). A relatively close result was obtained from the pine dominated site where the moist sample resulted in 332 GJ ha^{-1} and dry sample 497 GJ ha^{-1} (Table 3). The result from the spruce dominated site must be considered separately, since it included only branches and resulted with lowest calorific value, where in moist samples it was 164 GJ ha^{-1} and in dry sample 242 GJ ha^{-1} (Table 3). The heating value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and heating value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass (Fig. 3).

From the samples the ash content was obtained separately for branch and stem segments. The highest ash content in branch segments was registered for the black alder dominated site, where average ash content was 1.9%. This was followed by birch and spruce dominated

Table 3. Different characteristics of residues (mean ± standard deviation). Different letters indicate a statistically significant difference between parameters within tree species in the Tukey test $p < 0.05$.

Characteristic	Scots pine	Norway spruce*	Silver birch	Black alder
Fresh weight [tonnes]	31.8 ± 19.8^{a}	4.7 ± 2.2^{bc}	13.7 ± 7.6^{a}	42.5 ± 16.5^{a}
Dry weight [tonnes]	23.5 ± 13.1^{a}	3.5 ± 1.5^{bc}	9.6 ± 5.6^{b}	27.0 ± 10.0^{a}
Dry weight [t ha^{-1}]	24.5 ± 10.3^{a}	11.7 ± 5.0^{a}	28.6 ± 9.1^{a}	15.8 ± 4.2^{a}
Moisture content [%]	23.9 ± 6.5^{a}	23.3 ± 4.0^{a}	30.3 ± 1.8^{a}	36.0 ± 5.0^{bc}
Heating value [MJ kg^{-1}]				
Fresh residues	14.0 ± 1.5^{a}	14.1 ± 0.8^{a}	12.5 ± 1.4^{a}	11.3 ± 1.3^{a}
Dry residues	20.4 ± 0.4^{a}	20.6 ± 0.2^{a}	20.4 ± 0.4^{a}	20.4 ± 0.4^{a}
Energetic potential [GJ ha^{-1}]				
Fresh residues	332 ± 142^{a}	164 ± 63^{a}	365 ± 113^{a}	179 ± 56^{a}
Dry residues	497 ± 208^{a}	242 ± 106^{a}	585 ± 185^{a}	321 ± 86^{a}
Ash content [%]	0.48 ± 0.25^{a}	1.43 ± 0.37^{c}	1.0 ± 0.50^{c}	1.35 ± 0.69^{c}
Ash amount [t ha^{-1}]	0.10 ± 0.04^{a}	0.17 ± 0.07^{a}	0.32 ± 0.12^{b}	0.19 ± 0.06^{a}

*The data on Norway spruce contain only the characteristics of branches.

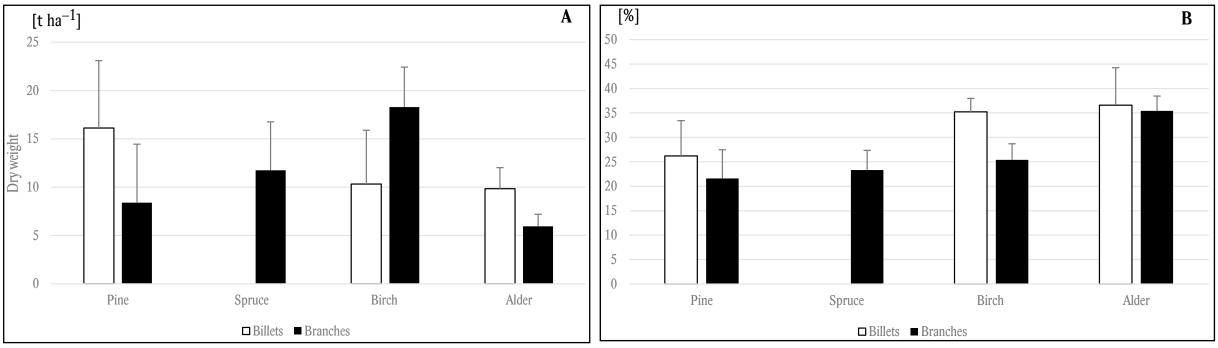

Fig. 2. The dry weight (t ha^{-1}) (A) and moisture content of residues (%) (B) (mean ± standard deviation).

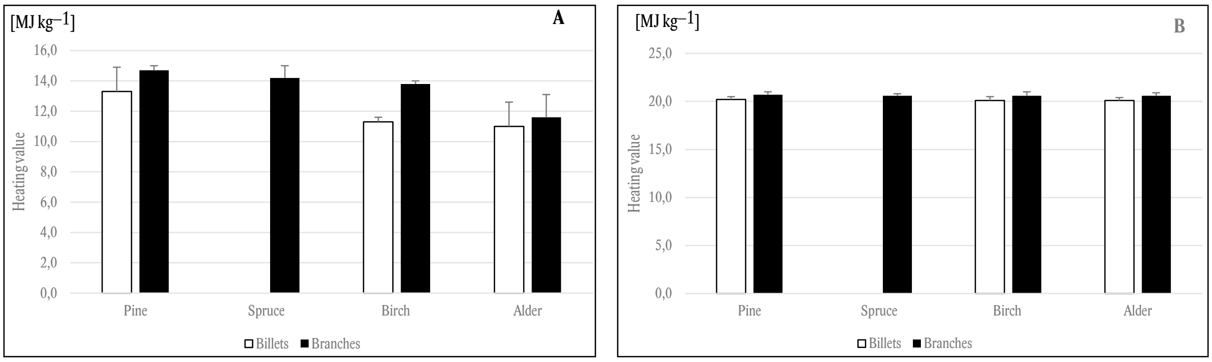

Fig. 3. The heating value of fresh (A) and dry residues (B) (MJ kg^{-1}) (mean ± standard deviation).

sites with 1.4%, where the branch ash content was statistically significantly ($p < 0.05$) higher than in the pine dominated site (0.7%) (Fig. 4). For the stem segments the highest ash content was also registered from the samples of the black alder dominated site (0.8%) and it was followed by birch (0.6%) and the pine dominated site 0.3% (Fig. 4). There were no stem residues left on the spruce dominated site. It appeared that not related to the species specific site difference the ash content in branch segments was statistically significantly ($p < 0.001$) higher (on average 2.5 times) than in stem segments (Fig. 4). In conclusion, the amount of ash in available logging residues was 0.1 tons per hectare on the pine dominated site, 0.2 tons per ha on spruce and black alder dominated sites and 0.3 tons per ha on the birch dominated site (Fig. 4).

4. Discussion

Living and dead branches, foliage, unmerchantable stemwood with bark, extracted stumps, small-diameter trees from early thinnings, also understory and broken pieces on the ground after harvesting merchantable wood are considered as primary forestry residues and have become a major source of bioenergy (Röser et al. 2008). The annual amount of felling residues reaches a total of 71 million m^3 in the Nordic and Baltic countries, with a potential of 44 million m^3 of residues (containing 6 million m^3 of stump wood) for energy production (Röser et al. 2008). Large differences exist in the amounts of residues of different species per hectare, depending mainly on the species- or mixture-specific shade tolerance, thickness of branches and bark, endurance of foli-

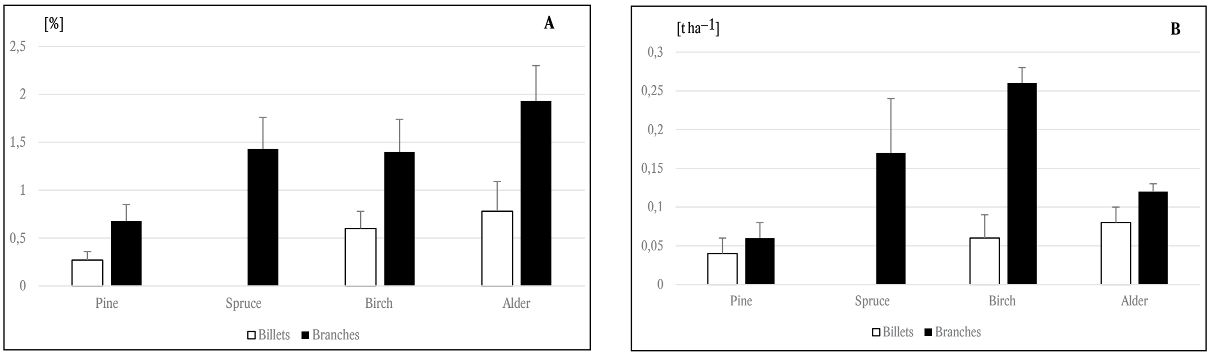

Fig. 4. The ash content of residues (%) (A) and the amount of ash (t ha^{-1}) (B) in the clear-cutting area (mean ± standard deviation).

age, durability of dead branches, the form and shape of the stem and the basic density of the different biomass components of a tree. Thinning of young pine stands was a long-time priority in Finland, because the territory of pine dominated forests was 80% of the total area of young forests (Vesisenaho & Nousainen 1997). During the last 20 years, the situation has changed in Finland – the total logging residue potential has risen from 8 million m^3 to 9.2 million m^3 – Norway spruce formed 5.6 million m^3 of the total potential, Scots pine 2.4 million m^3 and broadleaf species (mainly birches) 1.2 million m^3 (Räisänen & Athanassiadis 2013). Annual yield surveys of Estonian forests in 2002–2012 indicated that an average of 1.2 million m^3 of slash are generated every year, which amount to an average of 16.3% of logging residues of the total annual yield (Yearbook Forest 2014 2015). Average annual residues by tree species in 2008–2012 collected from different site types of Estonian forests are 33% spruce, 22% birch, 19% pine, 10% aspen, 7% grey alder, 6% black alder, and 3% other species.

In Estonia, 46% of heat energy is produced from biomass; it is possible to produce up to 2/3 of heat energy from local biomass (Statistical Yearbook of... 2017). The properties of biomass-based fuel and combustion tests showed that logging residues prove a promising renewable energy source, and their addition as surplus fuel to oil shale, the main local fuel in Estonia, could make the production of electricity from fossil oil shale more environmentally friendly and reduce the CO_2 emission from power plants (Kask et al. 2011). The use of low-quality wood for electricity production has reduced impacts on the environment: in 2011, the use of renewable biofuels decreased CO_2 emissions by 350,000–380,000 tonnes, and the amount of oil shale ash decreased by 180,000 tonnes (Eesti Energia 2012).

Potential quantities and the energetic value of the logging residues from fellings are high in Estonia, but logging residues from final fellings and first thinnings are still underutilized (Rosenvald 2001; Muiste et al. 2004). In 2000–2015, firewood fellings in Estonia amounted from 3 to 4.5 million solid cubic metres, of which the wood chips and waste proportion has changed from 47% to 66% (Yearbook Forest 2017 2018). Tree stumps removal is a novel potential source for renewable energy in Estonia (Uri et al. 2015). In 2013, only 33% of the total volume of potential residues was taken into use (Annual Report 2014). The sale of wood chips and residues collected from Estonian state forests has decreased from 330,000 m^3 in 2011 to 183,000 m^3 in 2016, forming 5–11% of the total volume of sold timber (Annual Report 2014, 2016; Yearbook Forest 2017, 2018). At the end of 2017, the demand for biomass for renewable energy production increased significantly (Yearbook Forest 2017, 2018). Wood pellets have become an important fuel type on the energy market in Estonia: in 2010–2015 the consumption of pellets increased more than seven times.

The volume of harvesting residues is very variable, depending mainly on the site type quality and species composition (Padari et al. 2010; Rytter et al. 2016). The technical biomass potential of forestry residues in Germany is between 37.9 and 61.8 million Mg (DM); energetic use ranges from 17.7 to 25.2 million Mg (DM) (Brosowski et al. 2016). Sweden demonstrated that increasing the use of harvesting residues by 2.5 times can be sustainable: the energy potential ranged from 40 PJ yr^{-1} (least intensive biomass harvest) to 155 PJ yr^{-1} (most intensive biomass harvest) (de Jong et al. 2017). Depending on the forest site type the oven dry weight of harvesting residues per m^3 of the stem varies from 22 m^3 ha^{-1} (raised bog site type) to 144 m^3 ha^{-1} (alder fen site type), the volume of stumps may be up to 130 m^3 ha^{-1}, and the share of harvesting residues of the volume of the stand varies from 4.4 to 28.8% (Padari et al. 2010; Uri et al. 2015).

Nurmi (1993) states that the quality and moisture content of fuelwood are much more important factors than the species from the users' point of view. Seasoned logging residues had the lowest dry matter loss, while the logging residues harvested and piled in autumn had the highest loss (Filbakk et al. 2011). The results of our study show that the dry weight of residues (billets and branches) was lower in the coniferous (pine and spruce) residues collected during spring than in the broadleaf species dominated stands (birch and alnus) where residues were collected in late autumn. Spruce dominated stands are considered the best sites for logging residue removal due to high yield – for instance Scots pine dominated stands produce ca half of the harvestable crown biomass of spruce dominated stands (Räisänen & Athanassiadis 2013; Yearbook Forest 2014, 2015). In our study the low quantity of spruce residues is due to the collecting of branches only.

The key question is how different handling and storage methods affect fuel properties (moisture content, dry matter losses, etc.) (Filbakk et al. 2011). The moisture content of logging residues is the most important quality factor affecting significantly the calorific value of woody biomass and transport costs (Pettersson & Nordfjell 2007). Weather and forest conditions have a greater impact on the moisture content of residues than the handling method (Nilsson et al. 2013), depending also on varying shapes of piles, differences in the material type and storage conditions, etc. (Pettersson & Nordfjell 2007; Kizha & Han 2017). Pettersson and Nordfjell (2007) reported that the moisture content fell to 18.2–20.7% for the covered and 18.8–24.9% for the uncovered material. The moisture content of tree tops and branches from broadleaf and coniferous forests may vary on a large scale from 25% to 60% (Garcia et al. 2015). Summertime, when the vapour pressure deficit of the ambient air is low, is usually the best season for open air drying of woody residues (Pettersson & Nordfjell 2007). Our study results show that the moisture content of coniferous (pine and spruce) residues collected during spring is lower (22–26%) than the moisture content of broadleaf species (birch and alnus) residues (25–37%) collected in late autumn. Thus, coniferous residues air-dried and achieved a moisture content equivalent to the moisture content of fire wood dried in the open air (approximately 20–25%) (Vares et al. 2005). The moisture content of pine and spruce branches is quite equal (22–23%) in our study area, but Hakkila (1989) observed a higher moisture content in fresh Scots pine branches (55%) than in Norway spruce branches (45%). The moisture content affected significantly dry matter loss (1–3% per month), with the highest dry matter loss being found in the samples with the least favourable drying conditions and in spruce bundles rather than in pine bundles (Filbakk et al. 2011).

Differences in the calorific value of logging residues depend on the chemical composition of different tree species and tree components (stem, branches, foliage, etc.) (Pettersson & Nordfjell 2007). Differences in the chemical composition are mainly due to the differences in cellulose and hemicelluloses in lignin, resin, terpenes and waxes that result in higher calorific values (Nurmi 1993). The net calorific value in the crown mass of young Norway spruce and Scots pine varies from 19.2 MJ kg^{-1} of dry mass for the foliage to 19.7 MJ kg^{-1} for the stem wood, respectively (Nurmi 1993). Corresponding values for Scots pine and Silver birch are 21.0 and 20.0 MJ kg^{-1} and 19.8 and 18.7 MJ kg^{-1}, respectively. The results of our study shows that the calorific value varied from 20.1 MJ kg^{-1} (billets) to 20.7 MJ kg^{-1} (branches) of dry mass. The heating value of the stem, branches and roots is highest in coniferous trees. The results of our study shows that the calorific value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and calorific value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass. The potential of residues from spruce dominated stands can reach 100 m^3 ha^{-1} equal to 1008 GJ ha^{-1}, and during forest harvesting the possible share of obtained residues suitable for use is 50–75% (Muiste et al. 2004). The potential energy content of harvested spruce stumps amounted to 290 MW h ha^{-1} (Uri et al. 2015). The average energy content of residues from final felling is 522 GJ ha^{-1} (maximum 831 GJ ha^{-1} in a birch and alder mixed stand) and from thinning 151 GJ ha^{-1} (maximum 259 GJ ha^{-1} in a pine stand) (Muiste et al. 2004). Results from our study area indicate that the energetic potential of fresh residues varies on a large scale: from 70 to 250 GJ ha^{-1} (fresh residues) and from 123 to 377 GJ ha^{-1} (dry residues).

Together with the rising interest towards the resource potential of harvest residues, there is a rising need to enhance the stand residues predictive capabilities of our forest biomass models (Eastaugh et al. 2013). Which general or site-specific equations are more accurate for estimating branch biomass, allometric studies could be give answer (Fortier et al. 2017). The young Norway spruce trees growing on soils with higher C/N ratio are more likely to have higher branches biomass (Dutcă et al. 2014). The strong environmental effect on the allometric relationship between diameter at breast height and compartment biomass have been observed (Forrester et al. 2017). Smaller diameeter at breast height trees had lower humidity content and lower proportion of branches (Fortier et al. 2017). Our results shows that from smaller average diameter at breast height stands with higher number of trees per hectare were collected higher amount of branches.

Investigations observed that the harvesting of residues will have positive and negative effects on the environment (soil and water quality, climate regulation, biodiversity, etc.) and ecosystem services (Jonsell 2008; de Jong et al. 2017; Ranius et al. 2018). Harvesting of Norway spruce stumps did not increase soil respiration intensity (Uri et al. 2015). CO_2 emissions decreased with an increasing rotation length: the highest annual biomass production was obtained with a rotation length of 40–60 years (Scots pine) and 80–100 years (Norway spruce) (Routa et al. 2012). Whole-tree clear cutting affected markedly the total amounts of carbon and nitrogen on the more fertile sites (Saarsalmi et al. 2010). Depending on harvesting intensity, the levels of macro- (N, P, K, Ca, Mg, S) and micronutrients (Mn, Zn, Cu) in forest soil and plants change, which either decreases or increases site productivity and biodiversity (Grønflaten et al. 2008; Jonsell 2008; Pyttel et al. 2015). Slash extraction has a stronger effect because the base cation contents, charge-balancing organic acid anions, are much higher in needles and branches compared with those in the stumps (de Jong et al. 2017). One way to compensate for nutrient loss is to return the ash from woody biomass burning to forest lands (Saarsalmi et al. 2005; Ingerslev et al. 2014; de Jong et al. 2017). Ash content of logging residues was in the range of 1.6–2.2% (mainly Norway spruce) and 1.0–1.2% for young trees (mainly downy birch) (Pettersson & Nordfjell 2007). Our research results show that the ash content of branches (0.7–1.9%) was more than 2 times higher than the ash content of billets (0.3–0.8%); the ash content of birch and alnus billets ranged from 0.6 to 0.8%. According to the residual biomass collected from our study areas the total amount of ash formed was 5.5 tonnes: 1, 0.1, 1.1 and 3.3 tonnes from pine, spruce, birch and alder sites, respectively. Based on the quantities of ash used in Scandinavia (2–3 tonnes per hectare in mineral soils or 4–5 tonnes per hectare in organic soils), ca 1–2 hectares of forests could be fertilized with ash from our study areas.

In the changed European security environment, concrete investments are required in the production of distributed renewable energy, because renewable energy solutions have proven their effectiveness while being the only sector of the energy industry with rapid innovations (Renewable Energy Yearbook 2016). Estonia has considerable renewable energy resources in the form of logging residues. This research only explored the use of logging residues as these are the main fuel for all heating power stations and combined heat and power plants heated with wood. In the middle of the 1990s, the transition of heating power stations to wood heating was started in Estonia with the support of the World Bank and other financial resources. Combined heat and power plants heated with wood have been built since 2009. All these additional facilities have increased the consumption of wood fuels. For the planned production of energy ca 4.6 million cubic metres of residues were needed (Hepner et al. 2010). Hence, the development of environmentally friendly and sustainable energy will require constantly increasing utilization of renewable energy sources in the future. However, the specific weight of logging residues is low and their distribution in a cutting area is widespread, and for this reason, collecting and processing them is labour-intensive and the used equipment are expensive (Vares et al. 2005). Logistics optimization is of great importance (selection of appropriate sites for chipping of residues, etc.) for assuring the economic feasibility of collecting logging residues. Taking into account the effects of implementing different technologies (intensive whole-tree harvesting, including stumps, thinning of only above-ground biomass, etc.) for collecting harvesting residues, which have been discussed in numerous studies, the future direction in Estonian conditions should be the cutting of above-ground biomass (stems and branches) exclusively. Compared to the production of forest chips, producing fuel from stumps requires using a completely different method, for example a special gripper attached to an excavator for uprooting, wood crushers instead of chippers for grinding stumps, and the obtained fuel, which has a high ash content, can only be burned in large CFB boilers. Neither economic nor ecological analyses support the practice of uprooting stumps; moreover, the latter lack a sufficient market in Estonia and there seem to be no current political or commercial interests in developing one. Although there is currently no interest in Estonia in such a fuel, the situation may change, because according to the framework convention on climate change which was adopted by several countries, carbon emissions have to be significantly reduced and alternatives to oil shale energy found.

5. Conclusions

The utilization of logging residues as fuel is a relatively affordable source of renewable energy. The quality (calorific potential and ash content) together with the moisture content of fuelwood are more important factors than the species from the users' point of view. Still the quality depends on the species-specific properties of the logging residues as well as on the species-specific chemical composition of the residues. Järvselja data indicate higher quality in conifer dominated sites, but a higher load of logging residues in broadleaf dominated stands. The moisture content of birch, pine and the spruce branch fraction was similar (21.6–25.4%); only on the black alder dominated site the moisture content (35.4%) was clearly different. The heating value of the billets and branches is highest in coniferous trees: the heating value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and heating value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass. It appeared that regardless of the species specifics and site differences, the ash content in branch segments was statistically significantly higher than in stem segments.

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