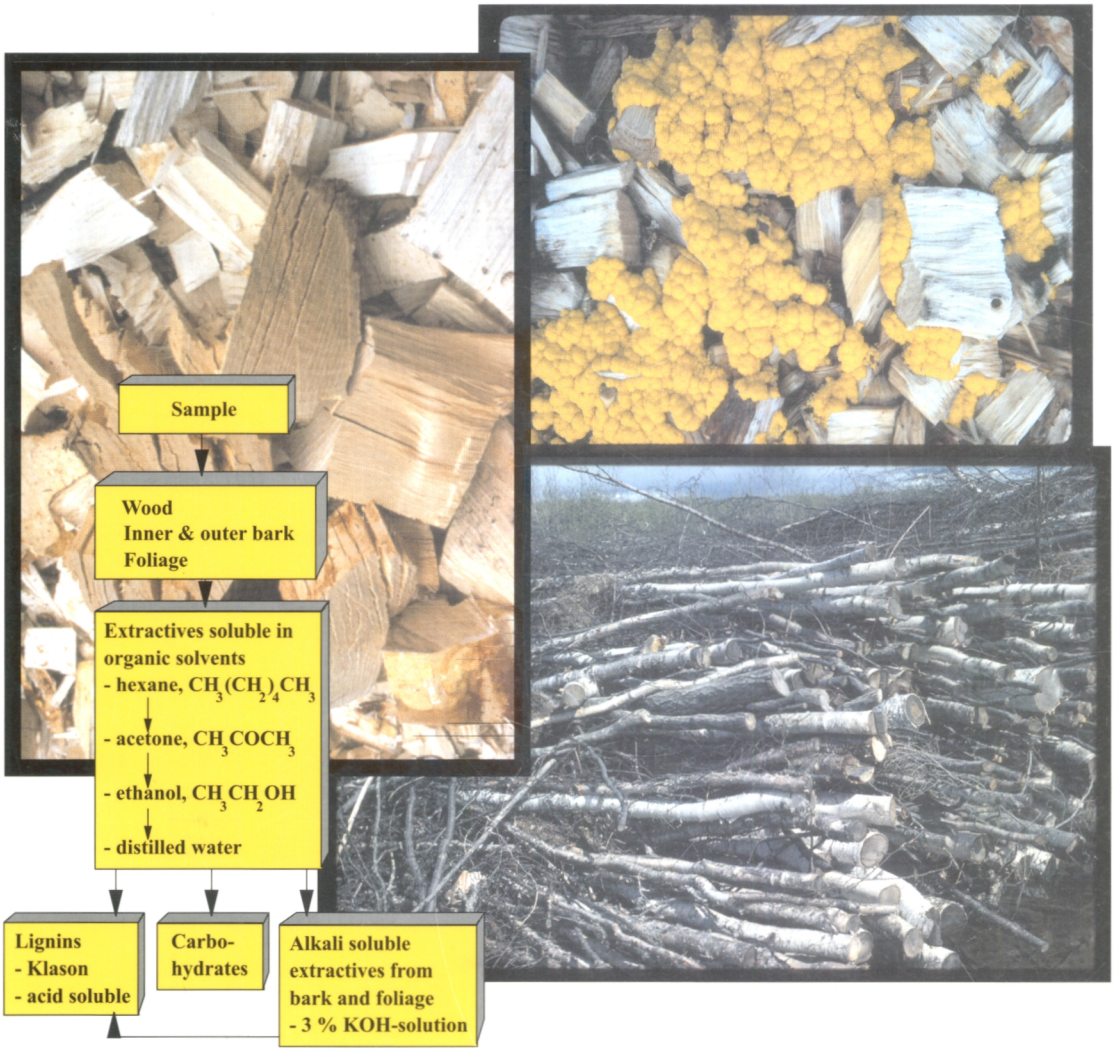
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Characteristics and storage of whole-tree biomass for energy

Juha Nurmi

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Characteristics and storage of whole-tree biomass for energy

Juha Nurmi

DOCTORAL DISSERTATION

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The objectives of this thesis are to describe fuelwood characteristics and to determine how they are affected by length of storage, type of storage, fuel composition and tree species. The fuel characteristics of whole-tree biomass are discussed in terms of proximate and ultimate analysis, bulk density, heating value, particle size, composition and tree species, and the storage schedules presented in the seven enclosed papers. The study material comprises of small-sized trees from cleanings and thinnings, and logging residue from regeneration cuttings. The species studied are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karsten), downy birch (*Betula pubescens* Ehrh.), silver birch (*Betula pendula* Roth), grey alder (*Alnus incana* (L.) Moench), black alder (*Alnus glutinosa* (L.) Gaertner) and trembling aspen (*Populus tremula* L.).

The variability of the chemical composition and the heating value is small in any given tree component (I-III). However, significant differences were found between whole-tree components and species. The species factor, however, diminishes when the weighted heating value of crown, whole-stems or stump-root-system are considered (II-III). Crown material from regeneration cuttings has higher heating value than small-sized stems and whole trees (III). Heating values of whole-tree components and whole trees are higher at the northern extent of their range than further south in Ostrobothnia (II). Some correlation between lignin, carbohydrate and extractive contents with effective heating value was found (II, III).

The most significant property of fuelwood is moisture content because it determines the effective heating value of the fuelwood (I-III). It also varies with a wide range (IV, VI). However, moisture content can be manipulated to some extent by choosing the right procurement schedules (IV-VII). Transpiration drying is a valid drying method prior to comminution which will shorten the time of artificial chip drying. It can be applied to both small-sized trees and logging residues (IV, VI, VII). Covering of residue windrows was not shown to have favourable effects on the fuelwood quality (VII). The nutrient release from needles in harvester heaps and roadside windrows is slow (VII). Loss of needles through seasoning will lower the harmful chloride and sodium concentrations in the residue fuelwood feedstock (VII).

The duration of chip storage in piles should be kept as short as possible to avoid dry matter losses and wetting of the fuelwood feedstock by microbial activity, respiration of living cells and precipitation (V). The drying rate of chunkwood proved to be faster than that of chips of smaller nominal size due to better ventilation. Faster drying of chunks provides better storage properties, greater gain in effective heating value and lower dry matter losses over chips (IV). Redistribution of moisture in piles by the chimney effect will result in a moist upper exterior and dry interior leading to inhomogenous feedstock. Precipitation should not be kept away by contact covers as it leads to increased dry matter losses, higher moisture content and lower effective heating value (V).

Key words: biomass, bulk density, feedstock, fuelwood, heating value, moisture content, nutrients, proximate analysis, logging residue, ultimate analysis, wood ash.

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In Memory of

Dr. Harold E. Young,
scholar, teacher and inspirer

Behold the fire and wood, but where is the lamb for a burned offering?
-Gen. 22:7

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The Roman numerals refer to the original papers listed below.

I Nurmi, J. 1992. Measurement and evaluation of wood fuel. Biomass and Bioenergy 2(1-6)157-171.

II Nurmi, J. 1993. Heating values of the above ground biomass of small-sized trees. Acta Forestalia Fennica 236. 30 p.

III Nurmi, J. 1997. Heating values of mature trees. Acta Folia Fennica 256. 28 p.

IV Nurmi, J. 1987. Polttohakkeen kuivatus traktorikonteissa. Summary: Drying of fuel chips and chunks in wooden bins. Folia Forestalia 687. 40 p.

V Nurmi, J. 1990. Polttohakkeen varastointi suurissa aumoissa. Summary: Longterm storage of fuel chips on large piles. Folia Forestalia 767. 18 p.

VI Nurmi, J. 1999. The storage of logging residue for fuel. Biomass and Bioenergy 17(1999) 41-47.

VII Nurmi, J. 1999. Hakkuutähteen ominaisuuksista. Metsäntutkimuslaitoksen tiedonantoja 722. 32 p.

1 INTRODUCTION

In Finland the share of wood based fuels of the total energy consumption was 19 % in 1998 (Energiakatsaus 1999). This is the highest level found in all industrialized countries. The figure is mostly made up of energy from industrial wood wastes such as black liquor. Only about 3 %-units of this share was used to provide heat for farms and other dwellings in the form of traditional split firewood and the share of forest chips was less than one 1% of the grand total. However, the potential to recover fuelwood in conjunction with forest management and roundwood harvesting operations is considerable. According to the 8th National Forest Inventory the average annual volume increment of stemwood during 1981-96 was 77.58 million m^3 (Metsätilastollinen ... 1998). The total annual growth of the above ground woody biomass, branches and foliage included, is some 110 million m^3. Of this volume 29 million m^3 is logging residue (Hakkila & Fredriksson 1996). However, taking the ecological, technological and economical considerations into account the harvestable volume including needles has been calculated at 8.6 million m^3/a. In addition to this reserve, Hakkila and Fredriksson (1996) have also estimated that the harvestable volume of fuelwood from precommercial thinnings is 1.2 million m^3/a and 0.9 million m^3/a from unproductive stands. A further 3.1 million m^3/a is available as processing residue from early commercial thinnings when the minimum roundwood diameter is 5 cm, and 5.1 million m^3/a if the diameter is 7 cm.

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. Unfortunately, the price of fossile fuels is a dictating factor for the expansion of fuelwood utilization.

Fuelwood properties can be described in terms of proximate and ultimate analysis, bulk density, heating value, particle size, composition and tree species. Much of the properties of fuelwood is dependent on the chemical structure. The major elemental constituents of wood are carbon (C), hydrogen (H) and oxygen (O). The first two are the major combustible elements. Oxygen is non-combustible but an essential structural element of cellulose, hemicellulose, lignin and resins. According to Kollmann (1951) broad-leaved species have an average carbon and hydrogen content of 49.0 % and 6.0 %, and conifers 50.7 % and 6.2 % respectively. The ultimate analysis of *P. sylvestris, P. abies* and *Betula sp.* has shown the carbon content to be the highest in stem bark and small branches, and the hydrogen content to be lowest in stem bark. Birch bark, however, has a higher concentration of hydrogen than other parts of the tree (Thörnqvist 1985). Virtanen (1963) found inner and outer bark of birch to contain 52.0 % and 65.8 % carbon, and 6.0 % and 8.4 % hydrogen respectively. When a kilogramme of hydrogen is fully combusted 141.97 MJ of energy is released. Correspondingly combustion of carbon releases 33.83 MJ of energy per kilogramme (Kollman 1951). When carbon and hydrogen are fully burned carbon dioxide and water are formed.

The ash content of bark and foliage components is variable. Depending on the species stem bark contains 2.5-3.5 %, stem wood 0.4-0.6 % and foliage as much as 2.2-8.7 % ash of the dry weight of the matter (Hakkila & Kalaja 1983, Voipio & Laakso 1992). The most important mineral nutrients found in the ash component are phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), boron (B), sulphur (S), copper (Cu), zink (Zn), molybdenum (Mo), clorine (Cl), sodium (Na), silicon (Si) and cobolt (Co). Plants needed them among other things for esterification with alcohol groups, energy transfer, electron transport, enzymic processes, oxidation-reduction reactions and anion balance (Mengel & Kirkby 1982). In ordinary logging operations the nutrient rich foliage component is left on the

site. However, if whole trees from cleanings and thinnings or logging residues from regeneration cuttings are recovered then vital nutrients may be removed in significant quantities (Jacobson et al. 1996). Lundkvist (1991) has studied nitrogen leaching from residue piles and found that storage in heaps did not increase nitrogen leaching as had been expected.

In woody plants the elements are arranged into complex molecules such as cellulose and hemicellulose sugars (carbohydrates), lignins and resins (waxes, fatty acids, alcohols and terpenes). Lignin and resins are richer in carbon and hydrogen and hence have a higher heating value than carbohydrates (Kollman 1951, Murphy & Masters 1978, Fuwape 1989). It is the quantity of these chemical compounds per unit weight that determines the heating value of fuelwood (Wang et.al. 1981). White (1987) showed the heating value of extractive-free wood to be highly correlated with the lignin content. It has also been shown that the weighted heating value of cellulose and lignin does not equal with that of the extractive-free wood. This has been accounted for by the loss of chemical bonding during extraction (Murphy & Masters 1978). Neither is the heating value of lignin and holocellulose from bark the same for all species (Sandala et al. 1981). Additionally heating value is not only the product of lignin and cellulose components but is also affected by the presence of extractives. Howard (1973) and White (1987) showed the heating value of wood to have a positive correlation with alcohol-benzene extractive content. Suberin and betuline are extractives with an especially high hydrogen content and hence a high heating value. Both of these are found in large quantities in birch outer bark and are thought to be responsible for the high heating value of birch bark (Ekman 1983). Since conifers usually have a higher content of lignin and extractives than broad-leaved species they also tend to have slightly higher heating values per unit weight (Howard 1973, Doat 1977, Musselman & Hocher 1981, Singh & Kostecky 1986 and White 1987).

When studying the heating values of tree components i.e., wood, bark and needles of *P. taeda*, Howard (1988) found needles to have higher heating value than wood or bark. Bark on hardwood trees growing in the southern United States has a lower heating value than wood (Manwiller in Koch 1985, Harris 1984, 1985). However, Manwiller's and Harris's results are not completely consistent. Harris's results do not indicate variation in wood or bark component from one tree part to another, whereas Manwiller's do. Neenan & Steinbeck's (1979) report on broad-leaved species, also from the southern United States claims that the differences between the tree components within a tree are greater than the differences between species. The more temperate North American spruce, pine and broad-leaved species have also been found to have significant differences between components, both within broad-leaved trees and conifers (Singh & Kostecky's 1986).

Differences in heating value have also been shown to exist between stems and branches (Howard 1988). The heating value of branches is higher than that of stems and hence whole trees have higher heating values than stemwood (Olofsson 1975). Olofsson (1975) has put the parts of whole trees in the following order: branches have higher heating value than stems and whole trees higher than stems alone. Furthermore, whole trees from cleanings have higher heating value than from thinnings due to a higher percentage of branches and needles. Logging residue falls between stems and branches. Also Howard (1988) reports branches to have higher heating value than whole trees from the northwestern United States. According to Olofsson (1975) the heating value of stems, branches and needles is higher in Scots pine than in Norway spruce and birch (*Betula* sp.)

The results on the clonal variation are also controversial. Bowersox et al. (1979) found no difference in heating value of *Populus* hybrids, whereas Sastry & Anderson (1980) found clonal differences. Similarly Ager et al. (1986) found significant differences in 31 willow clones. Among the factors that heating value does not seem to correlate with are degree of rot

(Salmi 1964), earlywood vs. latewood comparison (Howard 1973), wood density (Doat 1977), geographic location, growth rate, tree age (Howard 1973) and stem diameter (Stringer and Carpenter 1986).

Although it is the chemical composition of the material that determines the calorimetric heating value (q_v(gross)) it is the moisture content which governs the effective heating value (q_v(net)). This is because water is a non-combustible compound of the fuel and the energy required to evaporate it comes from the fuel itself. Hence, the higher the moisture content the lower the effective heating value (Lyons et al. 1985).

A living tree acquires its moisture through water intake from the soil. It is found as bound water in cell walls and free water in cell lumens of both wood and bark (Panhin & De Zeeuw 1970). The moisture content varies from one tree part to another (Liepinš 1933). It is often the lowest in the stem and increases towards the roots and the crown. Furthermore, moisture content of live trees varies with the season. With birch, alder and aspen species it is highest in the spring just before the breaking of the buds and lowest in the summer. With Norway spruce and Scots pine the moisture content is highest during the winter and lowest during the summer (Hakkila 1962, 1963, Simola & Mäkelä 1976, Sinclair et.al. 1984).

Once the tree is felled the connection to the roots is cut and no more moisture can be retrieved from the soil. After felling moisture content is dependent on the postharvest handling and storage conditions. Moisture may be lost through transpiration drying i.e., leaf seasoning through the foliage, or through the open wood surface. Transpiration drying is an old, well recognized form of drying whole trees (Jalava 1941, Heiskanen & Hakkila 1960, Levanto 1961, Warsta 1961, Hakkila 1962, 1963, Simola & Mäkelä 1976, Liss 1979, Faeste & Johansson 1982, Uusvaara 1984). It is based on the ability of the tree to evaporate free water via foliage. Among other things the rate of drying depends on ambient temperature, relative humidity, season, tree species, tree volume and even wind speed (Heiskanen 1953). The best season for drying is May through August when the vapor pressure deficit of the ambient air is the lowest. Transpiration drying can be successfully used with all domestic tree species but works best with spruce and broad-leaved species (Hakkila 1962). Moisture contents as low as 30 % may be reached given favourable conditions. In adverse conditions the result is not as good (Mitchell et al. 1988). Finally when wood has dried past the fiber saturation point foliage will wilt and fall.

Transpiration drying does not apply only to whole trees but also to logging residue. The moisture content of fresh logging residue is 55-60 % on green weight basis and it can be reduced to as low as 25-30 % (Mäkelä 1977, Thörnqvist 1984a, Jirjis, Gärdenäs & Hedman 1989, Jirjis & Lehtikangas 1993, Lehtikangas & Jirjis 1993a). However, excessive precipitation or low temperatures may hinder the efficiency of transpiration drying (Lehtikangas & Jirjis 1993a). If the storage on the clear-cut area is extended to late fall or even until winter the advantage gained by transpiration drying will be lost as the material will regain moisture directly from the air and through precipitation (Flinkman et al. 1986, Lehtikangas 1991). If the recovery is done in wintertime very little transpiration drying will take place.

Needles contain more moisture than other residue components. Furthermore Lehtikangas (1991) concluded that the moisture content of needles varies more from day to day than that of any other component. Also the relatively small size of residue heaps left by the harvester on the clear-cut area causes the heaps to dry quickly but the counter effect is that they also regain moisture very rapidly (Lehtikangas 1991, Flinkman et al. 1986).

The removal of nutrient rich residue material from the logging site has raised concern over the decrease of site productivity. Unfortunately the number of studies related to the field is very small and they have concentrated on the residue removal from thinning stands

(Andersson 1983, Tveite 1983, Jacobson et al. 1996). This is understandable since the nutrient requirement is highest in young stands at the time of first thinnings (Mälkönen 1974). The short-term growth response to residue removal in young Scots pine and Norway spruce stands has been reported to be variable (Jacobson et al. 1996). The effect of residue removal from regeneration cuttings on the initial growth of seedlings is yet to be shown. However, it has been shown that mineralization of nitrogen from needles is greatest not until 3-6 years after the harvest when the needles are already in the litter layer (Staaf 1984). According to Staff it takes a lot longer to release nutrients from the woody parts of the residue. Rosén & Lundmark-Thelin (1987) state that the inorganic nitrogen is immobilized in residue heaps but some organic nitrogen leaches out of the residue heaps over a long period of time and hardly takes place during the first summer (Lundqvist 1991). Furthermore it has been shown that nitrogen leaching from the soil humus layer underneath the residue heaps is much greater in magnitude than from the residue heaps themselves. An increased mineralization due to higher soil moisture content under the heaps is suggested to be the reason for this (Rosén & Lundmark-Thelin 1987). An intensive study on the decomposition of nutrient rich litter in the short-rotation forests was carried out by Slapokas & Granhall (1991) but the results can hardly be applied to coniferous foliage.

Fuelwood harvesting is characterized by long-term planning where storages are of vital importance to the fluent fuel supply during the winter months when the heat load is the greatest. Unfortunately the disadvantage of these storages are the dry matter losses, increased handling costs and tied up capital. When conditions are favourable any non-comminuted fuelwood e.g., whole trees, whole stems, split fire wood or logging residue, that is stored fresh on a roadside landing or a terminal is likely to loose moisture over time (Heiskanen 1961, Uusvaara 1984, Jirjis & Lehtikangas 1993). However, the drying process is not as rapid as transpiration drying and the results are variable (Uusvaara & Verkasalo 1987). It has also been shown that the covering of piled whole trees on the landing will result in reduced moisture content when compared with uncovered ones (Uusvaara 1984). Also the moisture variation is smaller within the covered stacks. The same observations have been made by Heiskanen (1961) with covered and uncovered stacks of split birch firewood. Uusvaara (1984) also indicates that the piles should be made as high as possible to be able to utilize the cover to its maximum effect. The covering of residue windrows with paper at various landing and terminal sites has also been found to be beneficial in the storage of both fresh and seasoned residue material (Jirjis et al. 1989, Lehtikangas & Jirjis 1993, Jirjis & Lehtikangas 1993). The choice of storage site will also affect the yield of residue recovery operations. Although the drying result is better on the clear-cut area than in windrows on the landing the yield can be as much as 30 % lower on the clear-cut area because of defoliation (Kuitto & Pajala 1982, Mäkelä 1977, Thörnqvist 1984a, Flinkman et. al.1986, Lehtikangas 1991). Wood proportion increases as a result of defoliation (Mäkelä 1977, Flinkman et al. 1986). It has also been found that smaller harvester heaps retain less needles than the bigger ones (Lehtikangas 1991). Hence the heap size may significantly affect the residue yield from a given site.

The latest technological advance in residue recovery is the bailing of residues. The idea has been tested from time to time over the past decade. These compact structures are, round bales resembling hay bales, 1.2 m diameter or oblong, log-like bales. The common advantage of bales over loose residues is easier storage, handling and transportation. The weight of round bales made of green logging residue has been reported to be 400 - 550 kg/bale and densities as high as 400 kg/m^3 (Jirjis 1996, Hudson 1998) but only 160 kg/m^3 for the log-like bales (Lehtikangas & Jirjis 1993b). In spite of the high density of round bales of Sitka spruce and lodgepole pine have been reported to dry to about 20 % moisture content in Scotland in one

summer (Hudson 1998). The Swedish studies report that the storage of Norway spruce logging residue in covered bale stacks will result in a lower moisture content than in uncovered stacks (Lehtikangas & Jirjis 1993, Jirjis and Lehtikangas 1998).

The dry matter losses can be high in fresh round bales due to high microbial activity: about 15 % in covered and 19 % in uncovered piles during 10-month storage trial. This was also observed as an equal loss in total energy content (Lehtikangas & Jirjis 1998). The authors suggest that storage in covered windrows will guarantee a better fuel quality than in baled residues. Although the advantage of log-shaped bales over round ones is easier handling and transportation properties, they do not always store as well as the round bales (Flinkman & Thörnqvist 1986). The difference in the results can be caused by the study conditions but also by the different bale dimensions. It is worth noting that Flinkman & Thörnqvist (1986) found that dry matter losses were smaller in fresh logging residue than in old ones which was thought to be caused by microbial breakdown having already initiated during the storage on the clear-cut area and which was then vitalized in the baled stacks.

Comminution marks a major turning point in the fuel properties of woody biomass. It is an essential part of procurement which enables transportation, handling, feeding and combustion of the material. The vast majority of forest chips used in heat and energy production are directly unloaded into silos for immediate use. However, to ensure the fluent supply of chips, heating plants are often forced to maintain buffer storages of chips on the plant yard. Storing large quantities of comminuted material is much more complex in nature than the storage of non-comminuted material as both biotic and abiotic heat generating processes may start and cause significant dry matter losses.

The living cells, which may survive for a long time in variable conditions (Feist et al. 1971), continue respiration in sapwood, bark and foliage. This respiration produces heat and moisture. Heat generation by microbes at early stages of storage has been observed by numerous scientists (Hatton 1970, Gislerud & Grønlien 1977, 1978a,b, Bergman & Nilsson 1979, Nylinder & Thörnqvist 1980, Thörnqvist & Gustafsson 1983, Saucier & Phillips 1985, Sampson & McBeath 1987, Gjølsjø 1995). The rate at which heat development sets in is quite dependent on the season (Taipale 1960a, White et al.1986) and the composition of the material (Thörnqvist 1983a). Eventually the initial material composition will change in such a manner that the share of bark and foliage components will decrease. Simultaneously the percentage of wood and fine particles will increase (Thörnqvist 1983a, 1984a, Thörnqvist & Gustafsson 1983).

Also the shape of the pile significantly affects the heat development as the shape will determine the ventilating chimney effect in the chip piles (Kubler1982). This effect is important as ventilation provides the oxygen needed by metabolic activity but it simultaneously cools the pile interior by convection. According to Kubler (1982) the self-heating is affected more by pile width than pile height.

Once the temperature reaches 42 °C respiration by living cells will start to drop and at 60 °C the production of CO_2 has ceased (Springer et al. 1971). Meanwhile fungi and bacteria have started to convert wood to CO_2 and water and produce heat, which causes significant dry matter losses. Some fungi can tolerate temperatures as high as 60 °C and bacteria 80 °C (Rothbaum 1963, Assersson et al. 1970). However, when moisture content of the substrate drops below 20 % water is found only in the cell walls which microbes can not utilize. Lowered moisture content may have a direct influence on the pile temperature (Taipale 1960a,b). Unfortunately, unlike the wood cells, fungi and bacteria can survive in dormancy and rewetting will revive them. Lack of oxygen and waterlogging are also detrimental to their life (Kubler 1987). The rapid temperature rise is often followed by a state where temperatures

decrease slowly over a long period of time (Björklund 1983). In small piles the temperature is strongly affected by ambient temperature (Gislerud 1974a). The dry matter losses caused by these processes are much dependent on the original moisture content. Forest chips with a moisture content below the fiber saturation point will suffer smaller losses than chips with higher moisture contents (Nilsson 1987a, Thörnqvist 1983a). Hence, chips made of fresh material will generate more heat and suffer greater losses than if they are made of seasoned material (Björklund 1982, Kubler 1987). Bigger piles and longer storage times will increase losses (Thörnqvist 1984b).

The quality of fuel chips is reduced not only by the high moisture content but also by the moisture distribution within the pile. Over time the interior of the pile warms up and moisture moves out condensing on the cooler outer parts and upper parts of the pile. As a result the interior can be at 20-25 % moisture content whereas the upper and outer parts are at 65 -70 %. This has been found on pulp chips as well as fresh logging residue chips (Taipale 1962, Nylinder & Thörnqvist 1980, Thörnqvist 1983a, 1984b, Thörnqvist & Gustafsson 1983, White et. al. 1983). Especially noticeable is an over-saturated 'cap' or a 'lens' on the top of the pile (Hatton 1970). Nontheless, contradicting results have been recorded on hardwood pulp chips (Eslyn 1967). In wintertime the cap causes real problems when the wet outer parts freeze and will be rejected as unusable. Fortunately this heterogenity can most often be overcome by mixing the material.

In addition abiotic processes such as moisture adsorption, pyrolysis and charring will further cause dry matter losses and generate heat. It has been shown that in storages where the pile temperature reaches high levels (300 °C) the breakdown of lignin and carbohydrates will take place. This is especially pronounced in needles and bark. The breakdown of carbohydrates will take place more readily than the breakdown of lignin components (Jirjis & Theander 1986, 1990). If the processes are allowed to continue they may result in combustion and open fire (Assersson et al. 1970, Bergman 1974, Thörnqvist 1987).

Air movement in and around the pile is of key importance to drying as it is the only medium which carries moisture out of the wood. Comminution drastically affects this process. It greatly increases the open wood surface area which shortens the distance required for water molecules to travel out of the wood particle. However, a given mass of chips is an aggregate of innumerable chip particles where drying and wetting is dependent on the air movement inside the mass. From the point of view of drying, the aggregation of chip particles means less air movement and results in decreased capabilities to loose moisture (Nisula 1980). Particle size has been found to affect the moisture content of chips. Larger gaps of space are left between large particles than between small particles, which is found to facilitate freer air movement and moisture transfer to the surrounding air through the particle mass (Gustafsson, 1980, Gislerud 1983, Sturos 1984a,b, Nellist et al. 1993). It follows that large particles i.e., chunks from stemwood, dry considerably faster in bins than chips of smaller nominal size (Nilsson 1987, Nurmi 1986, Gjølsjø 1988). With time the particles of all sizes will eventually come to the same moisture content as they approach an equilibrium state with the ambient air (Sturos 1984b, Nurmi 1986). In stacks where ventilation is not as good as in bins chips may dry faster than chunks (Nilsson 1987). Hudson (1988) did not find the particle size to be a significant factor on moisture when storing piled whole-tree chips and chunks of Sitka spruce. However, bigger particles have been found to reduce heat buildup in whole-tree piles (Björlund 1983, Fredrikson & Rutegard 1985), which for some reason does not necessarily result in a lower dry matter loss. Thörnqvist (1983c) has found in the case of forest residue that the large particles (200-300 mm) may actually cause piles to have the highest temperatures as well as highest dry matter losses.

When the annual consumption of fuel chips is relatively small, as in the case of farms, forced air drying can be used to lower moisture content (Thörnqvist & Gustafsson 1983, Nilsson 1987a). Two forms of this method exist i.e., cold, ambient air drying and warm air drying where the air has been artificially warmed to be able to retain more moisture. The former one is much less costly than the latter one but results are not as good (Thörnqvist & Gustafsson 1983). If ambient air is used, it is recommended to carry out drying in summer when air can retain more moisture (Gustafsson 1980). It has also been noted that particle size also affects the air permeability and hence the outcome of forced air drying. In a given time period chips may dry to a lower moisture content than the chunks of 100 mm nominal particle size (Nilsson 1987a). However, it should be noted that energy consumption is much higher with chips, since the fan size required to move air through the chips has to be bigger than with chunks. In a forced air trial carried out by Gislerud (1983), where the static air pressure was 500 Pa/m, four times more air was passed through 5 cm size chunks than through ordinary chips. Nilsson (1987a) has shown that pile temperatures and subsequently dry matter losses are much lower on artificially dried chip silos than in chip bins or piles.

The biological and chemical processes taking place in the material also have an effect on the ash concentration in the material. Thörnqvist (1983c) showed that the ash content of logging residue chips may increase by 50% in one year's time and the variation within the pile may be considerable. He also brings up the unfortunate fact that often the chips are contaminated by mineral soil particles due to careless material handling. Whole-tree chips and chunks of broad-leaved or coniferous species have not yielded equally high increases in ash content (Nilsson 1987a,b, Fredrikson & Rutegård 1985) which is a result of the large proportion of foliage in coniferous logging residues. Nilsson (1987a) did not find differences between pile, bin or silo storages, but chunks had higher ash content than chips. In non-comminuted logging residue the ash content is dependent on the proportion of foliage and of small diameter branches. During storages that take place on a clear-cut area and last for many years most of the needle mass is lost. As a consequence ash content of the residue mass decreases (Thörnqvist 1984a). Within the needles themselves the ash content seems to be unaffected by storage time (Lehtikangas 1991). In landing storage studies on windrowed residues both increases and decreases in ash content have been reported but no relevant reason for the differences has been given (Jirjis & Lehtikangas 1993, Lehtikangas & Jirjis 1993a).

2 OBJECTIVES

The main objectives of this thesis are to describe such characteristics of whole-tree biomass as moisture content, heating value, bulk density, basic density, nutrient content, ash content and dry matter losses; and to determine how they are affected by length of storage, type of storage, fuel composition and tree species. With these objectives in mind a series of studies were carried out to:

1) identify the properties that are relevant to the characterization of whole tree biomass (I)
2) determine the heating values of whole-tree components of those species that are native to Finland, and how heating value relates to species, chemical composition, soil type and geographic location (II,III)
3) study the effects of particle size, respiration drying, tree species, season and length of drying time on the rate of drying in simple wooden bins (IV)
4) study the effects of storage time and cover at high latitude on the fuel characteristics of birch whole-tree chips (V) and
5) determine how storage site, tree species, cover and compaction affect the fuel quality of logging residues as well as provide information on the release of nutrients from the residue material in different recovery schedules (VI, VII).

3 MATERIAL AND METHODS

The material used in each of the enclosed papers is a representative of the fuelwood supply from ordinary stand management and harvesting operations. The material covers small-sized trees from cleanings and thinnings (I,II,IV,V) and mature trees from regeneration cuttings (III,VI,VII), which are the two major sources of potential fuelwood available in Finland. The material presented in the first paper (I) is composed of results compiled in an International Energy Agency (IEA) project. Its purpose in this thesis is introductory, characterizing those factors important when evaluating the fuelwood characteristics.

The small-sized trees came from cleanings and pre-commercial thinnings. The species included in the studies on the heating values of small-sized and mature whole trees were Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karsten), downy birch (*Betula pubescens* Ehrh.), silver birch (*Betula pendula* Roth), grey alder (*Alnus incana* (L.) Moench), black alder (*Alnus glutinosa* (L.) Gaertner) and trembling aspen (*Populus tremula* L.) (II, III). The drying and storage studies on small-sized trees included downy and silver birch (IV, V) and grey alder (IV). The storage studies of logging residue from regeneration cuttings included Norway spruce (VI, VII) and Scots pine (VII) (Table 1).

In paper II the small-sized sample trees came from the central Ostrobothnian area. They were collected from both mineral and organic soils. To test the effect of latitude, specimens of Scots pine, Norway spruce and downy birch samples were also taken from the northern end of their natural range in the municipality of Inari (Figure 1). The mature trees (III) all came from mineral soils in the central Ostrobothnian area. No geographic or soil factors were included in this study. The execution of a rigorous study on the heating values of tree components required a detailed sampling of the selected trees. This lead to a high number of samples per tree. Furthermore the separation of inner bark, outer bark and wood components from stem, roots and especially from branches was very tedious and time-consuming limiting further the number of sample trees. As a result, a total of 28 small-sized trees and 14 mature trees were sampled. After separation the tree parts were dried to constant weight at 102 °C, milled and pelletized. The determination of calorimetric heating value was done with a bomb calorimeter (Leco AC 300). The detailed description of the method is given in publication II. A total of 2950 determinations of calorimetric heating value (q_v(gross)) were carried out. To calculate the effective heating value (q_v(net)) of a given material, which is the calorimetric heating value minus the heat of condensation of the water vapor created during combustion, it is necessary to know the hydrogen content of the fuel. This was done by analyzing the samples of each tree component with a Leco CHN-analyzer.

Duncan's multiple range test and analysis of variance were used to test the significance of species on the heating value of tree components, soil type and latitude. Furthermore the analysis of variance with repeated measures was used to test the significance of relative stem height, branch and root diameter on the effective heating value of mature trees.

To study the correlation between the heating value and the chemical composition lignin, carbohydrate, extractives soluble in organic solvents and hot water, and alkali soluble extractive contents of tree components were determined (II, III). To overcome the low number of sample trees the results on small-sized trees were pooled for statistical testing. However, this procedure caused difficulties in the interpretation of the results on small-sized trees and hence the data on mature trees was analyzed separately for each species.

Drying of whole-tree chips for farm and other small-scale uses (IV) was studied on five locations in southern and central Finland (Figure 1). Birch (*Betula* sp.) and grey alder fuelwood feedstocks came from cleanings and pre-commercial thinnings. The trees were chipped and dried in four sets both in 1981 and 1982:

-spring chipping of freshly cut trees
-summer chipping of freshly cut trees
-summer chipping of transpiration-dried trees
-autumn chipping of transpiration-dried trees

The idea was to have a drying unit with as simple a construction as possible. Nonetheless, it had to be a bin that was strong enough to be transported on a farm tractor trailer. As a result, 32 wooden bins each 15m^3 in volume with plastic roofing were built for the study. To find out the effect of particle size on the drying rate the experiments were repeated with chips (nominal particle length of 20 mm) and chunks (50-70 mm). The whole trees were chipped with small farm tractor-driven disc chippers and chunked with a conescrew chunker. Altogether 74 batches were dried. Moisture samples were taken in the beginning and at the end of the drying season and dried for two days at 102°C. In addition the drying rates were monitored by weighing the bins about once a week. This data was used to construct a drying model, where the dependent variable was moisture content on green weight basis and independent variable was drying time in weeks. Additional models were constructed where the dependent variable was moisture content which had been standardized in such a way that the initial moisture content was transformed to 100 % and subsequent moisture contents were presented as percentage figures of the initial moisture content. The bulk density (kg/m^3-loose) was also used as a dependent variable (IV).

To study the effects of long-term storage on the fuelwood properties of downy birch whole-tree chips an experiment including two 3000 m^3-loose piles was established in Sodankylä (V). The whole-tree fuelwood feedstock had been stored for a year in roadside piles. Chipping and piling took place in September 1983. Combinations of cover, under base and length of storage were used to make a total of eight treatments. The storage time extended from 5 1/2 to 18 months. Basic density, moisture content and effective heating values were measured in each treatment. Heating values were determined in Vapo Oy laboratory in Jyväskylä with an IKA calorimeter. The submersion method was used to determine the basic density, i.e., dry weight and wet volume, of the whole-tree chip samples. To be able to include the fine particles as well, an inverted conical shaped steel container with perforations was used to contain the sample during the submersion stage.

Sampling of the piles at the end of the experiment was made easier by placing nylon net bags in the pile. The bags were filled with chips, placed in a one-meter grid on a vertical plain and covered with chips. After the storage the bags were retrieved during the dismantling of the piles. Pile temperatures were also monitored at 0.5, 1.0, and 2.0 meter depths along the slopes of the piles at two-meter intervals. The relationships between basic density and the following independent variables: moisture content, heat sum of pile temperature, and pile height and depth were determined by using regression analysis. Both simple and multiple regressions were used.

The changes in the fuelwood properties of spruce logging residue were studied at three different types of storage conditions in 1994 through 1995 (VI). The original stand stocking of the 15 ha clear-cut area in paper VI was 233 m^3/ha and yielded 108 oven-dry tonnes of residual material per hectare on average. Storages of three types were established. The first storage was composed of some 60 tonnes of residual material which was freshly forwarded to a landing and stored in an uncovered windrow for one year from September 1994 until September 1995. The second storage was a 1.76 ha clear-cut area containing 125 oven-dry tonnes of logging residue stored in heaps formed by the single grip harvester during the delimbing phase (Nurmi 1994). The study material was kept on the clear-cut area from September 1994 until June 1995 and then forwarded to the landing. It was stored there until September 1995. The third storage was

made up of 175 fresh tonnes of residue hammermilled with a Morbark 1200 tubgrinder. The material was stored in a single pile on a mill yard from September 1994 until June 1995. Half of the pile was compacted with a crawler tractor, whereas the other half was not.

Moisture content on green weight basis was determined at the beginning and end of each stage of each treatment. Percentage of needle mass of the uncomminuted material was also determined before and after the storage. The possible dry matter losses of the needle mass were determined as a loss of relative mass. This was done by measuring the weight of 100 needles at each stage of the storage trials and expressing the weight in relation to the weight of the fresh needles collected in the beginning of the trial. The release of nutrients from the intact foliage was done by determining nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), manganese (Mn), magnesium (Mg), iron (Fe), zinc (Zn), copper (Cu) and boron (Bo) concentrations from the samples taken in September 1994, March 1995 and June 1995. The analyses were carried out with a standard method described by Halonen et al. (1983).

The temperature of the hammermilled material was monitored every weekday with a digital thermometer. This was done by placing heat sensors at 0.5, 1.0, 1.5 and 2.0 meter depths of both compacted and non-compacted parts of the pile. The analysis of carbon and hydrogen content was done with a Leco CHN-analyzer to find out whether the concentrations of these materials had changed.

To study the effects of storage time and cover on the fuel quality and nutrient release of logging residues two studies were set up (VII). In the first one 12 windrows of green spruce logging residue were formed on roadside landings in Mikkeli. Half of the windrows were covered with fiberglass enforced paper cover. The residue in windrows was stored for 4, 9 and 16 months and then chipped four windrows at a time, two covered and two uncovered. In the second part of the study logging residues of Scots pine and Norway spruce were stored over winter in heaps created by a single grip harvester on a clear-cut area. The heaps were sampled in August 1995, February and June 1996 and again in January 1997. In both studies on logging residues samples were taken to determine moisture content, percentage of ash, elements, percentage of needles and heating value.

Table 1. Summary of the study material and the measured variables.

Paper	Material	Species	Variable	Type of storage
I	woody biomass of various origins	NA[1)]	moisture content heating value particle size bulk density chemical composition elemental composition	NA
II	small-sized whole trees	*Alnus glutinosa* *Alnus incana* *Betula pendula* *Betula pubescens* *Picea abies* *Pinus sylvestris* *Populus tremula*	heating value carbohydrates lignin extractives latitude soils tree part/component elemental composition	NA
III	mature complete trees	*Alnus glutinosa* *Alnus incana* *Betula pendula* *Betula pubescens* *Picea abies* *Pinus sylvestris* *Populus tremula*	heating value carbohydrates lignin extractives tree part/component elemental composition	NA
IV	small-sized whole trees	*Alnus incana* *Betula* sp.	moisture content particle size dry matter losses bulk density transpiration drying storage time heating value	chip bins
V	small-sized whole trees	*Betula pubescens*	moisture content basic density heating value dry matter losses pile temperature storage time	chip piles
VI	logging residue	*Picea abies*	moisture content ultimate analysis ash content dry matter losses comminution compaction	residue heaps roadside windrows chip pile
VII	logging residue	*Picea abies* *Pinus sylvestris*	moisture content ultimate analysis ash content dry matter losses cover	roadside windrows residue heaps

[1] NA = not applicable

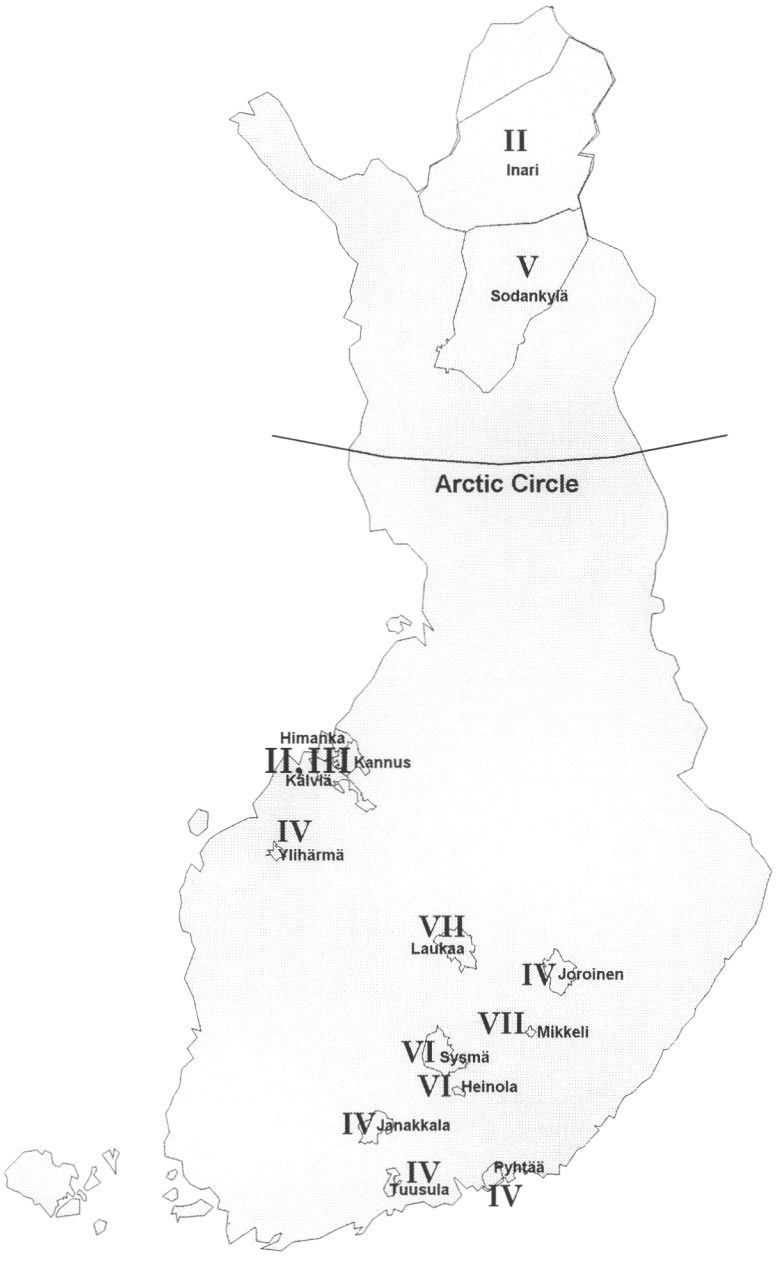


Figure 1. The location of study sites in reference to the enclosed papers.

4 RESULTS AND DISCUSSION

4.1 Heating values of whole-tree components

The magnitude of effective heating value of oven-dry matter (q_v(net)) of indigenous tree species growing in Finland is affected by such factors as species, tree part (stems, branches and roots) and tree component (wood, bark, foliage) and size of the tree. However, because we are dealing with a rather uniform organic material in terms of elemental composition the differences in q_v(net) are relatively small and not always significant.

The variation of q_v(net) in wood components from a tree part to another is such that stemwood - having very little variation along the longitudinal axis - has lower q_v(net) than branch wood. This difference is most noticeable in pine where branch wood (19.99 MJ/kg) has a significantly higher heating value than the stem (19.53 MJ/kg) (III). The stemwood and rootwood of pine are not statistically different, however. Howard (1973) has reported a similar result on *P. teaeda*. However, the greatest degree of variation is caused by pine stumps which have an q_v(net) of 22.36 MJ/kg. This value is higher than in any other wood found in the indigenous species and is caused by a high content of extractives soluble in organic solvents (18-20 %). Significant differences between tree parts are also found in alders and aspen. This variation, however, is not as great as in pine. In genus *Alnus* the wood of the aboveground portion of the tree has a lower q_v(net) than the belowground parts of the tree. The tree part is not a significant factor on the q_v(net) of spruce and birch wood. Similarly Musselman & Hocker (1981) did not find the tree part to have an effect on the q_v(net) of North American pines, spruces and broad-leaved species. Notwithstanding, Singh & Kostechy (1986) did find differences in their study on the same genera. One has to conclude that the variation in the q_v(net) of wood components from a tree part to another is species specific. Species is a significant factor when comparing the effective heating values of individual tree components. This holds true with both small-sized and mature trees (II, III). The effective heating value of the wood proper is higher in conifers than broad-leaved species and applies to all tree parts (II, III). The result is in agreement with earlier information on both Eurasian and North American species provided by Howard (1973), Olofsson (1975), Doat (1977), Musselman & Hocher (1981), Singh & Kostecky (1986) and White (1987). In conifers differences between the small-sized and mature tree components is scarce. However, the tree size was a significant factor in many but not all broad-leaved species.

Variation can also be found in inner bark and outer bark components. The general tendency is that effective heating value of bark components is higher in the stems than in the branches. However, these differences are not always statistically significant (II, III). The more interesting fact about the bark components is that unlike with wood q_v(net) varies with stem height. This variation is very much dependent on species and tree size, the variation being greater in small trees than in large, mature trees. Although some variation with tree height can be found in the coniferous inner bark this variation is still small when compared with outer bark of the studied species of the genera *Alnus* and *Betula*. Some vartiation can be found in other genera as well but it is modest when compared with these two (Figure 8 in II, Figure 4 in III). The phenomena is very much emphasized in downy and silver birches in which the decrease in effective heating value from the base to the top (1.5-2.5 MJ/kg) is caused by decreasing concentrations of betulin and suberin (Voipio & Laakso 1992). According to Ekman (1983) birch outer bark contains 315 g of triterpenoids per oven-dry kilogramme of bark, of which betulin accounts for 77 %. The amount of suberin is 322 g/kg.

Unlike with wood, the tree size has a significant effect on the q_v of inner bark. With just one exception the significant differences are always in favour of mature trees having the higher heating values (Table 5 in III). The effect of tree size can also be seen in outer bark but most

often they were not significant (Table 7 in III). Species is also a significant factor on the $q_v(net)$ of both inner and outer bark. Broad-leaved species have higher effective heating values than conifers due to high lignin content in inner bark and high extractive content in outer bark. As a result their stem bark, containing both inner and outer bark, has higher $q_v(net)$ than conifers. This was observed both in small-sized and mature trees (II, III).

The comparison of wood and bark components shows the $q_v(net)$ of outer bark always to be higher than that of inner bark or wood. This holds true for all species and is independent of the stem size (Figure 11 in II, Table 12 in III). The order of magnitude of inner bark and wood is much alike. It follows that as a result of higher extractive content the combined bark component always has higher $q_v(net)$ than the wood component (Musselman and Hocker 1981, Singh and Kostecky 1986). Olofsson (1975) also reports the $q_v(net)$ of the bark of Scots pine, birch (*Betula* sp.) and Norway spruce to be higher than the wood. An opposite result has been found by Neenan & Steinbeck (1979) who have found young broad-leaved trees from Georgia, United States to have higher heating value in wood than bark. The information, however, need not be contradictory as this relationship here again is probably species specific.

With respect to the difference of trees growing on mineral versus organic soils the results indicate the differences in $q_v(net)$ of tree components to be minor. On the other hand latitude has a significant effect on the $q_v(net)$ of all bark components (Table 2 in II). Very little data has been published on the significance of geographic location on the heating value. None is available on the indigenous species growing in Finland. However, Howard (1973) reports that geographic location has no effect on southern pines (*Pinus* sp.) growing in the southeastern United States. This difference between the two studies could be caused by species but it is more likely that the significance found in the results is caused by the greater climatic variation in paper II in comparison with Howard's study.

Fuel chips are made of whole trees, stems or logging residue and more rarely of the stump-root system and not of a single component. Hence, the effective heating value of these chips is the weighted average of these components. The proportion of these components depends on species, tree size and age, stem height and stand treatment. It also varies from one tree part to another (Taras 1978, Gislerud 1974b, Hakkila 1991). Wood is the prominent component in all fuel chips making it the single most important component to consider when heating values for different parts of the tree are calculated. Although outer bark is higher in heating value than the other two components there is only a small amount of it and it makes a lesser contribution to the average heating value than wood or even inner bark. As a result the high $q_v(net)$ of the birch outer bark has relatively little effect on the weighted $q_v(net)$ of stem biomass (II,III, Sandala et. al. 1981). In spite of the large differences in component proportions and heating values the differences between species actually turn out to be surprisingly small on the basis of stem or whole tree (Table 2).

A whole tree includes all the components of a tree above the stump cross-section (Hakkila 1989). Its effective heating value is somewhat dependent on the stem and crown biomass proportions. This in its turn is dependent on the stand history. The differences between species are small in whole trees. Pine has the highest and aspen the lowest $q_V(net)$ by a margin of only 5%. From a practical point of view the differences are insignificant and do not affect the value of fuelwood. One has to consider that errors of a similar magnitude may take place in timber scaling, not to speak of the moisture variation which has a much greater effect on the fuelwood value. The results also indicate that the heating value of stem, crown and whole-tree material is higher in the northern extent of the growing range than in the southern part of the country. This is mostly caused by the higher bark content at higher latitude (II).

The crown mass makes up the vast majority of logging residue from regeneration cuttings. It is formed by branches including wood, bark and foliage. The crown is also an important part of small-sized whole trees as it accounts for 15-35 % of the dry whole-tree mass (Simola 1977, Kärkkäinen 1980, Björklund 1984, Hakkila 1991). Bark accounts for roughly one third of the live, foliage-free branch mass. This presence of bark enhances the heating value of crown biomass as the q_v(net) of bark is higher than that of wood (Tables 9 and 10 in III). Of the mature trees pine has the highest and aspen the lowest foliage-free crown heating value. Other species are intermediate.

Table 2. The effective heating value (MJ/kg) of wood fuel by species, tree size and source. Olofsson's (1975) values are included for comparison.

Species	Tree size	Stems		Crown		Whole trees		Foliage		Stumps	Stump-root system	
			Olofsson		Olofsson		Olofsson		Olofsson			Olofsson
P.sylvestris	small	19.33	19.23	20.23	20.24	19.53	19.59	21.00	21.05	. .	. .	. .
	mature	19.55	19.28	20.09	20.50	19.63	. .	21.04	21.04	22.36	21.02	19.53
P. abies	small	19.02	19.02	19.77	19.76	19.29	19.19	19.22	19.79	. .	. .	. .
	mature	19.16	19.76	19.41	19.78	19.24	. .	19.19	20.00	19.18	19.32	19.07
B. pubescens	small	19.19	. .	19.94	. .	19.30	. .	19.77	. .	. .	. .	. .
	mature	19.06	. .	19.33	. .	19.09	. .	19.36	. .	18.61	. .	. .
B. pendula	small	19.15	19.02	19.53	20.28	19.21	19.04	19.72	. .	. .	. .	. .
	mature	18.96	18.84	19.61	19.75	19.05	. .	19.76	. .	18.50	. .	. .
A. incana	small	19.00	. .	20.03	. .	19.18	. .	20.57	. .	. .	. .	. .
	mature	19.14	. .	19.74	. .	19.22	. .	20.54	. .	19.27	. .	. .
A. glutinosa	small	19.31	. .	19.37	. .	19.31	. .	20.08	. .	. .	. .	. .
	mature	18.90	. .	19.47	. .	19.00	. .	19.78	. .	18.91	. .	. .
P. tremula	small	18.65	. .	18.61	. .	18.65	. .	19.18	. .	. .	. .	. .
	mature	18.62	. .	18.96	. .	18.66	. .	19.02	. .	18.32	. .	. .

Foliage is another major component of the live crown. It accounts for 25.5 % of mature pine and 37.6 % of spruce crown mass in mature stands in southern Finland (Hakkila 1991). It also contains a majority of many nutrients bound by the tree (Finér 1992). Significant differences were found in the q_v(net) between mature pine (21.038 MJ/kg) and spruce (19.188 MJ/kg) needles. The difference was slightly smaller in needles from small-sized trees and the tree size was not a significant factor (II, III). Olofsson (1975) reports similar values for the pine foliage but his figures for mature spruce are 0.8 MJ/kg higher than the values reported in this study (Table 2). It is possible that the geographic location could account for the difference. Another reason could be the xylén distillation method used by Olofsson to dry the samples instead of the regular oven-drying of samples. As the q_v(net) of needles is higher than that of branch wood they bring an important addition to the average effective heating value of logging residue by increasing the weighted average value (I-III). Although the proportion of foliage in broad-leaved trees is smaller than in conifers the effective heating values are comparable. In small-sized trees the range of species was 19.18-20.57 MJ/kg, and in mature trees 19.02-20.54 MJ/kg. Procurement and storage schedules will determine whether this component will be included in the fuelwood or not. The foliage-bearing crown material of pine (20.3 MJ/kg) is 1 MJ/kg higher in effective heating values than that of spruce (19.3 MJ/kg). 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 figures that are 0.2-0.4 MJ/kg higher for mature, foliage-bearing conifer branches than those determined in this study (Table 2). This difference, however, could be caused by the difference in the wood/bark/foliage ratio of the studied materials.

The crown mass without foliage has a higher $q_V(net)$ than stems. This is not affected by species or tree size. It is significant from the fuelwood utilization point of view, that should a greater degree of industrial utilization be targeted at small-sized stems, the logging residues with higher heating value will still remain available for energy use.

The stump-root system is the aboveground and belowground wood and bark mass of a tree below the stump cross-section (Hakkila 1989). The effective heating values of roots of mature trees differed only little from the stems. Pine and spruce are the only species to provide plentiful raw material for harvesting stump-root systems. Much of the mass of the pine stump-root system is concentrated in the stump component and the $q_v(net)$ is as high as 21.02 MJ/kg. Unlike pine the majority of spruce stump-root mass is in the root component. This has very little effect on the weighted $q_v(net)$ (19.32 MJ/kg) as the effective heating values of stumps and roots are not so different from each other (Table 2).

Inspite of the limited number of stems included in studies II and III the gathered information seems to be accurate enough to make conclusions and practical calculations on the heat content of a variety of stands and fuelwood feedstocks. This result is supported by the comparison with Olofsson's (1975) results which tell the heating values for comminuted small-sized whole trees of pine (19.59 MJ/kg), spruce (19.19 MJ/kg) and birch (19.04 MJ/kg). These are close to those presented in paper II and which are based on the weighed mean calculations: pine (19.53 MJ/kg), spruce (19.29 MJ/kg) and birch (19.21 MJ/kg) (Table 2).

4.2 Drying of chips and chunks in wooden bins

The feature common to both chips and chunks was the rapid drying during the first few weeks followed by a relatively slow drying over several weeks as the moisture content approached equilibrium state with the ambient air. The logarithmic model ($y_i=a+bx_i-clnx_i$, where y_i is moisture content on green weight bases and x_i is drying time in weeks, a, b and c are constants) was found to describe the drying rate best (Table 7 in IV). Major differences in drying rate were found between the two particle sizes and the seasons. This rate was found to be faster for chunks than for chips. The same result has been reached in American studies of convective drying of sugar maple (*Acer saccharum*) and trembling aspen (*Populus tremuloides*) (Sturos et al. 1983, Sturos 1984a,b) and of birch (*Betula* sp.) in Sweden (Nilsson 1987a). These results are also supported by another Finnish study (Nurmi 1986) where the effect of particle size was demonstrated by studying five different particle sizes with nominal lengths ranging from 20-130 mm (Figure 2). The reason for this faster drying in chunk bins is the higher pressure drop in the more compact chip bins. This drop restricts air movement in the chip mass decreasing ventilation and moisture transportation out of the bin (Sturos 1989, Gislerud 1983). The particle size factor was most significant with freshly comminuted material where chunks dried faster by a factor of two. The differences between particle sizes were less pronounced with material comminuted from previously transpiration-dried trees.

The season was found to be the most important factor affecting drying (Figures 21 and 22 in IV). As expected, summertime facilitated the fastest drying rate. Drying result was further enhanced by using transpiration-dried trees. It took the freshly comminuted material three times longer to reach the moisture content of the transpiration-dried material. The

difference was of the same order for both chips and chunks. This means that if passive drying is to be used and the number of bins is limited, transpiration drying will significantly reduce the drying time and hence increase the drying capacity of the bins. This capacity, however, becomes very limited in autumn as the vapor pressure deficit approaches zero. As a consequence the transpiration-dried material lost only 5% of moisture over 2-3 weeks in late September and early October. After moisture content reached equilibrium with the ambient air it stayed at the same level for the rest of the experiment. It should also be noted that when the particle moisture content approaches equilibrium moisture content also the particle size becomes insignificant (Gislerud 1983, Sturos 1984a,b).

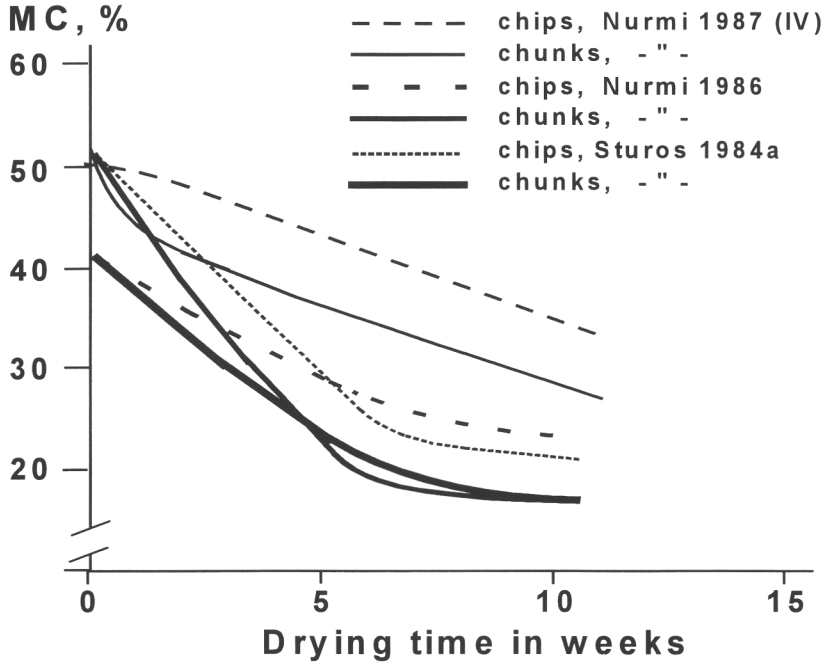


Figure 2. The effect of particle size on the drying rate of fuel chips.

The improvement in fuelwood quality by drying may be offset by dry matter losses. In wooden bins the dry matter losses were about 1.0 % per month. The advantages of transpiration drying do not seem to be limited only to better drying but it also reduces the dry matter losses (Table 5 in IV). The losses were also slightly higher for chips than for chunks. The result is in agreement with Nilsson's (1987a) results which report higher losses for bin-dried chips than chunks.

The accumulative effect of drying and dry matter losses caused changes in heating values per unit volume (Table 6 in IV). Chunks (+0.9-5.4 %) had a slightly higher net change than the chips (-2.5-+5.1 %) because of the better drying characteristics. The average net increase in the effective heating value was 1.3 % for chips and 3.4 % for chunks. Alhough Nilsson's (1987) results on bin drying support these results they do indicate a bigger difference in advantage of chunks over chips. This slight difference could be caused by weather conditions but is more likely due to the difference in chunk shapes in these two studies. In Nilsson's study a prototype chunker operating on a so-called involuted disc slicer principle produced 100 mm long, non-split pieces (Danielsson 1988). In paper VI the chunks were of

equal nominal length, but due to the cone screw cutting method the pieces were also split along the grain (Hakkila & Kalaja 1981). This splitting could have caused greater compaction and a lower degree of ventilation than in the Swedish study (Nilsson 1987).

No major differences in drying rate between alder and birch were found. Nevertheless, it should be noted that the initial and final moisture contents of birch were always lower. This was caused by the higher basic density of birch (Panshin & de Zeeuw 1970). This difference between birch and grey alder was maintained untill the end of the experiment (IV). Dry matter losses were equally small (1 %/month) but variable throughout the drying season being about twice as high for freshly comminuted material than for transpiration-dried material. Because of the higher basic density and lower moisture content the effective heating values per unit volume of birch chips and chunks were always greater than the heating values of alder. At the end of the experiment the difference was about 14 % on average i.e., about the same as in the beginning.

4.3 Large-scale, long-term storage of birch whole-tree chips

In Lokka, northern Finland, piling of chips was followed by a rapid temperature increase inside the pile (Figures 3 and 4 in V). This could be expected on the bases of previous studies by Bergman & Nilsson (1967, 1979) and Gislerud & Grølien (1977, 1978a,b). However, based on Björklund's (1982) results on fresh and transpiration-dried material one might expect a less radical temperature rise as this on dry, well-seasoned material. On the contrary, the temperature graphs show that the heat buildup was initiated rapidly in the upper, inner parts of the pile. Furthermore, this dependence on the location in the pile was statistically significant (Table 1 in VI). Temperatures also fluctuated with the season, being the lowest in winter and rising during the summer. However, the temperatures did not reach the high initial readings the summer after the start of the experiment. The observed fluctuation is greater than in a Swedish study (Björklund 1982) and could be caused by the more northerly and colder location of the experiment site in Lokka at latitude 68° N. Similar temperature fluctuations have been recorded in an Alaskan study by Sampson & McBeath (1987). There, however, the chip volumes were much smaller, which makes the pile temperature much more dependent on the ambient temperature.

Plastic cover and compaction by the front end loader were found to be temperature increasing factors (Table 2 in V). Kubler (1982) states that compaction prevents the removal of heat by aeration resulting in higher temperatures. The compaction, however, does not cause nearly as complete blockage of air movement as the plastic cover. Literature provides very little information on previous experience of contact covers. Taipale (1960a) reports that temperatures in covered conical piles rose faster than in uncovered ones. He attributes this increase to lower moisture content, but the more likely reason is blocked aeration which prevented heat dissipation from the pile and lead to higher temperatures. Plastic was also used under the piles in Lokka to keep ground moisture away from the chips but it could not be shown to have an effect on the pile temperature.

Seasoning of the whole trees in roadside piles for a year had brought the moisture content of the fuelwood feedstock to 31 %, which is a good result (Hakkila 1984, Uusvaara 1984). Extended storage time clearly increased moisture content of whole-tree chips (Table 3). When the chip piles were built, and the temperature increase initiated the chimney effect, moisture was dissipated from the inner parts of the pile to the outer layers of the pile (Figure 5 in V, Nylinder & Thörnqvist 1980, Thörnqvist 1983a,b, 1984b, White et. al. 1983). This increased heterogenity lowers fuel quality in the fuel chips and is seen as increased variation in

moisture content. The outer layers of the pile were further wetted by precipitation. In Lokka (V) the wet outer layer froze in wintertime to form a crust which could not be utilized as fuel and was left on the site as waste.

Table 3. The moisture content, basic density and dry matter losses in whole-tree chips by treatment during the long term storage in Lokka (V).

Pile	Treatment	Cover	Underbase	Storage time,	Moisture content,		Basic density, kg/m^3		Dry matter loss, %/mo.	n
				mo.	%	s		s		
1	start	. .	. .	. .	31,1	1.3	442	12	. .	142
1	1	no	yes	5.5	25.3	7.4	459	15	+0.6	33
1	4	no	no	5.5	31.4	14.6	437	21	-0.7	32
1	2	no	yes	14	39.0	20.2	423	40	-0.3	34
1	3	no	no	14	27.8	15.0	433	33	-0.1	31
2	start	. .	. .	. .	30.9	2.6	448	15	. .	123
2	5	no	yes	18	31.2	20.9	411	27	-0.4	18
2	6	yes	yes	18	41.9	23.5	406	44	-0.4	29
2	7	yes	no	18	39.0	20.2	402	42	-0.5	30
2	8	no	no	18	39.0	18.5	421	37	-0.3	31

The plastic cover did not only keep precipitation out of the pile; but it also kept the moisture created by microbial respiration inside the pile. As a net effect the pile cover increased the moisture content of the fuelwood feedstock (Table 3). Heding and Jakobsen (1985) report that it is essential to cover seasoned fuel chip piles of any species with tarpaulines. The difference in the results concerning the use of cover can most likely be credited to the difference in climatic conditions between Denmark and northern Finland.

Dry matter losses based on the changes in basic density increased with increasing storage time. There was some variability between treatments but the losses per month were still small (< 1%). Although the piles are considerably bigger than those reported by Björklund (1983) on birch chips, the losses were smaller in Lokka. Earlier it has been shown that the dry matter losses may be concentrated in the early part of storage (Thörnqvist 1983c). This was not confirmed by the data gathered in this study. Instead the losses were slightly higher where the pile was covered with plastic. Although one should note that the differences in basic density were not statistically significant (Table 4 in V). The overall low level of dry matter losses is most probably caused by the combined effect of harsh climatic conditions, low original moisture content and the lack of living parenchyma cells and green foliage.

Various combinations of independent variables were used to predict the basic density of chips. This proved difficult as the correlation between density and moisture content, heat sum or location in the pile were not significant. However, the use of moisture content and heat sum together in the models gave significant results. Contrary to expectations the location in the pile was not a significant factor (Table 5 in V).

The effective heating value of the birch whole-tree material at the time of chipping was in piles one and two 18.91 MJ/kg and 19.18 MJ/kg respectively. This shows variation within the material but the values are also lower than those reported on Table 11 in paper II for downy birch from both northern (19.65 MJ/kg) and southern (19.30 MJ/kg) Finland. This indicates that some volatiles have been lost during the storage of uncomminuted whole trees. No further reductions in heating value took place during chip storage. However, the heating values were significantly lowered by the introduction of mineral soil. In some treatments the average ash

content was as high as 5-6 % of the dry weight having been only 1.5 % in the clean chips at the start. This supports Thörnqvist's (1983c) findings on the effects of soil as a contaminating agent.

4.4 Drying and storage of logging residue from regeneration cuttings

In Sysmä, Finland, the average moisture content of fresh spruce logging residue was 56.0% in September 1994 (Figure 3, see also Hakkila 1991). By June of the following year moisture content in harvester heaps on the clear-cut area had dropped to 46.7 % having been as high as 61.4 % in midwinter. Further drying took place over the summer resulting in a moisture content of 28.5 % by the end of one year's storage (Mäkelä 1977, Thörnqvist 1984b). In the simultaneous study at the landing the drying result (42.2 %) in uncovered windrows was not as good. However, the final moisture content is lower than in a Swedish study carried out at same time of the year (Lehtikangas & Jirjis 1993a). The authors explained the poor result with the poor positioning of the windrow. In Mikkeli, where half of the twelve windrows were covered, moisture content fluctuated with the season. There was a definite increase in winter followed by a reduction in summer (Figure 3). This seasonal fluctuation was statistically significant (p= 0.027).

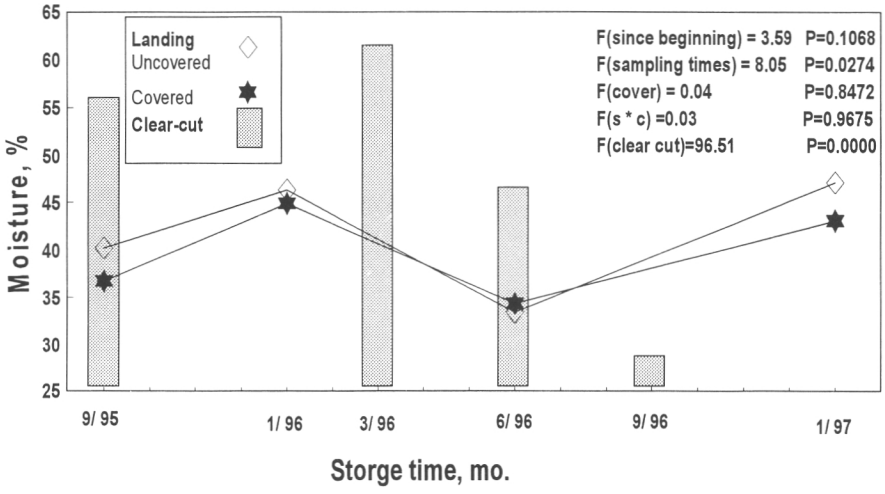


Figure 3. The moisture content of spruce logging residue in relation to storage time in covered and uncovered piles on landing and on the clear-cut area (VII).

Furthermore, residue baling is a new alternative for storage and transportation. Hence, the results have to be compared with those gained by the Swedish scientists on baled residues as well. In that context the results from the experiment in Mikkeli are not very encouraging as Lehtikangas & Jirjis (1993b) report the moisture content of fresh spruce logging residues to have reached 20% in covered and 24% in uncovered, stacked oblong bales. They also report similar good results on the round bales (Lehtikangas & Jirjis 1998). Neither of the bale types have been tested in Finland but should preferably be tested in near future.

The covering of windrows was not a significant factor (VII). This is contrary to the result published in Sweden where it has been shown that covering logging residue lowers the

moisture content in windrows (Jirjis et al. 1989, Jirjis & Lehtikangas 1993, Lehtikangas & Jirjis 1993a, Jirjis 1996). The differences in results could be caused by several reasons. The piles in Mikkeli were higher on average than those in Sweden. As a result only about half of the basal area of the windrow was actually covered, and the precipitation and runoff from the cover could accumulate through the sides of the pile. On the other hand, especially with the highest of the piles, the top part of the pile acted as a natural cover in catching precipitation. Some of this moisture was retained in the pile and some released through evaporation. Also, most of the studies carried out in Sweden took place further south than Sysmä and Mikkeli where a higher percentage of precipitation comes in the form of rain than in central Finland. Furthermore, the procurement personnel in Sweden have learned through experience to scale the windrow size so that it fully benefits from the cover. However, given the differences in weather and climatic conditions between Swedish and Finnish study sites, and not forgetting the differences in economic considerations, one can not recommend the use of cover as an improvement agent on fuel quality of the green logging residues stored in roadside windrows (VII).

The comminuted material stored at the mill yard in Heinola developed a rapid increase in temperature after the first two weeks of storage. The development started in the upper interior of the pile. The temperatures were lower in the compacted part of the pile, the difference being 10-15%-points over the whole storage period (Figure 1 and 2 in VI). Earlier it has been stated that compaction has the opposite effect (Kubler 1982, Thörnqvist 1987). The difference is difficult to explain. The result could partially be explained by the differences in material used in the studies referenced above. Pulp or foliage-free whole-tree chips are quite different in character from comminuted spruce logging residue. Another likely reason could be the high degree of compaction. It could be that the degree of compaction was high enough to significantly reduce oxygen flow inside the pile. Also the pile in Heinola was not as big as the ones mentioned by Thörnqvist (1987).

Moisture content in the comminuted pile in Heinola stayed much higher than that of the same material in simultaneous experiments on the clear-cut area and windrows in Sysmä. As a combined result of metabolic activity and precipitation the moisture content increased from 58.9% to 65.3% between September and June (Table 1 in VI). The change was statistically significant ($p < 0.001$). However, compaction did not prove to be a significant factor.

In Sysmä the percentage of foliage was 27.7% in green spruce logging residue (Table 2 in VI). This fits quite well with the 25-35% range given by Hakkila et al. (1998) for spruce logging residue from regeneration cuttings. During this one year of storage (September to September) the needle content of the residue stored on the clear-cut area in harvester heaps fell to 6.9%. In comparison the needle content of the residues stored in an uncovered windrow on the landing had a needle content of 18.9%. Lehtikangas (1991) notes that the heap size is an important factor in defoliation of residues on the clear-cut area. According to Lehtikangas (1991) residue piles less than 150 cm high, such as in Sysmä and Laukaa, shed more foliage than in bigger piles. This is due to better drying and ventilation and lower tendency of retaining the fallen needles.

The needle loss also includes dry matter losses by metabolic activity of living cells and microbes. After one year of storage on a clear-cut area in Sysmä the losses were 20% concerning spruce needles. However, on the clear-cut area in Laukaa, where the storage lasted from August 1996 until June 1997, spruce needles could not be shown to have gone through significant losses. The difference between these two results is caused by the shorter summertime storage in Laukaa. On the other hand, pine needles in Laukaa lost 20% of the dry matter, whereas spruce needles remained at 0% (Figure 2 in VII). What caused the difference

between pine and spruce can not be determined based on the data. Neither does the literature give the solution to this observation. Based on the evidence it seems that dry matter losses by metabolic activity are smaller in windrows than at the landing. In Sysmä, needle mass losses were 7% on the landing compared to the 20% on the clear-cut area, enforcing the idea of needles being more accessible to microbes on the clear-cut area. In Mikkeli, no statistically significant dry matter losses were found to take place in windrowed residue. Neither did cover have a significant factor on dry matter losses. Granhall and Slapokas (1984) have observed dry matter losses on broad-leaved foliage on the forest floor. They demonstrated a greater degree of dry matter loss (45%) in foliage of birch and alder than occurred with coniferous foliage in this study.

The ash percentage of logging residue in windrows significantly increased with storage time which is an indication of metabolic breakdown in biomass. The starting figure had been 2.0-2.5% for the logging residue and at the end of 16 months of storage the ash content was 3.0-3.5% (Figure 3 in VII). The difference between covered and uncovered windrows was small but significant ($p=0.041$) to the advantage of covered piles. The ash content of spruce residue increased even more rapidly in the harvester heaps on the clear-cut area. It tripled from less than one percent to almost three percent over ten months of storage and the content of spruce needles increased from 3 to 6 % (Figure 4 in VII). This was most likely caused by greater exposure to microbes on the clear-cut area as discussed above. The fact that Lehtikangas (1991) did not find any changes in ash content during a 4-month summertime storage of spruce logging residue may indicate that longer storage periods are needed to cause changes in ash content. The figures for pine needles were much lower than for spruce. Also, the ash content of pine residue material seems to decrease with the extension of storage time. The only likely explanation for this is a low percentage of foliage in the samples. Also Thörnqvist (1984a) reports that when residues are stored on the clear-cut area for as long as two years ash content will be reduced because of the total loss of needles. Based on these figures it seems that the quantity of ash may increase as much as 50-300%. The increase sounds substantial but this should not cause any problems in ash handling at the heating plants as they are designed to handle concentrations as high as this.

As dry matter losses take place over time, also changes in the nutrient concentration can be expected. This change, however, is slow (VI, VII). The changes found in the residue mass are a joint result of needle fall, leaching and metabolic activity. As needle mass contains higher concentrations of the major mineral nutrients than the branch wood or branch bark, defoliation usually decreases the concentration in the logging residue. The changes in potassium (K), manganese (Mn), calcium (Ca), magnesium (Mg), phosphorus (P), boron (B), sulphur (S) and sodium (Na) concentrations in spruce residue in harvester heaps on the clear-cut area in Laukaa were not significant, but in pine residue many of the changes were significant (Figure 8 in VII). This could be caused either by the low number of needles in the samples or the release of nutrients from needles. As most of the changes in pine needles were not significant, one has to conclude that the changes in the residue mass were caused by defoliation. Unlike pine, spruce needles showed significant changes in nutrient content over time.

The changes in nutrient concentrations were perhaps not as significant in windrows on the landing as in harvester heaps but the trend was often alike (Appendix 1-4 in VII). This is likely caused by the greater exposure to the ambient elements on the clear-cut area compared to windrows. This is in accordance with Slapokas & Granhall's results (1991). However, their results on the leaf litter of short-rotation species indicate a much higher rate of release than from coniferous needles. The loss of some elements has to be counterbalanced by an increased concentration of other elements. In this case it was the heavier elements, such as iron (Fe),

aluminum (Al), copper (Cu), sodium (Na), sulphur (S) and zinc (Zn), which are less mobile than other elements (Appendix 3, 5 and 6 in VII). Heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), molubdenum (Mo) and nickel (Ni) exist in such small concentrations that they were not identified in logging residue with the method used. This does not, however, mean that they are not present but could well be concentrated in the wood ash. Also to alleviate the concern of nitrogen being released from windrows to surface waters, it seems on the basis of evidence that it is released very slowly (Figure 6 in VII). This should strengthen Lundkvist's (1991) findings that nitrogen leaching from logging residue is slow at least during the first summer. But longer storage times will lead to leaching of organic nitrogen from the residue heaps (Rosén & Lundmark-Thelin 1987). May it also be pointed out that windrow cover had no significant effect on nutrient concentrations.

Sodium (Na) and chloride (Cl^-) are thought to be responsible for some of the corrosion in combined heat and power plants and are hence important elements from the conversion point of view. Sodium concentrates in spruce needles to some degree, but the concentrations are very low (20-40 ppm). No trend was found in pine needles. Chloride is an important element in photosynthesis (Mengele & Kirkby 1982). All of it is found in the needles and in much higher concentrations than sodium. Concentrations of chloride can be found at the rate of 400 ppm in fresh spruce needles and < 200 ppm in pine needles. The lower percentage of needles in pine residue further increases the difference between the two species. The fortunate aspect of chloride is that it is a mobile element and storage can radically decrease its concentrations. Also defoliation will considerably decrease its concentration in residue (VII).

Seasonal fluctuation was noted in both carbon and hydrogen contents of windrowed residue. Although the storage covered 16 months it could not be confirmed on the basis of this data whether this fluctuation was caused strictly by seasonality or not. Even so, the changes which had happened since the beginning of the study were not statistically significant (Figure 10 in VII). However, carbon and hydrogen have a strong relationship due to close bonding both in cellulose and lignin. On the contrary the results are quite different in a comminuted pile where the decomposition is faster. There the prevailing condition seems to affect the carbon-hydrogen ratio (Table 4 in VI). Hydrogen concentration has decreased while carbon has increased. The change could be caused by the loss of volatile matter.

The calorimetric heating value of windrowed spruce logging residues was not affected by 16 months storage in windrows (Figure 11 in VII). There was some fluctuation in $q_v(net)$ with time (19.8-20.1 MJ/kg), but this was not significant. A similar observation has been made by Lehtikangas & Jirjis (1993a, 1998) on windrowed material as well as on baled material. Although the season is not a significant factor, the heating values of spruce logging residue tended to be higher in winter than in summer in both studies. Why this is so remains a topic of debate. It should also be noted that covering of windrows had no significant effect on heating value either.

As in windrows the $q_v(net)$ of spruce residue was not affected by storage time in harvester made heaps, but pine residue was (Figure 12 in VII). The reason could be found in the heating value of the needle mass. Pine needles are higher in $q_v(net)$ than other residue components by a margin of about 1.5 MJ/kg. Any significant reduction in the proportion of this component should be seen as a reduction in the weighted heating value. Any defoliation of spruce residue should not cause equally significant changes as the $q_v(net)$ of spruce needles and branches are quite similar.

5 CONCLUSIONS

The effective heating value on dry weight basis of whole-tree biomass is quite similar in all domestic tree species growing in Finland. The relative proportion of such variables as crown and stem mass, as well as the proportion of wood, bark and foliage components, however, do have an influence on the weighted average heating value. This is because heating value varies from one component to another and is a product of the slight differences in chemical composition brought about by the separate functions of each tree component. In addition to the increased yield the higher heating value of crown mass over stem mass also promotes the utilization of whole trees over delimbed stems for fuelwood. The crown mass, i.e., logging residue, is a more favourable fuel than small-sized whole trees from cleanings and precommercial thinnings, not only because of the lower procurement cost, but also because of higher heating value per unit weight. The effective heating values of stem, crown and whole-tree biomass were higher in northern Finland than in Central Ostrobothnia, in southern Finland. In addition, from the practical point of view, the differences between trees from mineral and organic soils are insignificant.

The variability in chemical composition is small in any whole-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 in a given component is actually caused by the differences between parts of a tree. Although the results on small-sized trees show that heating value might be an indicator of carbohydrate content, it can not be considered as a reliable indicator of chemical composition in general.

The results on heating values provide practical information on whole trees, stems and crown mass of all domestic tree species. The figures can be used to estimate the heat content of a given fuelwood feedstock. Because the results are based on the heating values of individual tree components, they can be used as the basis for evaluation for other wood based fuels with variable compositions i.e., mill residues such as bark, shavings, etc.

The effective heating value on oven-dry basis stays nearly the same in all comminuted and non-comminuted storages. This indicates a rather uniform carbon/hydrogen ratio during storage. Only minor seasonal fluctuations can be expected possibly due to loss of volatile matter. The total available heat content of a given fuelwood feedstock, however, does not stay constant but changes over time in storage. The net change in heat content of a given feedstock is the product of changes in moisture content, the dry matter losses by the respiration of living cells and the metabolic rate of microbes. They are the greatest in fresh, comminuted fuels which contain sufficient moisture to sustain the life of microbes and living cells of the tree. Chip storages may experience considerable dry matter losses in just a few months. This is indicated by rapid increase in pile temperature. Once the microbial metabolism sets in, it is nearly impossible to stop, because the system is self-feeding. These losses accumulate as long as the storage phase lasts. But, it seems that the losses could decrease with increased latitudes due to colder climate.

Drying of fuelwood will reduce dry matter losses, because it decreases the amount of water available for the living cells and organisms. Transpiration drying is an old but still valid method when procurement schedules will allow it. It is best carried out in spring and summer when the vapor pressure deficit is the lowest. Transpiration drying will also shorten the time required by artificial chip drying. It is a most suitable method to be applied to the recovery of logging residues when site factors call for leaving the nutrient rich foliage on the site. Logging residues will also dry to a lower moisture content on a clear-cut area than on the landing in windrows. Dry residues will easily regain moisture on the clear-cut area and should hence be

windrowed when dry. Covering the windrows was not shown to have any advantage. In Sweden, however, the study results do encourage the use of cover, which may be caused by a greater experience with the concept as well as different climatic conditions.

In addition to the dry matter losses, moisture content can also be a problem in chip piles. The respiration and metabolism of living cells produce water which wets the chips. This moisture, however, is not evenly distributed throughout the pile but the chimney effect will transport it from the center part of the pile to the upper exterior. This will result in inhomogenous fuel with an unusable frozen surface on the pile. The situation can be especially bad when chips of fresh logging residue are stored for a long time in cold conditions. The result is a very wet feedstock which is unsuitable for any of the smaller heating plants. Hence the duration of large-scale chip storages should be limited to a few months. Furthermore, all contaminants should be kept out as they will severely increase the ash content and lower the effective heating value. It would be beneficial to store the material under a roof, but this method is far too expensive in conjunction with the marginally profitable fuel. Contact covers of plastic or any other material can not be recommended.

Particle size is significant property of fuel chips. Large particles leave large gaps in between, which facilitates better aeration. This results in faster drying than in chips of smaller nominal size by a factor of 2-3. This provides better storage properties, greater gain in effective heating value and lower dry matter losses. However, it should be remembered that the effectiveness of convective drying is always limited by the properties of ambient air.

The effect of compaction remains unclear. Contradicting results were gathered for whole-tree and spruce logging residue chips. On the bases of the results compaction in general is not recommended, but it may have a beneficial effect with comminuted logging residues when compaction is complete enough to prevent aeration. To minimize these problems, fuelwood should be stored in a non-comminuted form until the time of use. These storages are not protected from the deteriorating agents either, but the processes are known to be slower. Unfortunately, buffer storages of chips are often mandatory especially in wintertime.

Nutrients are found in much higher concentrations in foliage than in the branches of logging residue. The release of nutrients from needles found in the heaps and windrows is slow. This makes defoliation a more important factor from the point of view of the nutrient cycle. The concern of large quantities of nitrogen being leached out of windrows on landings into surface waters is not supported by the results. Seasoning and loss of needles will considerably decrease the amount of chloride and sodium, which are the elements thought to cause corrosion in combined heat and power plants. Heavy metal concentrations are undetectably low in logging residues but will concentrate in wood ash.

REFERENCES

Ager, A., Rönnberg-Wästljung, A., Thorsén, J. & Sirén, G. 1986. Genetic improvement of willows for energy forestry in Sweden. Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, Section of Energy Forestry. Repport 43. 47p.

Andersson, S.-O. 1983. Helträdsutnuttjande vid gallring och dess effect på trädens tillväxt. Sveriges Lantbruksuniversitet. Skogsfakta Supplement 1:18-23.

Arola, R., Sturos, J.B. & Radcliffe R.C. 1988. Chunkwood drying research with Northern U.S. Hardwoods. In: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6-7, 1988. Vol. II. Sveriges Lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134:101-119.

Assersson, A., Croon, I. & Frisk, E. 1970. Outside chip storage. Svensk Papperstidning 73(16):493-501.

Bergman, Ö. 1974. Termal degredation and spontaneos ignition in outdoor chip storage. Svensk Papperstidning 77(18):681-684.

Bergman, Ö. & Nilsson, T. 1967. Studier över utomhuslagring av aspvedsflis vid Hörnefors Sulfitfabrik. Skogshögskolan. Institutionen för Virkeslärä. Rapporter 55. 105 p.

- 1979. An experiment on outdoor storage of whole-tree chips. Sveriges Lantbruksuniversitet. Institutionen för Virkeslärä. Rapporter 109. 21 p.

Björklund, L. 1982. Lagring av bränsleflis i fraktionen 25-30 mm. Summary: Storage of fuelwood chips in fraction 25-30 mm. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Uppsatser 115. 26 p.

- 1983. Lagring av helträdsflis av olika trädslag samt i olika fraktioner. Summary: Storage of whole-tree chips of different species and in different fractions. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 143. 50 p.

Björklund, T. 1984. Tervalepän biomassa. Summary: Biomass of black alder. Metsäntutkimuslaitoksen tiedonantoja 151. 71 p.

Bowersox, T.W., Blankenhorn, P.R. & Murphey, W.K. 1979. Heat of combustion, ash content, nutrient content and chemical content of Populus hybrids. Wood Science 11:257-261.

Danielsson, B.-O. 1988. Evaluation of chunkwood as woodfuel and the Swedish experimental machine. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6-7, 1988. Vol. I. Sveriges Lantbruksuniversitet. Institutionen för skogsteknik. Uppsatser och resultater 134:34-43.

Doat, J. 1977. Le pouvoir calorifique des bois tropicaux. Bois et Forets des Tropiques 172:33-47.

Ekman, R. 1983. The suberin monomers and triterpenoids from the outer bark of *Betula verrucosa* Ehrh. Holzforschung 37:205-211.

Energiakatsaus 1/99. 1999. Kauppa- ja teollisuusministeriö, energiaosasto. 44 p.

Eslyn, W.E. 1967. Outside storage of hardwood chips in the Northeast. Tappi Journal 50(6):297-303.

Faeste, I. & Johansson, K.J. 1982. Tørkeforløp i syrefelte traer under forskjellige lagringsforhold. Zusammenfassung: Trocknungsverlauf bei ungeasteten Bäumen Unter verschiedenen Lagerungsverhältnissen. Norsk Institutt for Skogforskning. Rapporter 2. 32 p.

Feist, W.C., Springer, E.L. & Hajny, G.J. 1971. Viability of parenchyma cells in stored green wood. Tappi Journal 54(8):1295-1297.

Finér, L. 1992. Nutrient concentrations in *Pinus sylvestris* growing on an ombrotrophic pine bog, and the effects of PK and NPK fertilization. Scandinavian Journal of Forest research 7:205-218.

Flinkman, M., Fredrikson, H. & Thörnqvist, T. 1986. Barravfall hos hyggesrester som funktion av sommarexponeringens torkeffekt. Summary: Needle litter in heaps of logging residue during a growing period. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 174. 24 p.

Flinkman, M. & Thörnqvist, T. 1986. Lagring av buntade träddelar och hyggesrester. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 180. 49 p.

Fredrikson, H. & Rutegård, G. 1985. Lagring av småved och bränsleflis i binge. Summary: Storage of chunk wood and fuel chips in bins. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Uppsatser 151. 32 p.

Fuwape, J.A. 1989. Gross heat of combustion of Gmelina (*Gmelina arborea* (Roxb)) Chemical Components. Biomass 19:281-287.

Gislerud, O. 1974a. Heltreutnyttelse - V. Lagring av heltreflis. Summary: Whole tree utilization - Storing of whole tree chips. Norsk Institutt för Skogforskning. Skogteknologisk avdeling. Rapporter 4/74. 29 p.

Gislerud, O. 1974b. Heltreutnyttelse - II. Biomasse og biomasseegenskaper hos tynningsvirke av gran, furu, bjørk og or. Summary: Biomass and biomass properties of trees fromthinnings of spruce, pine, birch and alder. Norsk Institutt for Skogforskning. Skogteknologisk avdeling. Rapporter 6/74. 59 p.

- 1983. Experimental drying and storing of fuel chips. NISK. IUFRO -stencil. 5 p.

Gislerud, O. & Grølien, H. 1977. Lagring av heltreflis. Summary: Storage of whole-tree chips. Norsk Institutt för Skogforskning. Skogteknologisk avdeling. Rapporter 1/77. 26 p.

- 1978a. Lagring av heltreflis av or. Summary: Storage of whole-tree chips of alder. Norsk Institutt för Skogforskning. Skogteknologisk avdeling. Rapporter 1/78. 36 p.
- 1978b. Lagring av lauvtreflis. Norsk Institutt for Skogforskning. Skogteknologisk avdeling. Rapporter 9/78. 39 p.

Gjølsjø, S. 1988. Comparative studies on storage and drying of chips and chunks in Norway. In: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6-7, 1988. Vol. II. Sveriges Lantbruksuniversitet. Institutionen för Skogsteknik. Uppsatser och resultater 134:47-71.

- 1995. Storage of comminuted birch in piles in Norway. In: Mattsson, J.E., Mitchell, C.P. & Tordmar, K. (eds).: Preparation and supply of high quality wood fuel. IEA/BA Task IX Proceedings of a workshop held in Garpenberg, Sweden 13-16, June 1994. Sveriges Lantbruksuniversitet. Institutionen för Skogsteknik. Uppsatser och resultater 278:76-86.

Granhall, U. & Slapokas, T. 1984. Leaf litter decomposition in energy forestry. First year nutrient release and weight loss in relation to the chemical composition of different litter types. In: Perttu, K. (ed). Ecology and management of forest biomass production systems. Department of Ecology & Environmental Research. Swedish University of Agricultural Sciences. Rapporter 15:131-153.

Gustafsson, G. 1980, Torkning av bränsleflis - förutsättningar. Sveriges Lantbruksuniversitet. Institutionen för Lantbrukets Byggnadsteknik. Specialmeddelande 97. 64 p.

Hakkila, P. 1962. Polttohakepuun kuivuminen metsässä. Summary: Forest seasoning of wood intended for fuel chips. Communicationes Instituti Forestalis Fenniae 54(4). 82 p.

- 1963. Koivujen kuivuminen rasissa ja niistä tehtyjen pinotavarapölkkyjen vettyminen uitossa. Summary: The seasoning of leaf-felled birches and the waterlogging of cordwood of leaf-felled birch in floating. Communicationes Instituti Forestalis Fenniae 57(3). 32 p.
- 1975. Kanto- ja juuripuun kuoriprosentti, puuaineen tiheys ja asetoniuutteitten määrä. Summary: Bark percentage, basic density, and amount of acetone extractives in stump and root wood. Folia Forestalia 224. 14 p.
- 1984. Forest chips as fuel for heating plants in Finland. Tiivistelmä: Metsähake lämpölaitosten poltto-aineena Suomessa. Folia Forestalia 586. 62 p.
- 1989. Utilization of residual forest biomass. Springer Series in Wood Science. Springer-Verlag. 568 p.
- 1991. Hakkuupoistuman latvusmassa. Summary: Crown mass of trees at the harvesting phase. Folia Forestalia. 773. 24 p.

Hakkila, P. & Fredriksson T. 1996. Metsämme energian lähteenä. Metsäntutkimuslaitoksen tiedonantoja 613. 92 p.

Hakkila, P. & Kalaja, H. 1981. Kopo palahakejärjestelmä. Summary: Kopo block chip system. Folia Fororestalia 467. 24 p.

- 1983. Puu- ja kuorituhkan palauttamisen tekniikka. Summary: The technique of recycling wood and bark ash. Folia Forestalia. 552. 37 p.

Hakkila, P., Nurmi. J. & Kalaja, H. 1998. Metsän uudistusalojen hakkuutähde energialähteenä. Metsäntutkimuslaitoksen tiedonantoja 684. 68 p.

Halonen, O., Tulkki, H. & Derome, J. 1983. Nutrient analysis methods. Metsäntutkimuslaitoksen tiedonantoja 121. 28 p.

Harris, R.A. 1984. Fuel values of stems and branches in white oak, yellow poplar, and sweetgum. Forest Products Journal 34:25-26.

- 1985. Fuel values of stems and branches in post oak and red maple. Forest Products Journal 35(4):43-44.

Hatton, J.V. 1970. Precise studies on the effect of outside storage on fiber yield: white spruce and lodgepole pine. Tappi Journal Vol. 53(4)627-638.

Heiskanen, V. 1953. Polttopuiden kuivumisesta ja sen huomioonottamisesta varastoinnissa. Summary: On the drying of firewood and on its consideration in storage. Communicationes Instituti Forestalis Fenniae 41(4). 41 p.

- 1961. Tutkimuksia koivuhalkojen painosta ja kosteudesta. Summary: Studies on the weight and moisture of split birch fuelwood. Silva Fennica 108(2) 30 p.

Heiskanen, V. & Hakkila, P. 1960. Polttohakepuun kuivuminen rasissa. Pienpuualan Toimikunnan tiedotus 17. 6 p.

Heding, N. & Jakobsen H. 1985. Tørkning af grønflis til fyringsformål. Summary: Drying of green fuel chips. Skovteknisk Institut, Danmark. 2/85. 41 p.

Howard, E.T. 1973. Heat of combustion of various southern pine materials. Wood Science 5:194-197.

Howard, J.O. 1988. Energy values for whole trees and crowns of selected species. USDA For. Serv., Research Note PNW-RN-480. 6 p.

Hudson, B. 1998. UK Industry - baling and storage of logging residues. In: Hakkila, P., Heino, M. & Puranen, E. (Eds.): Wood fuels from conventional forestry. Metsäntutkimuslaitoksen tiedonantoja 680. 122 p.

Jacobson, S., Kukkola, M., Mälkönen, E., Tveite, B. & Möller, G. 1996. Growth response of coniferous stands to whole-tree harvesting in early thinnings. Scandinavian Journal of Forest Research 11:50-59.

Jalava, M. 1941. Rasiin kaadettujen puiden kuivumisesta. Metsätaloudellinen Aikakauskirja 58:173-176.

Jirjis, R. 1996. Handling and storage of uncomminuted forest residues. In: Hudson, J.B. & Kofman, P.D. (Eds.): Harvesting, storage and road transportation of logging residues. Proceedings of a workshop of IEA-BE-Task XII activity 1.2, held in Glasgow, Scotland - Danish Forest and Landscape Research Instute. Hørsholm, Denmark 83 p.

Jirjis, R., Gärdenäs, S. & Hedman, G. 1989. Lagring i täckta vältor - avverkningsrester från barrträd. Summary: Storage in covered windrows - logging residue from softwood. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Uppsatser No. 167. 32 p.

Jirjis, R. & Lehtikangas, P. 1993. Bränslekvalitet och substansförluster vid vältlagring av hyggesrester. Summary: Fuel quality and dry matter loss during storage of logging residue in a windrow. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 236. 26 p.

Jirjis, R. & Theander, O. 1986. Preliminära resultat av kemiska huvudkomponenternas förändring i lagrad trädbränsleflis. Summary: Preliminary results on chemical composition changes in stored forest fuel. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Uppsatser 161. 21 p.

- 1990. The effect of seasonal storage an the chemical compositions of forest residue chips. Scandinavian Journal of Forest Research. 5:437-448.

Koch, P. 1985. Utilization of hardwoods growing on southern pine sites: the raw material. U.S. Department of Agriculture. Forest Service. Agricultural Handbook 605. 1418 p.

Kollman, F. 1951. Technologie des Holzes und der Holzwerkstoffe I. Springer Verlag. 1050 p.

Kubler, H. 1982. Air convection in self-heating piles of wood chips. Tappi Journal Vol.65(8):79-63.

- 1987. Heat generation processes as cause of spontaneous ignition in forest products. Forest Products Abstracts. Vol. 10(11): 299-322.

Kuitto, P-J. & Pajala, P. 1982. Kokopuiden välivarastohaketus ja metsähakkeen kaukokuljetus. Metsätehon tiedote No. 372. 14 p.

Kärkkäinen, M. 1980. Haapakokopuiden tekniset ominaisuudet. Summary: Technical properties of aspen whole trees. Manuscript at University of Helsinki, Department of Forest Technology.

Laine, R., Kiukaanniemi, E. & Haapasalo, P. Pilkkeenkuivuminen rasissa. Valtion Teknillinen Tutkimuskeskus. Tutkimuksia 111. 60 p.

Lehtikangas, P. 1991. Avverkningsrester i hyggeshögar - avbarrning och bränslekvalitet. Del 1. Summary: Logging residue in piles - needle loss and fuel quality. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 223. 33 p.

Lehtikangas, P. & Jirjis, R. 1993a. Vältlagring av avverkningsrester från barrträd under varierande omständigheter. Summary: Storage of logging residue (softwood) in windrows under variable conditions. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 235. 45 p.

- 1993b. Lagring av buntade hyggesrester. Projekt Skogskraft. Rapporter 17. Vattenfall Utveckling AB, Dokumentationscentralen, 810 70 Älvkarleby. 18 p.
- 1998. Storage of logging residues in bales. Proceedings of Biomass for Energy and Industry, 10th European Conference, 8-11 June 1998. C.A.R.M.E.N., Rimper, Germany. 4 p.

Lehtonen, I. 1977. Puu polttoaineena. Kirjallisuuteen perustuva tarkastelu. Abstract: Wood as a fuel. A study based on literature. Folia Forestalia 293. 16 p.

Levanto, S. 1961. Tutkimuksia 2-metrisen koivupolttopuun hakkuusta kesällä sekä rasiinkaatoa käytettäessä. Summary: Studies on summer felling and preparation of 2-metre birch fuelwood. Pienpuualan Toimikunnan julkaisu 130. 54 p.

Liepinš, R. 1933. Die technischen eigenschaften der birke Lettlands. Summary: Latvialaisen koivun teknilliset ominaisuudet. Commentationes forestales 6. 15 p.

Liss, J.-E. 1979. Syrfällning. Skogshögskolan. Institutionen för Skogsteknik. Garpenberg. Stencil 73. 20 p.

Lundkvist, H. 1991. Utlakning av kväve under avverkningsrester i hyggeshögar. Summary: Nitrogen leaching under piles of logging residues. Del 2. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 223:34-44.

Lyons, G. Lunny, F. & Pollock, H. P. 1985. A procedure for estimating the value of forest fuels. Biomass 8:283-300.

Mengel, K. & Kirkby, E.A. 1982. Principles of plant nutrition. International Potash Institute, Bern. 3rd edition. 655 p.

Metsätilastollinen vuosikirja 1998. Metsäntutkimuslaitos. 344 p.

Mitchell, C.P., Hudson, J.B., Gardner, D.N.A. & Story, P. 1988. Studies on transpirational drying in the UK. In: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6-7, 1988. Vol. II. Sveriges Lantbruksuniversitet, Institutionen för Skogsteknik. Uppsatser och resultater 134:226-236.

Murphey, W.K. & Masters, K.R. 1978. Gross heat of combustion of northern red oak (*Quercus rubra* L.) chemical components. Wood Science 10:139-141.

Musselman, K. & Hocker, J. H.W. 1981. Caloric values of eight New Hampshire forest tree species. Canadian Journal of Forest Research 11:409-412.

Mäkelä, M. 1977. Hakkuutähteen ominaisuuksien muuttuminen. Summary: Changes in the quality of logging residues. Folia Forestalia 309. 16 p.

Mälkönen, E. 1974. Annual primary production and nutrient cycle in some Scots pine stands. Communicationes Instituti Forestalis Fenniae 84(5). 87 p.

Neenan, M. & Steinbeck, K. 1979. Caloric values for young sprouts of nine hardwood species. Forest Science 25:455-461.

Nellist, M.E., Lamond, W.J., Pringle, R.T. & Burfoot, D. 1993. Storage and drying of comminuted forest residues. Vol. 1. Energy technology support unit. Department.of Trade and Industry report B/W1/00146, Silsoe Research Institute. UK. 82 p.

Nicholls, D.L. & Feng, Y. 1992. Properties of open-stored wood fuel during winter months in Northern Michigan. Forest Products Journal 42(7/8):37-40.

Nilsson, T. 1987a. Jämförande lagringsstudie av småved och bränsleflis. Summary: Comparison of storages of chunk wood and fuel chips. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 192. 76 p.
- 1987b. Lagring av småved i mindre stackar. Summary: Storage of chunk wood in smaller piles. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 196. 57 p.

Nisula, P. 1980. Näkökohtia polttohakkeen kuivaamisesta. Summary: Aspects of the drying of fuel chips. Folia Forestalia. 440. 14 p.

Nurmi, J. 1986. Chunking and chipping with conescrew chipper. Summary: Palahakkeen ja hakkeen valmistus kartioruuvihakkurilla. Folia Forestalia 659. 23 p.

- 1994. Työtavan vaikutus hakkuukoneen tuotokseen ja hakkuutähteen kasautumiseen. Folia Forestalia 2:113-122.

Nylinder, M & Thörnqvist, T. 1980. Lagring av grenar och toppar i olika fraktioner. Summary: Storing of branches and tops of different fractions. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 113. 45 p.

Olofsson, L. 1975. Värmevärden för olika delar av tall, gran och björk. Summary: Heating values for different parts of pine, spruce and birch. Sveriges Lantbruks Universitet. Institutionen för Skogsteknik. Rapporter och Uppsatser 90. 39 p.

Panshin, P.J. & de Zeeuw, C. 1970. Textbook of wood technology. Vol. 1. McGraw-Hill Book Company. 705 p.

Rosén, K. & Lundmark-Thelin, A. 1987. Increased nitrogen leaching under piles of slash - a consequence of modern forest harvesting techniques. Scandinavian Journal of Forest Research 2:21-29.

Rothbaum, H.P. 1963. Spontaneous combustion of hay. Journal of Applied Chemistry. 13(7):291-302.

Salmi, J. 1964. Lahovikaisuuden vaikutus koivupuun lämpöarvoon. Summary: The influence of decay on the heat value of birch wood. Pienpuualan toimikunta. Julkaisuja 168. 26 p.

Sampson, G.R. & McBeath, J.H. 1987. Temperature changes in an initially frozen wood chip pile. U.S. Dept. of Agric. Forest Service. Research Note PNW-RN-454. 10 p.

Sandala, M.G., Blankenhorn, P.R. & Kline, D.E. 1981. Thermal analysis of white oak, northern red oak, and black cherry bark chemical components. Wood Science 13(3): 157-165.

Sastry, C.B.R. & Anderson, H.W. 1980. Clonal variation in gross heat of combustion of juvenile Populus hybrids. Canadian Journal Forest Research 10:245-249.

Saucier, J.R. & Phillips, D.R. 1985. Storing whole-tree fuelwood chips for maximum energy. Forest Products Journal 35(6):53-56.

Simola, P. & Mäkelä, M. 1976. Rasiinkaato kokopuiden korjuussa. Summary: Leaf-seasoning method in whole-tree logging. Folia Forestalia 273. 18 p.

Simola, P. 1977. Pienikokoisen lehtipuuston biomassa. Summary: The biomass of small-sized hardwood trees. Folia Forestalia 302. 16 p.

Sinclair, S.A., Hassler, C. & Bolstad, K. 1984. Moisture loss in aspen logging residue. Wood and Fiber Science 16(1):93-96.

Singh, T. & Kostecky, M. 1986. Calorific value variations in components of 10 Canadian tree species. Canadian Journal of Forest Research 16:1378-1381.

Slapokas, T. & Granhall, U. 1991. Decomposition of litter in fertilized short-rotation forests on a low-humified peat bog. Forest Ecology and Management 41:143-165.

Springer, E.L., Hajny, G.J. & Feist, W.C. 1971. Spontaneous heating value in piled wood chips. II. Effect of temperature. Tappi Journal 54(4):589-591.

Staff, H. 1984. Harvesting of logging slash on highly productive sites. Buffering of negative effects. In: Andersson, B. & Falk, S. (Eds.). Forest energy in Sweden. Sveriges Lantbruksuniversitet. pp. 96-97.

Stringer, J.W. and Carpenter, S.B. 1986. Energy yield of black locust biomass fuel. Forest Science. 32(4):1049-1057.

Sturos, J.B. 1984a. Ambient Air Drying Trials - Chunkwood versus Chips. Biomass Fuel Drying Conference Proceedings 1984-08-08. Office of Special Programs, 405 Coffey Hall, Univ. of MN., St. Paul, MN 55108. 19 p.
- 1984b. Characterization and Air Drying of Chunkwood and Chips. USDA. For. Serv. Res. Note NC-308. 6 p.
- 1989. Airflow resistance of chunkwood. Forest Products Journal 39(3):19-24.

Sturos, J.B., Coyer, L.A. & Arola, R.A. 1983. Air drying of chunkwood and chips. Forest Service - U.S.D.A. Research Note NC-293. 4 p.

Taipale, A. 1960a.Tutkimuksia polttohakkeen varastoinnista. Summary: Studies of the storage of fuel chips. Pienpuualan toimikunta. Julkaisuja 100. 47 p.
- 1960b. Hakkeen varastointikokeita. Pienpuualan toimikunnan tiedotus 13. 5 p.
- 1962. Sahanhakkeen kuivuminen avokeossa ja katetussa varastossa. Summary: seasoning of chips made of sawmill waste in uncovered stack and covered store. Pienpuualan toimikunta. Julkaisuja 141. 27 p.

Taras, M.A. 1978. Biomass of southern pines and their product yields. In:McMillin, C.W. (Ed.) Complete tree utilization of southern pine. Forest Products Research Society Madison, pp. 15-23.

Thörnqvist, T.1983a. Lagring av sönderdelade hyggesrester. Summary: Storing of disintegrated logging residuals. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 137. 78 p.
- 1983b. Lagring av hyggesrester sönderdelade i olika fraktioner. Summary: Storage of logging residues which have been reduced into different fractions. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 146. 21 p.
- 1983c. Bränsleflis förändring under ett års lagring. Summary: Fuel chips change during one year of storage. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 148. 65 p.
- 1984a. Hyggesresternas förändringar på hygget under två vegetationsperioder. Summary: The change of logging residues during storing at the clear cutting area in two growing seasons. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 150. 69 p.
- 1984b. Hyggesrester som råvara för energiproduktion - torkning, lagring, hantering och kvalitet. Summary: Logging residues as a feedstock for energy production - drying, storing, handling and grading. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 152. 104 p.
- 1985. Trädbränslekvalitet - vad är det? Summary: Wood fuel quality - what is it? Sveriges Lantbruksuniversitet. Skog-Industri-Marknad Studier. Uppsatser 14. 18 p.
- 1987. Bränder i stackar med sönderdelat trädbränsle. Summary: Spontaneous combustion in piles with comminuted wood fuel. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Uppsatser 163. 17 p.

Thörnqvist, T. & Gustafsson, G. 1983. Kalluftstorkningens betydelse för bränsleflisens lagringsbarhet. Summary: The importance of air drying for the storing property of fuel chips. Sveriges Lantbruksuniversitet. Institutionen för Virkeslära. Rapporter 142. 75 p.

Tveite, B. 1983. Heiltretynning - fare for tilveksttap. Aktuelt fra Statens fagtjeneste for landbruket 3:98-105.

Uusvaara, O. 1984. Hakepuun kosteuden alentaminen ennen haketusta korjuuseen ja varastointiin liittyvin toimenpitein. Summary: Decreasing the moisture content of chipwood before chipping, harvesting and storage measures. Folia Forestalia 599. 31 p.

Uusvaara, O. & Verkasalo, E. 1987. Metsähakkeen tiiviys ja muita teknisiä ominaisuuksia. Summary: Solid content and other technical properties of forest chips. Folia Forestalia 683. 53 p.

Virtanen, P. 1963. Fuel properties of barking refuse from Finnish tree species. Paperi ja Puu 45:313-330.

Voipio, R. & Laakso, T. 1992. Pienikokoisten puiden maanpäällisen biomassan kemiallinen koostumus. Summary: Chemical composition of the above ground biomass of small-sized trees. Folia Forestalia 789. 22 p.

Wang, S., Huffman, J.B. & Littell, R.C. 1981. Characterization of Melaleuca biomass as a fuel for direct combustion. Wood Science 13:216-219.

Warsta, O. 1961. Rasiin kaadetun koivun ja lepän kuivumisesta. Pienpuualan Toimikunnan tiedotus 43. 8 p.

White, M.S., Curtis, M.L., Sarles, R.L. & Green, D.W. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part 1. Moisture content and temperature. Forest Products Journal. 33(6):31-38.

White.M.S., Argent, R.M. & Sarles, R.L. 1986. Effect of outside storage on the energy potential of hardwood particulate fuels: Part III. Specific gravity, ash content, and pH of water solubles. Forest Products Journal 36(4):69-73.

White, R.H. 1987. Effect of lignin content and extractives on the higher heating value of wood. Wood and Fiber Science 19:446-452.

Total of 137 references

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MEASUREMENT AND EVALUATION OF WOOD FUEL

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ABSTRACT

Measurement of fuelwood is done by volume or weight scaling. Evaluation determines quality in terms of moisture content, density, heating value, chemical properties and impurities. Both measurement and evaluation involve sampling. The report surveys the existing measurement and evaluation methods, sampling for moisture content, heating values and other fuel properties including nonwood materials.

KEYWORDS

Fuelwood, scaling, weighing, moisture, heating value, lignin, carbohydrates, extractives

MEASUREMENT OF FUELWOOD

Fuelwood appraisal can be done in terms of both quantity and quality. Quantity is determined through measurement. Scaling is needed to:
- fix purchase prices for fuelwood;
- determine contract fees for harvesting, forest and long distance transportation and comminution;
- control the quantity of transported fuelwood;
- do cost analysis and compare costs of various fuels.

Quality, on the other hand, can be characterized, for example, in terms of moisture content, bulk density, heating value, particle size, species, proximate and ultimate analysis. Both measurement and evaluation require sampling. In practice the sampling techniques vary according to the measured property and the person who does the sampling. No widely accepted common sampling rules exist. The only common aim of sampling seems to be that the sample should be as 'representative' as possible.

Scaling of chips by volume

The fundamental differences in the scaling of fuelwood compared with the scaling of roundwood are caused by the heterogenity of the material. Fuel chips are often made up of various tree species with various proportions of wood (60 - 85 %), bark, foliage, twigs, buds and even cones (Hakkila *et al.*, 1975). As a result, difficulties exist in the determination of solid volume. Nonetheless volumetric scaling has been a tradition in Nordic countries and is a simple and inexpensive method which speaks for its use.

The solid volume of forest chips is in practice determined by the loose volume of chip load (scaling

unit loose m^3) and a conversion factor (m^3 solid/m^3 loose). The measurement of the loose volume of a chip load is an uncomplicated, rapid and inexpensive measure, which is probably the most important reason for the popularity of the scaling of forest chips by loose volume. When the nominal dimensions of the vehicle load space are known, only the measurement of the mean deficiency, or excess, in chip load height is needed. Regarding general truck and tractor loads of 25 - 60 loose m^3, an error of 5 cm in the estimate of the height causes an error of only 2 - 3 % in the measurement of loose volume.

Some heating plants determine the chip volumes as equal to the nominal load volumes. This results in a systematic overestimate in the chip volume, even if the vehicle is fully loaded in the forest. This is due to the settling of the chips by 2 - 14 % during transport. The maximum solid contents for each chip type is reached in nearly every haulage, since most of the settling occurs during the first kilometers. That is why the measurement of loose volume should be done at the delivery point of the chips.

The greatest risk for the validity of the results is the use of solid content factor, which is needed in the conversion of loose volume to solid volume. The true variation between chip loads has been 0.34 - 0.56, which means an error of -29 - +18 % in the estimation of solid volume (Verkasalo and Nurmi, 1990). The problems involved in the use of factors have been studied rather extensively in the Nordic countries in the 1970s and 1980s. As a rule, the softer the wood the higher the factor. Kanninen *et al.* (1979) found the solid volume percentages of 42.1, 38.9 and 48.4 for pine, birch and alder wholetree chips on arrival at a mill. Hakkila (1984) has recommended the solid content factors of 0.43 for pine, 0.39 for birch and 0.46 for alder in practice. Nylinder and Toernmarck (1986) found the factors 0.39 - 0.43 for forest chips of oak and 0.42 - 0.48 for that of mixed tree species. Based on Nurmi's (1986) results, the approximate solid content for whole-tree and slash chunks is 0.33 - 0.35 and 0.40 for pulpwood chunks. Additional results have been presented by Gislerud (1974), Kuitto (1983), Metsola (1983), Pietilä (1984), Rantamaula (1981) and Uusvaara (1984).

The Finnish Forest Research Institute carried out a comprehensive research study on the factors affecting the solid content of forest chips in 1984 - 1985 (Uusvaara and Verkasalo 1987). The material consisted of 879 loads of chips comminuted by 10 different mobile chippers and of 10 kinds of chips. The solid content depended mostly on the chipper type (the force of discharge, comminution principle and particle size) and origin of chips (tree species and assortment). They accounted for 49.1 % of the variation. Other factors (size and drying time of wood, season of comminution, transport vehicle and distance) had only a minor effect on the solid content. Table 1 presents the solid content factor of forest chips by chipper type, tree species, timber assortment and season.

Scaling by weight

The aim in scaling fuel chips or wood by weight is to find out the dry mass of the load. This is the best commercial method for measuring the load. To get the dry weight the fresh weight and moisture content of the load must be determined. The advantage of this method over volumetric scaling is that it will result in fairer pricing and improved chip quality. It is the most commonly used method in the United States and Canada when fuelwood is purchased by a forest company of electric utility (Baker, 1990). In Sweden larger heating installations often have weighbridges as well which makes weight scaling possible (Derler, 1988). In Finland, however, fuelwood is often used at rather small installations and weight scaling is thus considered an expensive approach (Verkasalo and Nurmi, 1990).

The loads can be weighed either with stationary equipment or with portable axle weight scales. An extremely good weighing accuracy of 0.5 - 1 % is reached with stationary equipment, if the equipment is regularly calibrated and its surface is kept clear of ice and snow in winter. The ergonomy is good as well, because no work out of doors is needed. Weighing with axle weight scales takes 6 - 40 minutes/load and the accuracy of the results is highly affected by external conditions (temperature, ground flatness) (Verkasalo 1987b). In addition, the ergonomic conditions are unsatisfactory in winter time. Both the accuracy and the ergonomy can be improved, if the weighings are done in a covered space where the load cells have stationary places made of concrete. Electronic load cells installed below the loading spot of the timber truck have been introduced in the United States and France

(Lewis, 1987). Practical applications for chip transport might be possible.

Table 1.Recommendations for the solid content factor (m^3/m^3 loose) by chipper type tree species and timber assortment in summer (S) and winter (W) (Verkasalo and Nurmi, 1990).

		Timber assorment								
Chipper type	Season	Whole tree				Tree length			Slash	
		Pine	Spruce	Birch	Alder	Pine	Birch	Alder	Fresh	Seasoned
Disc chipper, blow from the back of the load	S	0.47	0.44	0.44	0.54	0.48	0.44	0.56	-	-
	W	0.50	0.44	0.46	0.54	0.51	0.44	0.56	-	-
Disc chipper, blow from the top of the load	S	0.48	0.44	0.45	0.54	0.49	0.43	0.56	-	-
	W	0.49	0.44	0.50	0.54	0.50	0.43	0.56	-	-
Disc chipper, tip-up	S	0.45	0.39	0.38	0.48	0.41	0.46	0.50	-	-
	W	0.48	0.39	0.43	0.48	0.42	0.46	0.50	-	-
Drum chipper, blow from the back of the load	S	0.46	0.43	0.43	0.52	0.47	0.43	0.54	0.36	0.39
	W	0.49	0.43	0.44	0.52	0.50	0.44	0.54	0.38	0.41
Drum chipper, blow from the top of the load	S	0.41	0.39	0.40	0.52	0.42	0.40	0.53	-	-
	W	0.44	0.39	0.42	0.53	0.44	0.40	0.53	-	-
Drum chipper, tip-up	S	0.38	0.36	0.37	0.45	0.39	0.37	0.45	-	-
	W	0.40	0.36	0.39	0.45	0.41	0.37	0.45	-	-
Crush, belt conveyor	S	-	-	-	-	-	-	-	0.39	0.39
	W	-	-	-	-	-	-	-	0.39	0.30

The most difficult part of weight scaling is sampling for moisture content. Because of the variation in biomass composition, ability to freeze, temperature, bulk density and basic density, the continuous measurement of moisture content in a chip load with X-rays, infrared radiation etc. has not been able to replace sampling. The number of samples needed depends on the required accuracy and on the variation of chip properties.

Variation in moisture content is found both within and between loads. Variation between loads is caused by the storage conditions at the landing, season, storage time and size of the storage. More variation is found in seasoned than in freshly comminuted wood. However, the moisture content is lower in seasoned wood. Variation within a load is both random and systematic. Systematic variation is caused a) by sorting of chips by size and weight when the chips are blown in the load space and b) by drying of the top layer of the load during fair weather and of wetting during rain. Verkasalo (1987a) found that moisture variation between different parts of a chip load was 0.6 - 2.3 %-units. The lowest values came from the top of the load space. Least amount of variation was present when the load was sampled after dumping (also Nisula, 1961; Uusvaara, 1978).

In sampling for moisture content the required accuracy determines the number of samples. Most often

the number is only one per load independent of the size of the load (Baker, 1990). This, however, is much less than what should be taken. Below are listed the sampling intensity for chips of different origin permitting error of 2 % of the mean:

Type of chips	number of samples	size, dm^3	author
sawmill chips	5-15	2	Nylinder, 1972
fuel chips	7	1	Heiskanen, 1963
fuel chips	6	--	Laine and Haapasalo, 1981

Verkasalo (1987a) reports the amount of samples per load of chips required for different assortments. The calculations in table 2 are based on (1) Lönner's (1966) and (2) Liedes and Manninens's (1975) formulas.

$$n = \frac{Nt^2 + V^2}{Nd^2 + t^2V^2} \quad (1)$$

where
n = number of samples
N = number of chip loads
t = t distribution at 95 % confidence level
V = sample coefficient of variation
d = allowed error of mean moisture content

$$n = \frac{(100st)^2}{dk} \quad (2)$$

where
n = number of samples
s = sample standard deviation in a load or pile
t = t distribution at 95 % confidence level
d = allowed error of mean moisture content
k = mean moisture content in a load or pile

The formula have been used by Verkasalo (1987a) to create table 2. It shows how radically the number of samples needed increases when the permitted error decreases. The number of samples becomes so large with seasoned wood that one has to accept errors higher than 10 %.

PHYSICAL PROPERTIES OF FUELWOOD

Moisture content

Moisture content is the most commonly used property of fuel wood. Its quantity is inversely proportional to the amount of heat that is recovered from conventional combustion where the latent heat of evaporation is lost with flue gases. Moisture content varies over a wide range but is easy to determine. Originally a living tree acquires its moisture through water uptake from the soil. It is found as bound water in cell walls and free water in cell lumens of both wood and bark. The moisture content varies from one tree part to another. It is often the lowest in the stem and increases towards the roots and the crown. Seasons are also known to effect moisture content (Hakkila, 1962). When a tree is felled the water supply is cut off and the tree will slowly come to an equilibrium moisture content with the ambient air. The equilibrium moisture content depends on the temperature and relative humidity of the ambient air. The method where wood is left on the ground or in a pile to dry is called seasoning. If the leaves are still intact it is called leaf seasoning. Seasoning is the most effective method used to

increase the effective heating value of fuelwood. It is also simple and low in cost if interest is not considered over the storage period.

Table 2. Number of moisture content samples needed to determine the average moisture content of chip load by kind of chipwood and degree of dryness. The samples are taken from various parts of chip load (Verkasalo, 1987a).

Assortment	Permitted error, per cent of mean				
	10	5	3	2	1
	Amount of samples /chip load				
Softwood whole trees					
Green	1	2	4	8	32
Seasoned	3	12	33	74	295
Total	2	5	12	27	105
Hardwood whole tree					
Green	2	6	17	38	152
Seasoned	3	9	25	56	223
Total	2	8	21	46	187
Boles					
Green	1	1	3	6	23
Seasoned	5	20	54	120	480
Total	3	9	25	55	220
Slash					
Green	2	6	17	37	148
Seasoned	3	11	30	67	268
Total	2	8	22	49	196

Drying of wood samples in drying ovens. Even though some experimental instruments have been used to determine the moisture content of fuelwood the use of drying ovens remains as the only practical method. A large variety of ovens are used. They vary from convection or blower type laboratory ovens to old kitchen ovens. The first ones mostly being used in laboratory conditions whereas the last category can be found in some small heating installations. Both in laboratory and in commercial moisture analysis the aim is to keep the sample in 100-105°C until constant weight is reached. Björklund *et al.* (1990) tested how the position in an oven effected oven temperature and drying rate of different wood particles. They found that the temperature in the oven varies to a considerable degree. The lower part of the oven was always in a higher temperature region. The gradient was greatest in the beginning but was still as high as 10-15°C at the end of the drying period. It was also found that the samples dry faster on the lowest, ie. warmest shelf (Fig. 1). The wood assortment also effected the rate of drying as seen in figure 2. It should also be noted that the time required to reach constant weight is much shorter than the commonly used 48 hours.

The effects of high and low drying temperatures were also studied. Sawmill chips were dried at three different temperatures, 85 °C, 103 °C and 120 °C. The results are shown in figure 3. The temperature was very important in terms of drying time. At 120 °C 16 hours were needed, at 103 °C 20 hours and at 85 °C 28 hours to reach constant weight. Dried samples were also exposed to an excessive temperature of 150 °C for eight hours. This was done on drill shavings and on chipped logging residues. An extra weight loss of only 0.3 and 0.5 % respectively were reached. Introduction of fresh samples into the oven in the middle of drying procedure had no effect on the drying of the samples introduced initially.

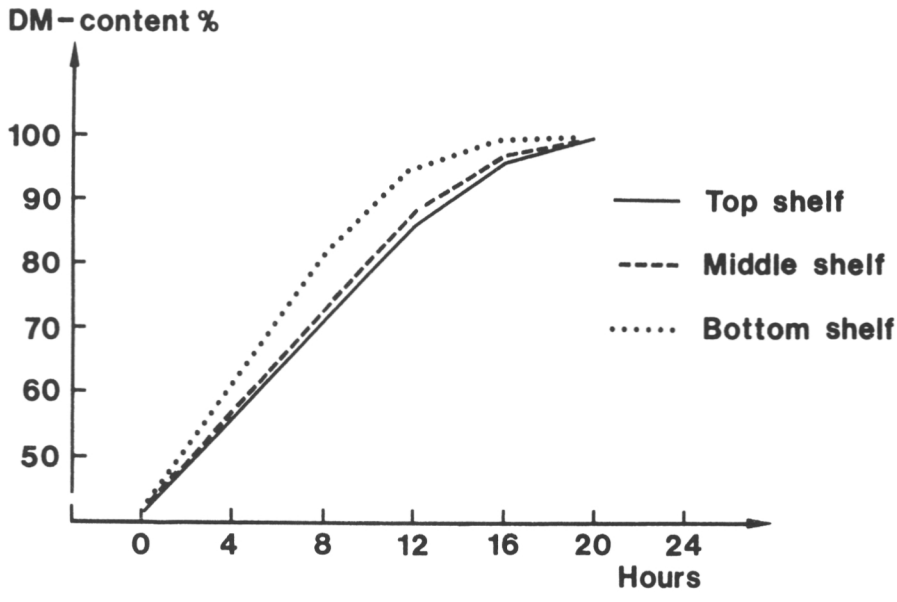


Figure 1. Drying rate of samples on different shelves (Björklund *et al.*, 1990).

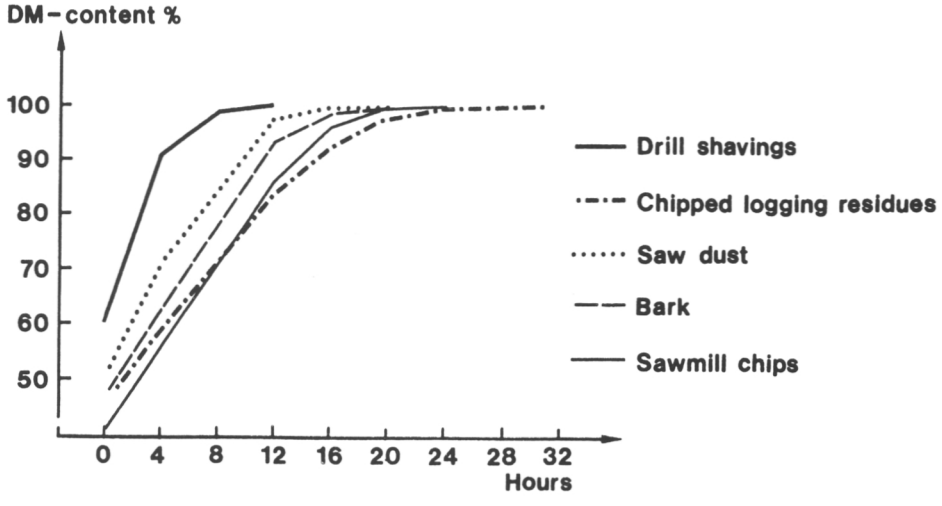


Figure 2. Drying rate according to the assortment (Björklund *et al.*, 1990).

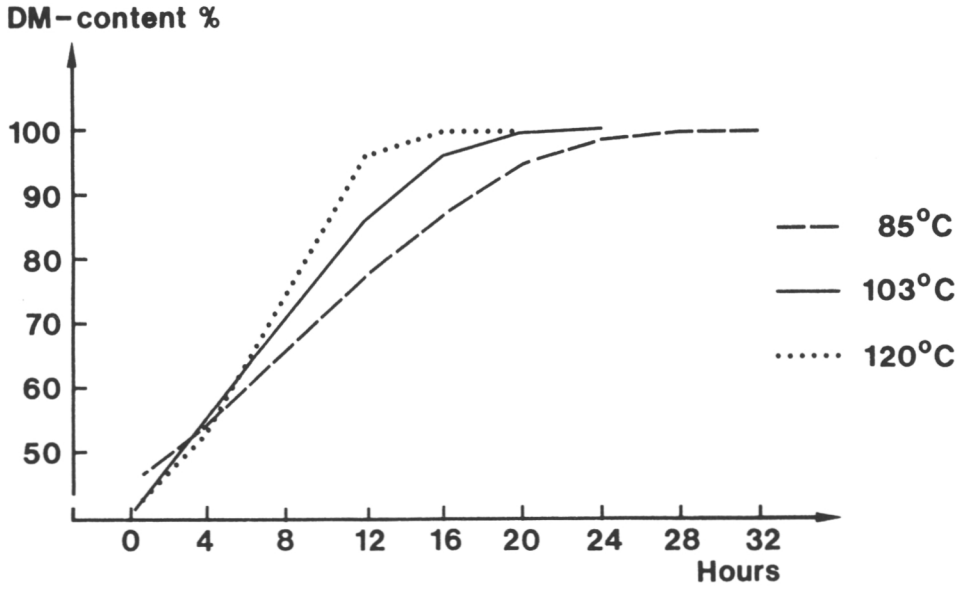


Figure 3. Drying rate of sawmill chips at three different temperatures (Björklund *et al.*, 1990).

Heating value

Three different measures of energy content can be used. Calorimetric heating value (W_c), effective heating value of oven dry biomass (W_{ea}) and effective heating value of biomass with moisture (W_{em}). 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 combustion of the sample. This is directly proportional to the amount of hydrogen in the combustible matter. In free combustion, however, this water escapes with flue gases resulting in a loss of energy. The recovered energy is called effective heating value. It can be calculated for both oven dry (W_{ea}) and moist material (W_{em}) as follows. The following formula is used for oven dry material:

$$W_{ea}=W_c-2.45x0.09H_2$$
$$=W_c-0.22H_2$$

where W_c = calorimetric heating value.
2.45 MJ/kg = the energy required to evaporate 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 heat energy for evaporation comes from the burning fuel. This lowers the amount of usable energy. This is the effective heating value of moist biomass which is proportionate to the fuel moisture content in the following way:

$$W_{em} = W_{ea} - 2.45x \frac{MC}{100 - MC}$$

where W_{em} = effective heating value of biomass with moisture (MJ/kg dry mass)
W_{ea} = the effective heating value of dry biomass (MJ/kg dry mass)
MC = the moisture content on fresh mass basis (%).

Stem biomass is composed of wood, inner bark and outer bark. The proportions of these 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 which makes it the single most important component to consider when a heating value for the whole stem is calculated. Its heating value does not vary a great deal from one species to another, but it is slightly higher in coniferous species than in broad-leaved species (fig. 4). This is caused by a higher lignin and resin content.

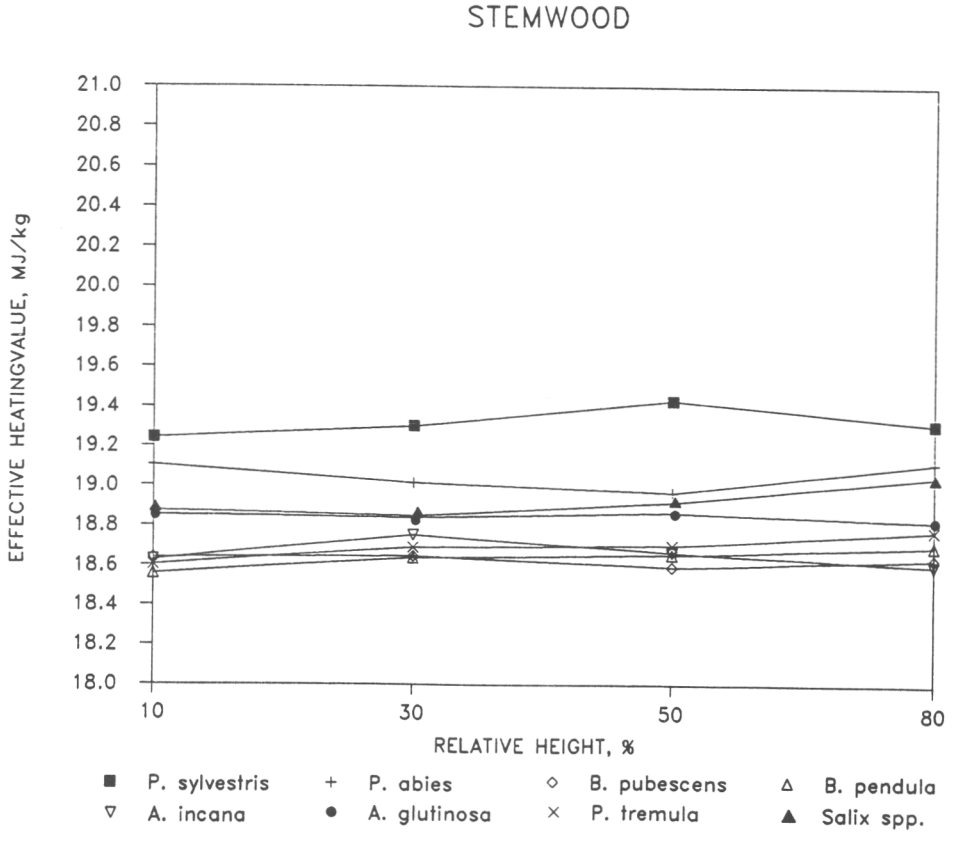


Figure 4. The effective heating value of stemwood by species as a function of stem height (Nurmi, 1991).

In Northern European tree species the heating value of outer bark is higher than those of wood or inner bark. Its proportion of stem mass, however, is smallest of the three. This means that it makes a lesser contribution to the weighted heating value of the stem than inner bark or wood (Nurmi, 1991). The heating value of combined bark components are higher than that of wood for all species except for aspen and southern spruce. Musselman and Hocker (1981) and Singh and Kostecky (1986) found that species in genera Pinus, Picea, Betula and Populus from New Hampshire and Manitoba had higher heating values in bark than wood. These results mean that bark is a desirable component in fuelwood, unlike in industrial processes, because it enhances the energy content of the fuel (tables 3-5). The average heating value of stem biomass is the weighted mean of wood and bark values as shown for each species in tables 3-6. In spite of the large differences in heating value and proportions of stem component the differences between species actually are very small on whole stem bases (Olofsson, 1975; Nurmi, 1991). In Canada Singh and Kostechky (1986) found the differences between species to be somewhat larger.

The significance of bark component is more pronounced in branches and crown than in stem as it makes up roughly one third of the branch mass. The foliage mass is also a considerable factor in branches under 5 mm as it makes up roughly half of their mass. However, the crown heating value itself is not greatly effected by their presence or absence because the heating value of foliage is of the same magnitude as that of the branch mass. This means that if foliage is lost during seasoning it will not greatly effect the heating value per unit weight.

Branches and crown have higher heating values than stems because of the higher bark content. The previously quoted references with the addition of Hughes (1971) show this to be a common phenomema for many genera. From the fuelwood point of view this is a positive aspect because branches are a low quality, low value and most often a totally unacceptable raw material for most sectors of the woodworking industry. When trees are harvested with branches intact the energy recovery will increase in mass and per unit weight of wood. In spite of the differences within each component, the differences between species for the total stem, crown or whole-tree biomass are small and may not be very significant.

CHEMICAL PROPERTIES FUELWOOD

From the traditional combustion point of view the chemical structure of wood may not seem all that important. However, in the future this area of fuelwood evaluation may become increasingly important if transportation fuels and other chemical products are to be produced from forest biomass (Koch 1985). The structural elements of the organic portion of wood are carbon, oxygen, hydrogen and nitrogen. The distinct advantage of woody biomass over fossil fuels is the low level of sulphur. The ultimate analysis of tree components of some Northern European tree species shows the carbon and hydrogen content to be rather uniform among species (table 6). However, the bark components do have a higher percentage of carbon and hydrogen than wood. This is most pronounced with the genera *Betula* and *Alnus* where the carbon content of outer bark is 60-70% and hydrogen 8-9%. These elements make the organic polymer substance of wood i.e. carbohydrates and phenolics. Carbohydrates form cellulose and hemicellulose, and polymeric phenolics form lignin. It is found in the secondary layer and middle lamella of the cell wall. Lignin has a very close relationship with hemicellulose by acting as a kind of glue which fixes the bunches of cellulose chains in plant tissues together, in this way giving mechanical strength to the plant stem (Levin and Repyah, 1984). Lignin is rich in carbon and hydrogen,which are the heat producing elements and hence has a higher heating value than carbohydrates. Table 7 by Voipio (1990) shows the carbohydrate and lignin content of biomass components of some Northern European species.

Table 3. Effective heating values (MJ/kg) of oven dry biomass. Crown includes foliage (Nurmi, 1991).

Species	Stemwood	Stembark	Total Stem	Crown	Foliage	Whole-tree
P.sylvestris	19.308	19.529	19.329	20.549	20.996	19.463
P.abies	19.048	18.803	19.010	19.552	19.224	19.146
B.pubescens	18.617	22.745	19.175	19.663	19.766	19.236
B.pendula	18.611	22.525	19.033	19.486	19.723	19.049
A.incana	18.670	21.566	19.029	19.960	20.571	19.100
A.glutinosa	18.883	21.438	19.369	19.779	20.080	19.403
P.tremula	18.668	18.574	18.655	18.684	19.180	18.657

Table 4. Calorimetric heating values (MJ/kg) of oven dry tree components by Singh and Kostecky (1986).

SPECIES	STUMP	STEM	TREETOP	BARK	FOLIAGE	BRANCHES	MEAN
White spruce	19.834	19.018	21.558	19.830	20.558	21.144	20.324
Black spruce	19.197	18.784	21.562	19.478	20.873	20.679	20.096
Jack pine	19.953	19.443	21.225	21.299	21.430	21.374	20.787
Eastern white cedar	19.370	19.960	19.542	18.737	21.446	18.668	19.620
Tamarack	19.889	18.783	21.283	19.490	20.089	21.463	20.166
Balsam fir	19.656	18.746	21.425	18.527	21.504	20.570	20.071
Aspen	18.744	18.669	20.249	19.509	18.804	19.905	19.313
Balsam poplar	18.474	17.709	20.500	19.467	17.660	19.100	18.818
White birch	18.875	18.527	19.846	20.230	21.119	19.721	19.719
Manitoba maple	18.697	18.680	19.770	18.563	17.230	19.455	18.732

Table 5. Calorimetric heating values of oven dry tree components. Modified from Neenan and Steinbeck (1979).

SPECIES	WOOD	BARK	BRANCHES	TWIGS	LEAVES
Green ash	19.958	19.330	20.331	20.168	21.428
Black cherry	19.950	20.712	20.264	20.369	21.901
Boxelder	20.486	18.087	20.431	20.251	21.047
Redbud	20.360	19.385	19.833	19.824	21.298
Red maple	20.126	19.075	19.925	19.967	20.829
Sweetgum	19.762	19.125	19.607	19.682	19.498
Sycamore	19.908	20.004	20.327	20.394	21.645
Water oak	19.996	19.347	19.908	20.168	21.281
Yellow-poplar	20.172	19.385	20.092	20.017	21.210

Table 6. The elemental composition of tree components of some Northern European tree species.

	Wood			Innerbark		Outerbark		Bark	Foliage
	Stem	Branches > 5mm	Branches < 5mm	Stem	Branches > 5mm	Stem	Branches > 5mm	Branches < 5mm	
CARBON									
P. sylvestris	52.34	53.53	50.87	50.83	52.33	55.75	56.35	54.99	54.20
P. abies	52.43	53.36	50.37	49.70	50.20	55.56	56.10	54.02	51.30
B. pubescens	50.97	50.97	48.39	52.20	52.49	72.64	68.37	57.82	49.12
B. pendula	47.43	48.67	48.05	48.00	48.60	66.71	64.34	50.24	48.68
A. incana	49.09	48.21	49.17	49.67	48.34	64.09	60.58	51.53	49.75
A. glutinosa	46.64	47.90	48.45	50.29	50.09	58.52	62.06	53.97	50.95
P. tremula	46.21	46.84	50.23	48.95	47.81	52.71	52.94	48.05	48.23
HYDROGEN									
P. sylvestris	6.09	6.03	5.23	6.17	6.36	5.68	6.12	6.70	6.82
P. abies	5.86	5.61	5.14	5.59	5.62	5.85	5.77	5.95	6.28
B. pubescens	5.86	5.80	5.15	5.79	6.10	9.37	8.43	6.55	6.13
B. pendula	5.22	5.25	5.18	5.10	5.01	9.41	8.40	5.33	6.08
A. incana	5.77	5.16	5.71	6.15	5.94	8.59	7.66	6.48	6.22
A. glutinosa	5.01	5.84	5.89	5.77	5.57	6.37	7.56	6.23	5.90
P. tremula	4.98	5.09	5.98	5.74	5.73	6.42	6.18	5.77	5.95

Table 7. The lignin and carbohydrate content of biomass components by species.

Tree species	Relative stem height 20%			Relative stem height 80%			Branches > 5mm			Branches < 5mm		
	Wood Foliage	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	
LIGNIN												
P. sylvestris	25.5	5.3	29.5	27.0	7.2	17.9	29.7	7.1	15.7	27.8	10.5	9.8
P. abies	27.8	7.7	22.9	28.2	9.2	23.9	31.7	7.2	24.7	30.2	18.7	11.5
B. pubescens	22.2	24.2	6.2	21.5	21.9	6.3	21.5	17.7	11.2	22.5	14.1	14.6
B. pendula	21.9	21.6	11.7	22.7	20.2	7.9	21.9	16.8	10.1	22.8	14.5	18.5
A. incana	23.0	26.7	26.0	22.4	16.4	11.7	23.8	21.9	18.9	26.5	19.0	21.5
A. glutinosa	24.8	28.4	32.0	25.2	24.6	19.6	25.9	23.5	21.4	27.5	22.0	25.0
P. tremula	20.1	14.8	16.9	19.8	15.2	12.5	18.4	14.9	17.0	21.2	17.5	18.6
CARBOHYDRATES												
P. sylvestris	69.6	41.8	35.4	66.1	37.0	38.4	56.6	37.6	33.2	51.6	31.1	37.4
P. abies	78.9	49.1	31.5	74.5	48.2	36.3	66.2	49.6	30.3	63.3	36.5	31.7
B. pubescens	67.0	38.4	5.3	65.3	35.8	5.8	64.2	32.9	7.8	60.0	23.4	20.1
B. pendula	69.9	41.8	13.9	65.9	46.2	10.3	64.6	41.6	14.0	63.0	26.0	22.3
A. incana	69.0	33.8	20.0	62.6	33.9	14.2	63.0	34.0	17.1	55.0	28.3	20.4
A. glutinosa	69.8	37.6	24.9	64.8	44.2	28.1	63.9	33.8	20.9	57.0	25.9	23.8
P. tremula	74.6	41.1	31.6	69.1	49.8	26.1	69.3	48.0	40.3	58.8	38.5	24.8

Wood and bark also contain substances called extractives. Many of them are soluble in organic solvents (hexane, acetone, ethanol) and hot water. The amount of extractives extracted from wood is relatively small if compared with the amount of extractives from bark and foliage (Table 8). The extractive content of the inner bark of softwood is remarkably larger than that in the outer bark while in hardwoods, except in birch, the extractive content both in the outer and inner bark is rather similar. On the other hand the extractive content of birch outerbark is rather high compared with that of inner bark. This phenomenon is due to a compound named betulinol (even 30% of the dry matter of birch outer bark). Betulinol is a triterpene in structure and dissolves in hot organic solutions. The white colour of birch outer bark comes from betulinol (Jääskeläinen, 1982).

Table 8. The content of extractives soluble in organic solvents and hot water in tree biomass.

Tree species	Sampling height						Branches > 5mm			Branches < 5mm		
	20%			80%								
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	Foliage
P. sylvestris	5.0	39.5	15.9	5.4	44.4	23.3	9.1	43.3	28.4	14.1	38.2	40.6
P. abies	3.5	37.4	23.4	4.9	38.7	20.9	5.2	30.5	22.0	9.6	26.4	43.3
B. pubescens	4.4	21.3	33.2	5.8	23.7	29.6	6.8	29.0	24.1	9.1	23.9	32.5
B. pendula	4.2	18.8	31.6	5.8	18.9	32.7	7.0	19.5	26.5	8.2	20.5	33.4
A. incana	4.4	20.4	27.8	7.5	38.2	39.0	8.2	21.3	22.7	11.3	22.5	28.3
A. glutinosa	5.1	20.5	14.9	6.2	22.4	22.2	8.3	23.5	24.1	9.8	21.1	27.6
P. tremula	4.5	23.1	26.5	6.1	20.5	25.2	8.6	20.0	19.0	14.8	19.5	25.4

Alkali soluble extractives are not found in wood. Suberin is a typical compound especially in the outer bark of *Quercus suber* and birch species (suberin content may be more than 50% of dry matter). It is composed of several monocarboxylic and dicarbocsylic aliphatic acids and in some species phenolic constituents may be part of the suberin complex. On the other hand the suberin content of inner bark in birch and other tree species is only 2-5% of dry matter.

As mentioned earlier, bark and foliage samples were extracted by alkaline solution before lignin analysis. The solution used was according to Ekman (1983) appropriate to the determination of suberin. In table 9 we observe that the results of the outer bark of birches, rich in suberin, differ clearly from the results of the outer and inner barks of other tree species.

Because of the heterogeneity of bark, many different factors have an effect on its chemical composition, for example growth site, season, storing circumstances, age of tree, etc. Acetyl groups connected with hemicellulose molecules may increase the yield of alkali-soluble extracts. These groups can split off from the polysaccharide molecules affecting a hydrolysis where some of polysaccharides will turn into monosaccharides, which then will dissolve in alkaline solution (Voipio, 1990).

Table 9. The content of alkali-soluble matter in the bark and foliage of different tree species (Voipio, 1990).

Tree species	Sampling height				Branches > 5mm		Branches < 5mm	
	20%		80%					
	Inner bark	Outer bark	Inner bark	Outer bark	Inner bark	Outer bark	All bark	Foliage
P. sylvestris	18.8	18.9	19.2	26.7	21.1	30.7	24.4	17.7
P. abies	15.2	18.8	17.6	16.0	24.5	18.3	19.7	13.0
B. pubescens	15.3	55.0	15.5	57.0	17.7	54.7	36.6	25.6
B. pendula	14.1	46.3	14.5	45.6	18.5	44.6	33.0	23.9
A. incana	14.2	20.5	19.5	36.9	24.1	37.5	29.9	25.2
A. glutinosa	16.4	24.0	14.5	32.2	18.2	34.4	29.9	22.8
P. tremula	26.9	22.6	16.7	25.5	26.1	26.0	22.5	28.1

Nonwood materials

Residue wood such as plywood, composition boards and sludge from the primary and secondary manufacture and disposal of wood products, such as wood pallets, wood rail ties and demolition wood, represent an alternative energy source. However, environmental regulations are concerned about the environmental impact of combustion of such material because the residue may contain adhesives, resins, plastics, preservatives and paints containing heavy metals.

Table 10 lists nonwood components present in wood products manufactured by primary and secondary wood products industries. In primary forest products industries, the phenol formaldehyde resin found in exterior plywood is usually catalyzed with sodium hydroxide. Extenders are based on wcod or agricultural products. The urea formaldehyde resin in interior plywood is usually catalyzed with an acid such as hydrochloric acid or aluminum chloride.

The adhesives found in the resins from the secondary forest products industries are similar to those found in residue from primary industries. Overlays are mostly melamine resins and pigments. Finishes contain urethanes, condensed oils and alkyd and latex resins. The drying agents contain cobalt, manganese and zink. Pigments contain many different inorganic elements such as lead, titanium, zinc, iron and cadmium. Paper may contain clay fillers, wet-strength resins, dyes and inks.

Table 10. Nonwood components of forest industry residue (Baker, 1991).

Forest products industry	Product	Nonwood residue
Primary	Exterior plywood	Phenol formaldehyde resin, extenders
	Interior plywood	Urea formaldehyde resin
	Composition board	
	Wet-process hardboard	Phenol formaldehyde resin, wax, tempering oil (e.g., linseed oil), alum, sulfuric acid
	Dry-process hardboard	Phenol formaldehyde resin, wax
	Particleboard	Urea formaldehyde resin, wax
	Flakeboard	Phenol formaldehyde resin, wax
	Pulp and paper	Sludges: dyes, inks Dyes and inks: heavy metals
Secondary	Furniture, cabinets, windows, doors, mill-work, prefab buildings	Adhesives, plastic overlays, resins, pigmrnts, urethanes, oils, inorganic materials, clay fillers, dyes, inks.

Because demolition wood comes from many sources, it contains many different nonwood components. The wood is usually mixed with wallboard, cement, roofing, insulation, metal, plastics and dirt. Manual and automatic processing can separate the wood from most contaminants; painted wood can be removed from the demolition residue.

Demolition wood is often treated with preservatives or fire retardants. Preservatives that increase the resistance of the wood to decay, insects and marine borers include creosote, pentachlorophenol, copper-8-quinolate, copper naphtenate, borate and salt compounds made with copper, chromium, arsenic and zinc. Wood structural materials are treated with chemicals to increase resistance to fire. Chemicals used for fire retardants include borates, phosphates, ammonium sulfate and resins (Baker 1991).

REFERENCES

Baker, A. (1990). Practices for sampling and testing wood fuel in the United States. In: *Measurement and evaluation of wood fuel. Proceedings of the IEA/BE Task VI Activity 5 workshop in Jyväskylä, Finland, October 25-27, 1989.* J. Nurmi and K. Polet (eds). Metsäntutkimuslaitoksen tiedonantoja 346.

Baker, A. (1991). Research on combustion of wood containing nonwood materials. In: *Proceedings from joint-meeting IEA/BEA Activity 4 and 5 Silsoe Research Institute 12th-14th of June 1991.* K. Suadicani (ed).Danish Forest and Landscape Research Institute. Research report No. 10.

Björklund, L. (1990). Drying of wood samples in drying ovens. In: *Measurement and evaluation of wood fuel. Proc. of the IEA/BE Task VI Activity 5 workshop in Jyväskylä, Finland, October 25-27, 1989.* J. Nurmi and K. Polet (eds). Metsäntutkimuslaitoksen tiedonantoja 346.

Derler, R. (1988). *Measurements of tree fuel at eleven district heating plants in Sweden. IEA Bioenergy Agreement Task VI. Activity 5 report.* SLU, Virkeslära, Uppsala. 52pp.

Ekman, R. (1983). The suberin monomers and triterpenoids from the outer bark of Betula verrucosa Ehrh. *Holzforschung* 37: 205-211.

Gislerud, O. (1974). *Heltreutnyttelse. II. Biomasse og biomasse egenskaper hos tynningsvirke av gran, furu, bjork og or. Summary: Biomass and biomass properties of trees from thinnings of spruce, pine, birch and alder.* Norsk Institutt for Skogforskning. Skogteknologiskavdeling. Rapport 6. 59 pp.

Hakkila, P. (1962). Polttohakepuun kuivuminen metsässä. Summary: Forest seasoning of wood intended for fuel chips. *Communicationes Instituti Forestalis Fenniae* 54(4). 82 s.

- , Kalaja, H. & Mäkelä, M. (1975). Kokopuunkäyttö pienpuuongelman ratkaisuna. Summary: Full-tree utilization as a solution to the problem of small-sized trees. *Folia For.* 240. 78pp.

Hakkila, P. (1984). Metsähakkeen hankinta lämpölaitosten polttoaineeksi. Abstract: The Procurement of Forest Chips for Use as Fuel in Heating Plants. Project on Development of Regional Usage of Peat and Wood Fuels. The Finnish Ministry of Trade and Industry, Energy Department. *SITRA.* No. 33. 121 pp.

Heiskanen, V. (1963). Kosteuden vaihtelut kenttähakkureilla lastutetuissa hakekuormissa. Summary: Variations of moisture in loads of chips chipped with portable chipping machines. *Pienpuualan Toimikunnan Tiedotus* 80. 4pp.

Hughes, M.K. (1971). Seasonal calorific values from a deciduous woodland in England. *Ecology* 52: 923-926.

Jääskeläinen, P. (1981). Betulinol and its utilization. *Paperi ja puu* 10: 599-603.

Kanninen, K., Uusvaara, O. & Valonen, P. (1979). Kokopuuraaka-aineen mittaus ja ominaisuudet. Summary: Measuring and properties of whole-tree raw material. *Folia Forestalia* 403: 1-53.

Kuitto, P.J. (1983). (In Finnish) "Harvesting logging residues after mechanized harvesting of roundwood". *Metsäteho, the Forest Work Study Section of the Central Association of Finnish Forest Industries.* Leaflet 25.1.1983. 24 pp.

Koch, P. (1985). *Utilization of hardwoods growing on southern pine sites: the raw material.* U.S. Dept. Agr. For. Serv., Agr. Handbook 605. Vol. 3.

Laine, R. & Haapasalo, P. (1981). *(In Finnish) "Classification of chips and control of their energy value".* Vapo Co. & The Technical Research Centre of the State, Laboratory for Domestic Fuel Research. Jyväskylä. 47 pp. Unpublished.

Levin, E.D. & Repjah, S.M. (1984). *Pererabotka drevesnoi zeleni. Moskva 'Lesnaja promyilennost'* 1984. 120 c.

Lewis, R. (1987). *On-board scales pay their way.* American Pulpwood Association Inc. Washington, DC. Technical Release 87-R-25. 2 pp.

Liedes, M. & Manninen, P. (1975). *Otantamenetelmät.* 255pp. Gaudeamus. Helsinki.

Lönner, G. (1966). *Stickprovsmetoder.* Forskningsstiftelsen Skogsarbeten. Stockholm. Handledning nr.1.

Metsola, E. (1983). (In Finnish) *"Properties of forest chips comminuted by various chippers".* University of Helsinki, The Department of Logging and Utilization of Forest Products. Post-gradu thesis. 72 pp. Unpublished.

Neenan, M. & Steinbeck, K. (1979). Caloric values for young sprouts of nine hardwood species. *Forest Science* 25(3): 455-461.

Nisula, P. (1961). Polttohakkeen kuiva-ainepitoisuuden määrittäminen painomittausta käyttäen. Summary: Determination of the dry matter content of fuel chips when using measurement by the weight. *Pienpuualatoimikunnan julkaisuja* 131. 49pp.

Nurmi, J. (1986). Chunking and chipping with conescrew chipper. *Folia Forestalia* 659. 23 pp.

Nurmi, J. (1991) *Heating values of whole-tree biomass in young forests in Finland.* Manuscript in Finnish Forest Research Institute. 66p.

Musselman, K. & Hocker, Jr., H.W. (1981). Caloric values of eight New Hampshire forest tree species. *Canadian Journal of Forest Research* 11: 409-412.

Nylinder, M. & Toernmarck, J. (1986). *Mätning an bränsleflis, spen och bark. Summary: Scaling of Fuel Chips, Sawdust and Bark.* The Swedish University of Agricultural Sciences, Department of Forest Products. Report No 173. 63 pp.

Nylinder, P. (1972). *Measuring of wood chips.* Skoghögskolan. Institutionen för virkeslära. Rapporter 79. 13pp.

Olofsson, L. (1975). *Värmevärden för olika delar av tall, gran och björk. Summary: Heating values for different parts of pine, spruce and birch.* Dept. of Operational Efficiency. Research Notes 90. 39 pp.

Pietilä, J. (1984). (In Finnish) *"On the properties of whole-tree chips and the factors affecting the harvesting of chipwood".* University of Helsinki, The Department of Logging and Utilization of Forest Products. Post-graduate thesis. 74 pp. Unpublished.

Rantamaula, J. (1981). Hakkuutähteiden haketus kevyellä kalustolla. Summary: Chipping logging residues with lightweight equipment. *Folia Forestalia* 498. 24 pp.

Singh, T. & Kostecky, M.M. (1986). Calorific value variations in components of 10 Canadian tree species. *Canadian Journal of Forest Research* 16: 1378-1381.

Taras, M.A. (1978). Biomass of southern pines and their product yields. In: *Complete tree utilization of southern pine.* C.W. McMillin (ed).Forest Products Research Society Madison, 15-23.

Uusvaara, O. (1978). Teollisuushakkeen ja purun mittaus. Summary: Estimation of industrial chips and sawdust weight. *Folia Forestalia* 341. 18pp.

Uusvaara, O. (1984). Hakepuun kosteuden alentaminen ennen haketusta korjuuseen ja varastointiin liittyvin toimenpitein. Summary: Decreasing the moisture content of chipwood before chipping, harvesting and storage measures. *Folia Forestalia* 599. 31 pp.

- & Verkasalo, E. (1987). Metsähakkeen tiiviys ja muita teknisiä ominaisuuksia. Summary: Solid content and other technical properties of forest chips. *Folia Forestalia* 683. 53 pp.

Verkasalo, E. (1987a). Metsähakkeen kosteuden ja kuivamassan mittaus kuormaotantamenetelmillä. Summary: Measurement of moisture content and dry weight of forest chips by load sampling methods. *Folia Forestalia* 694. 35 pp.

- (1987b). *Polttohakkeen painomittauskokeilu akselipainovaa'alla. Summary: Experiment on weight scaling of fuel chips with axle weight scales.* The Finnish Forest Research Institute. Bulletin 274. 32 pp.

- ,Verkasalo, E & Nurmi, J. (1990). Scaling of forest chips and chipwood. In: *Measurement and evaluation of wood fuel. Proceedings of the IEA/BE Task VI Activity 5 workshop in Jyväskylä, Finland, October 25-27, 1989.* J. Nurmi and K. Polet (eds) Metsäntutkimuslaitoksen tiedonantoja 346.

Voipio, R. 1990. The chemical composition of small tree biomass in Finland. In: *Measurement and evaluation of wood fuel. Proceedings of the IEA/BE Task VI Activity 5 workshop in Jyväskylä, Finland, October 25-27, 1989.* J. Nurmi and K. Polet (eds). Metsäntutkimuslaitoksen tiedonantoja 346.

II

ACTA FORESTALIA FENNICA 236

HEATING VALUES OF THE ABOVE GROUND BIOMASS OF SMALL-SIZED TREES

Pienikokoisten puiden maanpäällisen biomassan lämpöarvot

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Nurmi, J. 1993. Heating values of the above ground biomass of small-sized trees. Tiivistelmä: Pienikokoisten puiden maanpäällisen biomassan lämpöarvot. Acta Forestalia Fennica 236. 30 p.

The heating values of wood, inner and outer bark, and foliage components of seven small-size tree species were studied. Significant differences were found between species within each 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 increase with increasing latitude.

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

Tutkimuksella selvitettiin pieniläpimittaisen puuston puu-, kuori- ja neulasositteiden lämpöarvot. Erot puulajien välillä olivat merkitsevät kaikkissa kokopuun ositteissa. Puulajien kesken ei havaittu suuria eroja rungon, latvan ja kokopuun painotetuissa lämpöarvoissa.

Kivennäis- ja turvemaalla kasvaneiden puiden lämpöarvoissa havaittiin merkitseviä eroja vain ulkokuoressa. Maantieteellinen sijainti sensijaan vaikutti merkitsevästi useimpien kokopuun ositteiden lämpöarvoihin. Rungon, latvan ja kokopuun lämpöarvot olivat pohjoisessa etelän vastaavia arvoja korkeammat.

Tehollinen lämpöarvo selitti merkitsevästi joidenkin puunositteiden kemiallista rakennetta. Aineisto antaa olettaa, että lämpöarvon määritystä voitaisiin käyttää pikamenetelmänä havupuiden puuaineen selluloosapitoisuuden arvioinnissa.

Keywords: heating value, small-sized trees, whole-tree biomass, wood chemistry.
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Symbols

A = Scots pine, *Pinus sylvestris*
B = Norway spruce, *Picea abies*
ß = regression coefficient, slope
C = downy birch *Betula pubescens*
D = silver birch *Betula pendula*
E = grey alder *Alnus incana*
F = black alder *Alnus glutinosa*
G = trembling aspen *Populus tremula*
MC = moisture content on fresh mass 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^2 = coefficient of determination in multiple regression
r^2 = coefficient of determination in simple regression
$s_{y \cdot x}$ = standard error of estimate of a regression
t = t-value

1 Introduction

On a global scale fuelwood accounts for 5.4 % of the total energy consumption. The corresponding figure for developed countries is only 0.7 % but is as high as 57.9 % in Africa. The more astounding fact is that half of the world population is dependent on the availability of fuelwood and charcoal in their daily living. It has been predicted that 2770 million people will suffer from the fuelwood deficit by the year 2000 (Report of... 1981).

In Finland the share of woodbased fuels in the total energy consumption is (13 %) which is one of the highest in all industrialized countries (Energiakatsaus 1992). This figure includes black liquor and other industrial wastes. The annual production of stemwood is 79 Mm^3/a (Hakkila 1992). When crown, stumps and roots are included the annual biomass production amounts to 126 Mm^3/a. According to the same source 10 Mm^3/a of slash and small-sized trees would be technically harvestable for energy production. This would equal to 6 % of the nations primary energy production.

A literature search was carried out to find out how much is known of the heating values of the temperate region. Some two hundred references were found but a large percentage of them delt with tropical species or gave information on material where tree components or even species were were mixed. Only a small share dealt with the temperate species and an even smaller percentage with genera *Pinus*, *Picea*, *Betula*, *Alnus*, and *Populus*, those which would be directly beneficial to this study. The more important references are reviewed in this context.

The major elemental constituents of wood are carbon, hydrogen and oxygen. The first two are the major combustible elements, whereas oxygen is non-combustible but an essential structural component of cellulose, hemicellulose, lignin and extractives. It is the relative quantity of these chemical compounds that determine the heating value of wood (Wang et al. 1981). According to Kollmann (1951) broad-leaved species have an average carbon and hydrogen content of 49.0 % and 6.0 % respectively. For conifers the figures are 50.7 % and 6.2 %. When carbon and hydrogen combine with oxygen the following reactions take place and energy is released (Kollman 1951):

$C + {}^1/_2O_2 = CO + 10.215MJ$
$CO + {}^1/_2O_2 = CO_2 + 23.616MJ$
$C + O_2 = CO_2 + 33.829MJ$
$H_2 + {}^1/_2O_2 = H_2O + 141.974MJ$

Lignin and resins are rich in carbon and hydrogen and hence have a higher heating value than carbohydrates, such as cellulose and hemicellulose which have a lower concentration of these elements. It follows that those tree components which are high in lignin and extractives should also have high heating values. Since conifers usually have a higher content of lignin and extractives than broad-leaved species they also tend to have slightly higher heating values per unit weight (Howard 1973, Doat 1977 and White 1987). Both Howard and White show that the heating value of wood has a positive correlation with alcohol-benzene extractive content. White in his study also shows heating value to be highly correlated with the lignin content of extractive-free wood.

Thörnqvist (1985) made an ultimate analysis for *Pinus sylvestris*, *Picea abies* and *Betula* sp. which showed the carbon content to be the highest in stem bark and small branches, and the hydrogen content to be lowest in stem bark. The exception to the rule is birch bark, which had the highest concentration of hydrogen. Virtanen (1963) found inner and outer bark to contain 52.0 % and 65.8 % carbon, and 6.0 % and 8.4 % hydrogen respectively. The higher amounts of carbon and hydrogen were caused by the suberin and betulin which were found in high concentrations in birch outer bark (Thörnqvist 1985). Additional elemental information as well as heating values on Central European tree species have been compiled by Kollmann (1951) from a number of German and Swiss sources.

Kollmann (1951) reported effective heating values for cellulose (17.375–18.213 MJ/kg), lignin (25.539 MJ/kg) and resins (35.588–38.100 MJ/kg) and pointed out that genera rich in cellulose (e.g., *Salix* and *Populus*) had relatively low heating values.

Murphey & Masters (1978) isolated cellulose (17.030 MJ/kg), hemicellulose (16.670 MJ/kg) and lignin (21.180 MJ/kg) from red oak (*Quercus rubra*) to determine the heating values of cellulose, hemicellulose and lignin to compare

them to that of extractive free wood (19.950 MJ/kg). The proportionate sum of the three components was 17.900 MJ/kg which is only 89.72 % of the heating value of the extractive free wood. The authors suggest that this was caused by the chemical destruction of the bonds during extraction providing an opportunity for oxidation, thus lowering the energy potential of a unit mass of each separate chemical component. Results from a Nigerian study on *Gmelia arborea* by Fuwape (1989) are of different magnitude. The heating value of holocellulose, alpha-cellulose and lignin were 19.715, 19.704 and 25.383 MJ/kg respectively. Although Murphey and Masters were also quoted in the Nigerian study no explanation for the difference in heating values between these two studies was given.

In a another study by Sandala et al. (1981) the heating values of lignin and holocellulose from bark were found to be different for red oak (*Q. rubra*), white oak (*Q. alba*) and black cherry (*Prunus serotina*). Also the values for the holocellulose fraction from inner bark were found to be lower than from outer bark. It was suggested to be caused by an insufficient delignification process. Outer bark had higher lignin concentration — and higher heating value — and a failure in its removal would have made the heating value of the holocellulose from outer bark greater. They also found the heating value of outer bark to be higher than inner bark.

Olofsson (1975) has made one of the most concise reports on the heating values of North European tree species. He studied the stems, whole-trees and logging slash of *Pinus sylvestris*, *Picea abies* and *Betula* sp. He found that the differences in heating value per unit mass were very small between various parts of the tree at the same moisture content. It was also found that in all species the trees from cleaning cuttings had higher heating values than whole-trees from thinnings. This was caused by the higher percentage of needles and branches which had higher heating values than stems. Stems had the lowest values and showed very little difference between species. Logging residue consisted of branches and tops and its heating value lay between the values of stems and branches. Of the three species pine had the highest values for all the assortments except for bark. Olofsson's data has been adapted to the conditions prevailing in Southern Finland by Hakkila (1978). He has tabulated effective heating values for different timber assortments and species at different moisture contents. Energy contents are given both in terms of mass and volume. It is the most referenced publication in this field in Finland. On the other hand slightly lower values were recorded by Fredrikson & Rutegård (1985) for the mixed pine and spruce logging slash components. They reported that small branches with bark and wood had the highest heating value followed by needles, wood and bark.

Howard (1988) compared western hemlock, Douglas-fir and Western redcedar whole-tree and crown material from northwest Washington, USA. He found crown material to contain more energy per unit mass than whole-trees. Western redcedar crown material had a higher heating value than Douglas-fir or hemlock because of its high resin content. In his study Howard also quoted Arola (1977) and Corder (1973) who showed that the bark of Douglas-fir and hemlock had higher heating values than wood, whereas western redcedar wood contained more energy than bark does.

The physical and chemical characteristics of both pines and broad-leaved species growing in the southern United States are well recorded. These studies also provide some information on their fuel characteristics. Howard (1973) found that loblolly pine (*Pinus taeda*) heating values for earlywood, latewood and rootwood were not significantly different. On the contrary, samples from 1-inch top (wood and bark) had significantly lower values. The bark of spruce pine (*Pinus glabra*) decreased in heating value from the base with increasing axial height. It was suggested that this was caused by the increasing proportion of inner bark. The geographic region, growth rate and age of tree and bark density had no significant effect on bark values. Needles had higher values than wood or bark.

The heating values of stems and branches of 6-inch trees of 22 broad-leaved species growing on southern pine sites were studied by Manwiller (Koch 1985). The compiled data indicated that on average wood had a higher heating value than bark. This was also supported by Harris' studies of five southern broad-leaved species (1984 and 1985). He also found that the position in the tree has no effect on heating value. This, however, is not supported by Manwiller who indicated that stemwood has higher values than branch wood and branch bark has a higher heating value than stem bark. Wood from the stump-root system was found to have the highest value of all.

Neenan & Steinbeck (1979) studied 6 to 15 year-old sprouts of nine broad-leaved species from Georgia, USA. They found that differences

in the heating values of wood and bark are greater within species than the small but significant difference between species. On average bark had a lower heating value than wood, branches and twigs. Leaves had the highest values of all components. Stringer & Carpenter (1986) pointed out in their study of black locust (*Robinia pseudoacasia*) biomass fuel that it is the leaves that are of key importance in young (2–10 years) whole-tree stems.

More temperate North American pines, spruces and broadleaved species have been studied by Singh & Kostecky (1986) and Musselman & Hocker (1981). The species are not the same in these two studies but they mostly belong to the same genera. Conifers in general were found to have significantly higher heating values than broad-leaved species. Within conifer or broad-leaved species there was no difference between species. Musselman and Hocker did not find any difference among broad-leaved bole and branches either with or without bark. This is contrary to Singh's and Kostechky's results which showed highly significant differences between tree components for both conifer and broad-leaved species.

Geographic location, growth rate, tree age (Howard 1973) and stem diameter (Stringer & Carpenter 1986) are among the factors that heating value does not seem to correlate with. Doat (1977) studied 111 tropical species from Africa, Asia and South America and four temperate species. He found that there was no correlation between wood density and heating value expressed per unit mass.

Clonal research is very much involved with yield. Only minor interest is shown in the clonal effect on heating value. Neenan and Steinbeck also pointed out that differences in yield potential were likely to outweigh variation in heating value. Bowersox et al. (1979) found there to be no difference between *Populus* hybrids, whereas Sastry & Anderson (1980) found four clonal groups with significantly different heating values. The authors of the latter study suggest that the different conclusions drawn were possibly caused by differences in genetic material. Ager et al. (1986) studied 31 willow clones and found heating values to be significantly different.

1.1 The aim

The primary aims of this study are to determine the heating values of tree components of those species that are native to Finland, how heating values relate to wood chemistry, and whether species effect the heating value. On the basis of previous knowledge it is hypothesised that latitude does not affect the heating value, the heating values of all studied tree components are assumed not to be the same for all species. Also, due to the absence of information on the effect of soil type it is hypothesised not to have an effect on the heating value.

From paper making point of view the trees that have a high cellulose content are favourable. It has been shown that cellulose and extractive content do vary with the provenance (Hakkila 1969). One of the goals of the tree improvement has been to select trees with higher cellulose content. Even though Zobel et al. (1989) state that the high cellulose content as a genetic characteristic is poorly inherited it would useful to find a fast and easy method for the determination of cellulose content. Hence, an attempt is made to find out if heating value could be used to determine carbohydrate contents. As mentioned earlier the heating value of cellulose is lower than that of lignin and extractives. This means that high heating value of wood proper is an indication of low cellulose content.

The final aim is to give practical information on the energy content of stem, branch and whole-tree biomass of seven native tree species at different moisture contents for the evaluation and pricing of fuelwood.

The author acknowledges Heikki Leppänen for the selection of sample tree stands, Markku Parhiala for field work, Arto Ketola from University of Joensuu for statistical analysis, Maire Ala-Pöntiö and Keijo Polet for helping with the layout, and Raili Voipio for the chemical analysis. Thanks are due to Professors Pentti Hakkila and Olli Uusvaara from the Finnish Forest Research Institute, Professor Matti Kärkkäinen from Jaakko Pöyry Consulting and Dr. Paul Mitchell from Aberdeen University for guidence and for reading the manuscript, and Jyrki Hytönen for fruitful discussions. Finally, special thanks to Reetta Kolppanen for doing alone all the hard work in the laboratory.

2 Research material and methods

2.1 Selection and handling of sample trees

The study was carried out at the Kannus Research Station. It is located in Central Ostrobothnia where the share of young forests is greater than anywhere else in the country. Thus it was natural that the majority of the study material was gathered from the vicinity of the station. Eleven stands in five locations were chosen to represent the southern material. Also two stands from northern Finland were selected to study the possible geographical effects. All the stands except one were managed by the Finnish Forest Research Institute.

The sample trees were taken for heating value, chemical composition and proportion of wood, inner bark, outer bark and foliage as follows. In southern Finland two Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), downy birch (*Betula pubescens*) and black alder (*Alnus glutinosa*) sample trees were selected from both mineral and organic soils. Silver birch (*Betula pendula*), grey alder (*Alnus incana*) and trembling aspen (*Populus tremula*) trees were taken only from mineral soils as they are seldom found on organic soils. The northern specimens included pine, spruce and downy birch which were collected from mineral soils at their northern growing extent (Figure 1 and Table 1). 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 in any situation.

It is well documented that some wood characteristics such as the proportion of juvenile and heart wood, wood density, fibre characteristics and moisture content vary with the relative stem height. This is why the heating values were also

Table 1. Sample tree data.

Species	Tree number	Diameter, cm	Length, m	Soil type	Latitude	Municipality
P. sylvestris	1	9.6	11.7	mineral	south	Kannus
	2	10.7	10.0	mineral	south	Kannus
	3	10.2	6.6	organic	south	Kannus
	4	11.8	6.0	organic	south	Kannus
	5	11.8	7.0	mineral	north	Inari
	6	9.2	5.0	mineral	north	Inari
P. abies	1	8.7	8.3	mineral	south	Kannus
	2	9.8	8.0	mineral	south	Kannus
	3	8.3	7.4	organic	south	Kannus
	4	11.0	10.5	organic	south	Kannus
	5	9.4	13.2	mineral	north	Inari
	6	10.2	7.3	mineral	north	Inari
B. pubescens	1	9.0	10.0	mineral	south	Kälviä
	2	8.8	10.0	mineral	south	Kälviä
	3	8.1	10.8	organic	south	Kälviä
	4	8.6	10.6	organic	south	Kälviä
	5	9.6	7.6	mineral	north	Inari
	6	8.9	6.6	mineral	north	Inari
B. pendula	1	10.2	14.6	mineral	south	Kälviä
	2	10.0	13.1	mineral	south	Kälviä
A. incana	1	7.8	9.0	mineral	south	Kannus
	2	8.0	9.1	mineral	south	Kannus
A. glutinosa	1	11.2	12.0	mineral	south	Kälviä
	2	11.6	12.1	mineral	south	Kälviä
	3	10.2	11.0	organic	south	Himanka
	4	11.8	9.5	organic	south	Himanka
P. tremula	1	9.7	12.7	mineral	south	Kälviä
	2	10.0	14.8	mineral	south	Kälviä

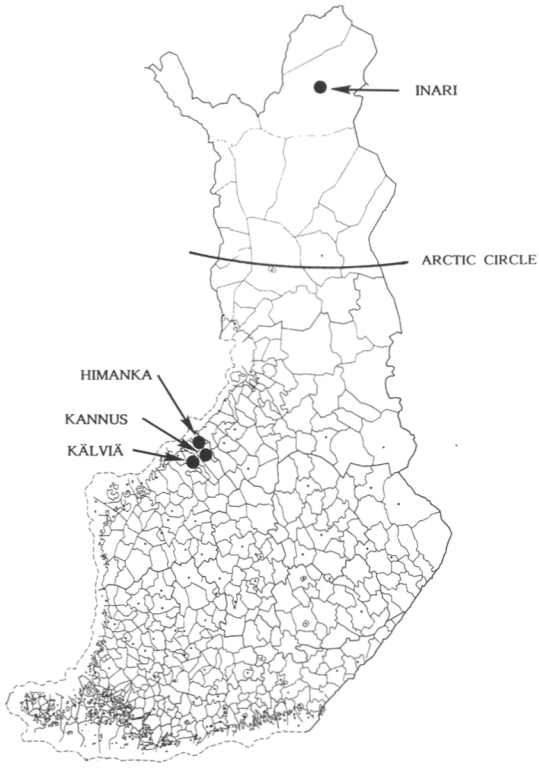


Figure 1. The locations of sampling sites.

studied in relation to the stem height. After delimbing the stem the sample discs were sawn off each stem for heating value and proportion of wood, inner bark and outer bark at relative heights of 10, 30, 50 and 80 %. In this manner more samples were taken at the lower part of the tree where more biomass is concentrated. One to two sample discs of 5–10 cm in length were taken from both sides of the relative height measurement. Wether the disc contained branch wood or not did not matter. Samples for the analysis of the chemical composition were collected in a similar manner. But, only at 20 and 80 % relative heights were used because resources for a more detailed study were not available.

All the branches in the crown were divided into branch sections over and under 5 mm in diameter. The latter one including foliage. Dead branches were excluded because most of the sample trees did not have them in sufficient quanties to supply a single sample. It should be noted that the largest branches on any species practically never exceeded 25 mm measured at the base of the branch. The samples were attained with a chainsaw without bar oil, bow saw and clippers. The entire branch was always included in the sample so that the portions under and over 5 mm were placed in different bags. The samples were placed in a freezer at the research station to prevent deterioration.

Each sample tree was weighed. The stems were weighed by first bucking them at the centre between sampling points i.e. at 20, 40 and 65 % of the relative height. This was done to determine the stem mass that each sample represented and to enable the calculation of weighted heating values. Then all the branches were cut and separated according to the diameter and weighed.

2.2 Preparation of samples

The laboratory handling of the samples included separation of wood, bark and leaf 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 point the information on the fuel and structural properties of the two bark components of tree species native to Finland is nil. 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. Bark was separated from the branches less than 5 mm in diameter 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. But, with grey alder and black alder and trembling aspen the separation was extremely tideous. After separation the samples were dried to constant weight at 102 °C and weighed to find out the proportion of each component at each sample point.

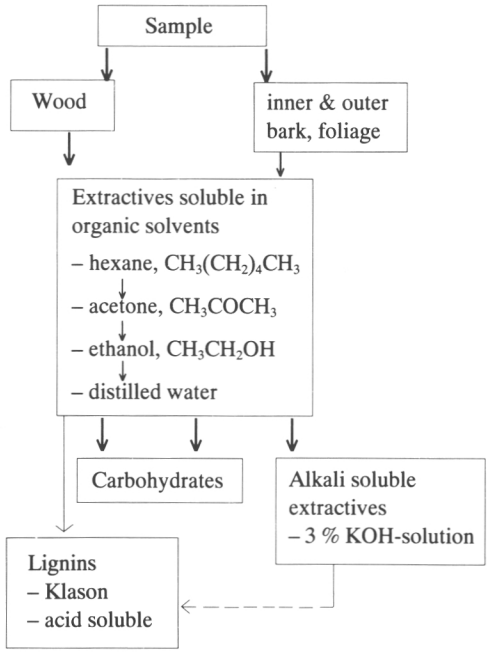
The milling of each entire component e.g. whole discs in the case of the wood component was done with a Retsch SM-1 cutting mill. Stainless steel bottom sieves with 0.5, 1 and 10 mm perforations were used. The sieve with the largest openings was used for primary reduction of the sample followed by milling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

nating 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 some of each sample was 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 sample size range for the used calorimeter was 0.6–1.2 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 in Finland keep 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 degrees. 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 4–8 %. The samples were periodically cross-checked by drying them in a conventional convection oven.

The extraction of chemical components 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 and branch in the following order:



A more detailed description of the procedures used is given by Voipio and Laakso (1992).

However, it is noted here that the extractive composition is given as a percentage of the dry weight of the sample whereas 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 are given in Appendix 1 by species for those trees listed in Table 1. These figures in Appendix 1 are the arithmetic means of all the sample trees and are separately calculated for the southern and northern parts of the country.

2.3 Determination of the calorimetric and effective heating values.

Three different measures of energy content can be used. 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 heat-

ing 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:

$$q_v(\text{net}) = q_v(\text{gross}) - 2.45 \times 0.09H_2 = q_v(\text{gross}) - 0.22H_2 \quad [1]$$

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 heat energy for evaporation comes from the burning fuel which lowers the amount of usable energy. This is called the effective heating value of moist biomass which is proportionate to the fuel moisture content in the following way:

$$q_v(\text{moist}) = q_v(\text{net}) - 2.45 \times \frac{MC}{100 - MC} \quad [2]$$

where

q_v(moist) = effective heating value of biomass with moisture (MJ/kg of dry mass)

MC = the moisture content on fresh mass 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 date editing; LB-80 analytical balance; and a vessel compartment.

The operation of the calorimeter is as follows. The prepared sample pellet is placed in a tared crucible on a sample pan of the balance. The weight is entered into the memory of the calorimeter. The crucible is placed in a sample holder of the bomb and the fuse is attached. The sample holder is placed in the combustion chamber and closed with the bomb cap. The bomb is pressurized to 3 MPa and placed in the vessel compartment where it is automatically surrounded with water of known volume. The sample is ignited and the water temperature is recorded by the calorimeter. Based on the temperature profile the calorimeter calculates the calorimetric heating value. The moisture content of the sample is entered and the calorimeter calculates the calorimetric value for an oven dry sample. A total of about 2000 determinations were made from the 28 sample trees. The calorimetric values were then converted to effective heating values on dry mass basis using formula 1.

To have constantly accurate readings the equipment has to be calibrated from time to time with a benzoic acid standard the calorimetric heating value of which is known to be 26.4534 ± 0.0037 MJ/kg (Bureau... 1988). When analyzing fossil fuels the nitrogen and sulphur content are often rather high and their effect on the calorimetric heating value has to be taken into consideration. Wood, however, contains so minute quantities of these elements that they can be neglected.

The number of sample trees per species was small (n= 2–6) from the statistical point of view. However, analysis of variance was carried out to see if the data supported the hypothesis on the effects of soil type and latitude on the heating values of whole-tree components. To make the data suitable for the analysis the weighted mean heating values of stemwood, inner bark and outer bark of each sample tree were calculated from those values determined at 10, 30, 50 and 80 % relative heights. When testing the effect of soil type only those species growing both on mineral and organic soils in Southern Finland i.e. Scots pine, Norway spruce, downy birch and black alder were included. Similarly, to test the effect of latitude only those species which grew on mineral soils both in northern and southern Finland, i.e. Scots pine, Norway spruce and downy birch were included, as the northern specimens came only from mineral soils.

The data was arranged in the same manner as above to test the effect of tree species on the heating values of tree components. The analysis of variance and Duncan's multiple range tests were used. Tests were done separately for data from southern and northern trees. In the case of southern sample trees the data from mineral and

organic soils was pooled.

The regressions were done separately for wood and the two bark components. For this purpose data from stem and branch components of both southern and northern sample trees were pooled. To overcome the low number of sample trees the species were pooled (n= 30–40). The same method has been applied earlier by Doat (1977) and White (1987). The dependent variables were the percentage of lignin, carbohydrates, extractives soluble in organic solvents and hot water, and alkali soluble extractives. The dependent variables were matched with 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 do not match for the lower 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 wood-bark and stem-crown proportions were quoted from larger biomass studies to calculate the weighted heating values of stem, crown and whole-tree biomass. The proportions and the references used are listed in appendix 3. When needed the diameter of 10 cm and/or the height of 10 meters were used on tables or substituted for equations. 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 proportions of inner and outer bark were determined in this study.

3 Results and discussion

3.1 Heating value of biomass components

Biofuels are made of three basic elements carbon, oxygen and hydrogen. They usually make up 95 % of the chemical composition. When carbon and hydrogen are combusted heat is generated. The higher their share of the combusted material the higher the heat output. Oxygen has a contrary effect and is already present in abundant quantities in the air. Wood and bark are composed of carbohydrates, lignin and a number of extractives, i.e. resins, terpenes and waxes. Carbohydrates are lower in carbon and hydrogen than the other chemical compounds making it lower in thermal energy. The q_v(net) is 17.4–18.2 MJ/kg for carbohydrates, 25.5 MJ/kg for lignin and 35.6–38.1 MJ/kg for resins (Kollmann 1951).

Wood, inner bark and outer bark have different carbohydrate, lignin and extractive contents due to the differences in their physiological origins. From this it follows that q_v(net) is likely to be different for different components. An attempt is made to search for the relations between heating values and the chemical compositions of different tree components.

3.1.1 Wood

The heating values of stemwood of all sample trees of all species are shown as a function of relative stem height in Figure 2. The tree numbers refer to Table 1. Each data point on the figure is a mean of three replicative determinations. The standard deviation of these three replications were small ranging from 0.001–0.085 MJ/kg. This is an indication of well homogenized samples. The corresponding ranges for inner and outer bark were 0.001–0.098 MJ/kg and 0.001–0.305 MJ/kg. In all species q_v(net) approaches homoscedasticity. This indicates a uniform chemical structure along the stem. Also, the deviation around the mean is of the same magnitude for all species.

The effect of soil and geographic factors were tested prior to testing the differences between species. The results on the analysis of variance support the hypothesis that soil type and latitude should not effect the q_v(net) of wood (Table 2.). The hypothesis was rejected only when branch wood was tested against latitude.

Next, the analysis of variance and Duncan's multiple range test were carried out to test if q_v(net) was effected by species. The test statistics support the hypothesis that heating value should not be the same for all species (Table 3). The heating values of coniferous wood were significantly different from each other as well as

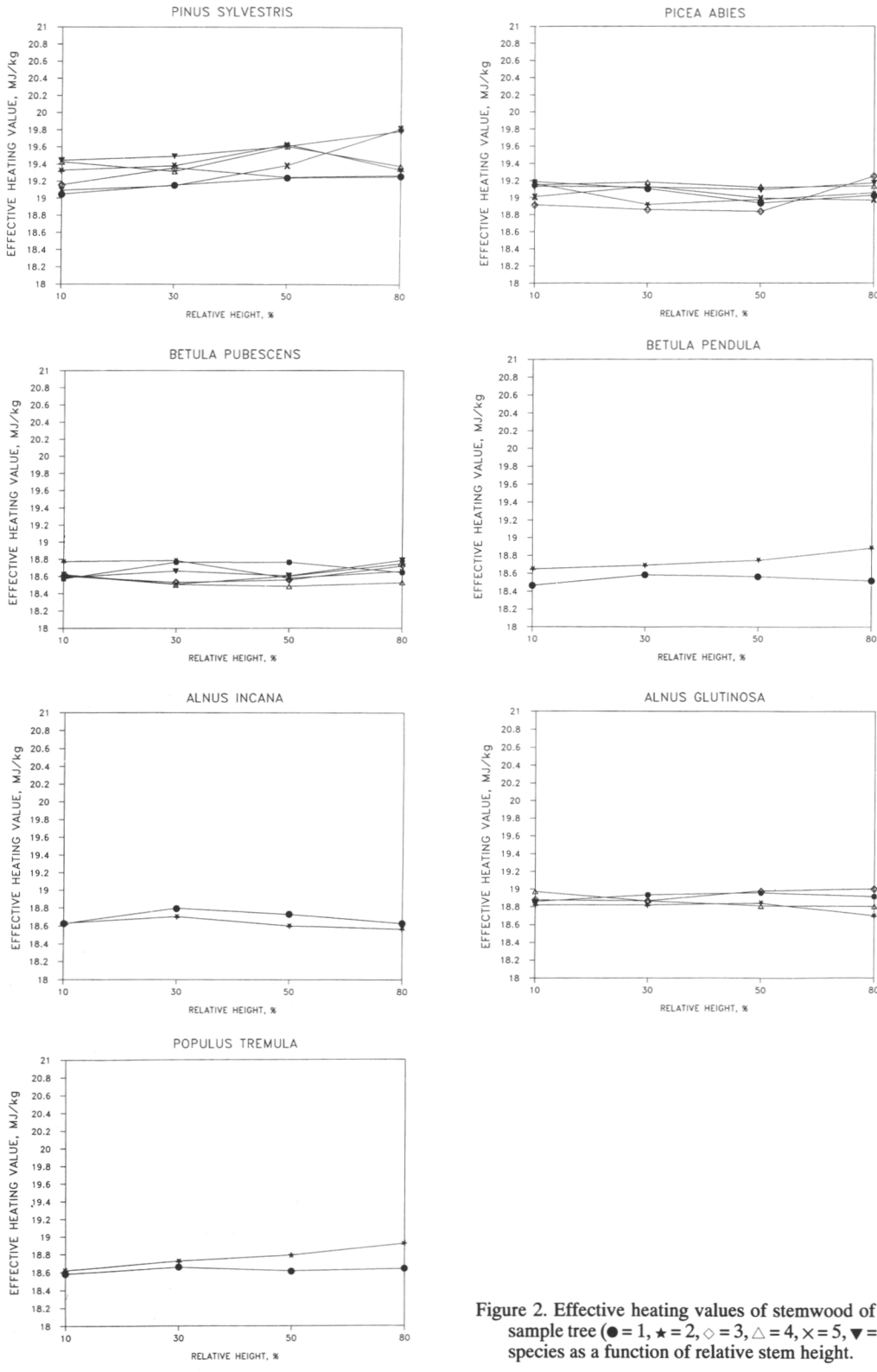


Figure 2. Effective heating values of stemwood of each sample tree (● = 1, ★ = 2, ◇ = 3, △ = 4, × = 5, ▼ =6) by species as a function of relative stem height.

from all the other species. This can also be seen in Figure 3 which shows the average heating values as a function of stem height. The higher percentage of lignin in coniferous wood explains to a large extent why it has a higher q_v(net) than the wood of broad-leaved species. The two birch species, grey alder and aspen were not shown to be different from each other. Black alder, however, is different from all the other species and has a q_v(net) between the coniferous and other broad-leaved species. Olofsson's (1975) q_v(net) is slightly lower for pine and higher for silver birch.

Branch wood has a higher q_v(net) than stem wood. It increases with decreasing branch diameter. The explanation for this is not so self evident. It is known that in coniferous branches compression wood is formed. It is characterized by increased lignin content. In thicker branches the stresses are greater and hence more compression wood is created, i.e. lignin content is increased (Appendix 1). This means that q_v(net) would decrease with decreasing diameter if we had extractive free wood. However, wood in the smallest branches is richer in extractives than other woody components. This explains why branches <5 mm have a higher q_v(net).

In broad-leaved species the reasoning is more self-evident. The lignin gradient is the opposite to coniferous wood as tension wood is characterized by lack of cell wall lignification. Hence, the extractive content and heating value increase with decreasing branch diameter but to a lesser degree than in conifers. The only exception to the rule is

Table 2. F-ratios for one way analysis of variance with repeated measures for soil type and latitude.

Whole-tree component		Factor: Soil type	Factor: Latitude
Wood	stem	0.02	0.78
	branches	0.00	10.79*
Inner bark	stem	0.60	74.00***
	branches	0.60	4.58
Outer bark	stem	8.08*	44.70***
	branches	30.74***	36.81***

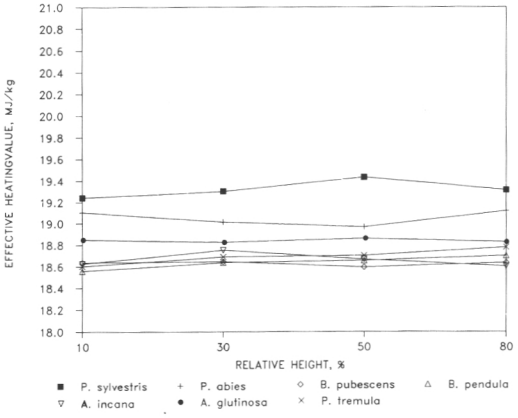


Figure 3. The average effective heating values of stemwood as a function of stem height for all species.

Table 3. The effective heating values (MJ/kg) and test statistics for wood components.

Whole-tree component	Latitude		Species: *Pinus sylvestris*	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus remula*	F-ratio
Stem	South		19.308**a**	19.048**b**	18.617**c**	18.611**c**	18.670**c**	18.883**d**	18.668**c**	27.59***
		s=	0.147	0.125	0.100	0.071	0.071	0.077	0.106	
Branches >5 mm	–"–		19.796**a**	19.627**a**	18.672**b**	18.726**b**	18.935**b**	18.725**b**	18.790**b**	18.53***
		s=	0.028	0.142	0.067	0.095	0.121	0.285	0.196	
Branches <5 mm	–"–		20.150**a**	19.793**b**	18.885**c**	18.732**c**	19.035**c**	18.875**c**	18.763**c**	41.01***
		s=	0.263	0.140	0.079	0.030	2.974	0.107	0.017	
Stem	North		19.392**a**	19.083**b**	18.606**c**					33.10***
		s=	0.249	0.071	0.083					
Branches >5 mm	–"–		20.051**a**	19.432**b**	19.011**b**					27.64*
		s=	0.178	0.072	0.046					
Branches <5 mm	–"–		20.839**a**	20.052**b**	19.172**c**					37.14**
		s=	0.188	3.268	0.097					

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

aspen. Its chemical composition should suggest a similar trend from large to small branches. On the contrary q_v(net) decreases with decreasing diameter. Why this should be could not be determined on the basis of the available data.

The northern branch specimens possess the same trend in q_v(net) as the southern ones (Table 3). But, the effect of branch diameter is somewhat more pronounced due to the relatively large amounts of extractives soluble to organic solvent. This makes the differences larger in the north. Subsequent reductions are noted in the carbohydrate contents.

The relationship of q_v(net) and chemical compounds can be seen in Figure 4. Here q_v(net) is used as an independent variable and lignin, carbohydrate and extractives as dependent variables. For all three regressions $\beta \neq 0$. Of the three regressions heating value and lignin give the best fitness. For lignin and extractives soluble in organic solvents and hot water the relationship with heating value is positive and for carbohydrates a negative one. The correlation of lignin and extractives with heating value has also been noted by Doat (1977) and White (1987) for tropical and North American species. However, their correlations were better than those given by this study. This could be caused by the fact that these authors used only samples from the stem whereas in this study branch material was also included.

One of the aims of this study was to see if the determination of heating value could be used as a mean to predict the cellulose content of wood. For this reason and inspite of the fact that the number of sample trees per species is small the test statistics concerning the relationship between carbohydrate content and heating value are also reported separately for each species in Table 4. As with the pooled data the relationship is negative for individual species. The test statistics suggest that this method might give a good predic-

Table 4. Carbohydrate content of wood (Y) as a function of effective heating value (X).

Species	Regression model	R2	P	n
P. sylvestris	23.054 – 0.053X	0.852	0.001	8
P. abies	22.198 – 0.041X	0.918	0.001	8
B. pubescens	19.759 – 0.014X	0.358	0.117	8
B. pendula	20.055 – 0.021X	0.953	0.024	4
A. incana	18.826 + 136X^{-6}	0.000	0.990	4
A. glutinosa	20.387 – 0.025X	0.504	0.290	4
P. tremula	19.119 – 0.006X	0.300	0.452	4

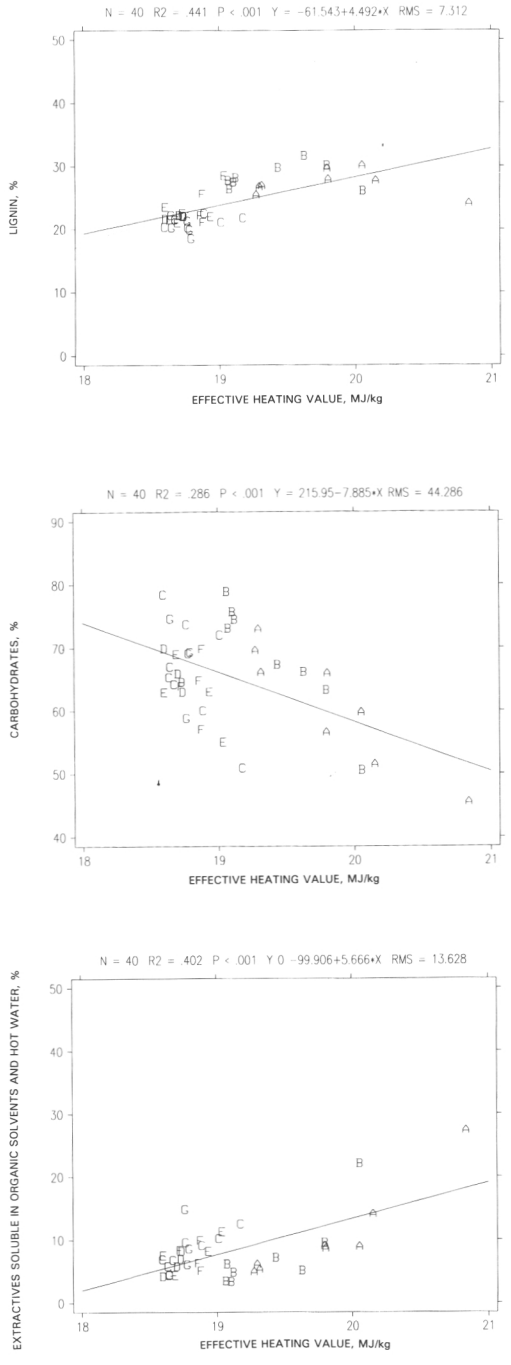


Figure 4. The chemical composition of wood as a function of effective heating value. Tree species A = *P. sylvestris*, B = *P. abies*, C = *B. pubescens*, D = *B. pendula*, E = *A. incana*, F = *A. glutinosa*, G = *P. tremula*.

Table 5. The effective heating values (MJ/kg) and test statistics for inner bark components.

Whole-tree component	Latitude		Species							F-ratio
			Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*	
Stem	South		18.758**a**	17.844**b**	18.965**a**	18.846**a**	20.14**c**	19.262**d**	18.049**b**	84.41***
		s=	0.249	0.282	1.457	0.101	0.149	0.107	0.248	
Branches >5 mm	-"-		19.441**a**	18.481**b**	18.985**a**	18.763**ab**	19.491**a**	19.413**a**	17.822**b**	4.61**
		s=	0.282	0.738	0.332	0.161	0.073	0.160	0.146	
Stem	North		19.089**a**	18.828**a**	19.181**a**					0.13
		s=	0.574	0.696	0.084					
Branches >5 mm	-"-		20.379**a**	18.258**b**	18.975**ab**					10.12*
		s=	0.525	0.304	0.036					

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

tion of cellulose content on coniferous wood. It might be useful to take a more detailed look to this approach to determine the cellulose content.

3.1.2 Bark

3.1.2.1 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. Together they make up 10–20 % of the dry stem mass and as much as 60 % of the small branches. On average two thirds of the bark component is inner bark (Appendix 3). In comparison with wood, bark is more complex in chemical structure. It contains compounds that are present in wood in only minor quanties or not at all. Such compounds include fenolic acids and polyestolids which are soluble only in alkaline solvents.

The heating values of individual stems by species are shown as a function of relative stem height in Figure 5. The first observation is that there is more variation in conifers than in broad-leaved species. Second, the trend in broad-leaved species is more linear than in conifers. This non-linearity is most evident in the northern specimens of pine and spruce. This is also supported by the results of analysis of variance which show latitude to have a significant effect on heating value (Table 2). Hence, Duncan's test was made separately for southern and northern trees. Data from mineral and organic soils was combined. The test statistics on southern trees supports the hypothesis which assumes that q_v(net) should not be the same in all species. This is illustrated in Figure 6 which shows the range of species to be about 2.4 MJ/kg at any given stem height. This is threefold compared to stemwood indicating a greater variation in chemical structure as well.

Conifers and broad-leaved species are distinctly different in terms of lignin and extractives soluble in organic solvents and hot water. Coniferous inner bark contains low quantities of lignin whereas in broad-leaved species the concentration is three to four fold. The extractive content is higher in conifers but by a smaller margin than lignin in broad-leaved species.

On the basis of information presented above one would expect to find little deviation in heating values within subdivisions. However, we can see from Table 5 that the q_v(net) of southern spruce is considerably lower than that of pine or spruce specimens from northern Finland. Its chemical structure suggests that the reason might be found in the concentration of extractives soluble in organic solvents and hot water. The higher concentration of these extractives in the north increases the heating value. As a result analysis of variance testing does not support the hypothesis of species being different in the north.

The q_v(net) of branch inner bark was determined only on those branches over 5 mm in diameter. There is less variability between species in branch than stem inner bark. One would expect this to reflect a greater degree of homogenity in chemical structure among species. However, no evidence for this was found.

Of the four regressions of Figure 7 carbohydrates and alkali soluble extractives do support

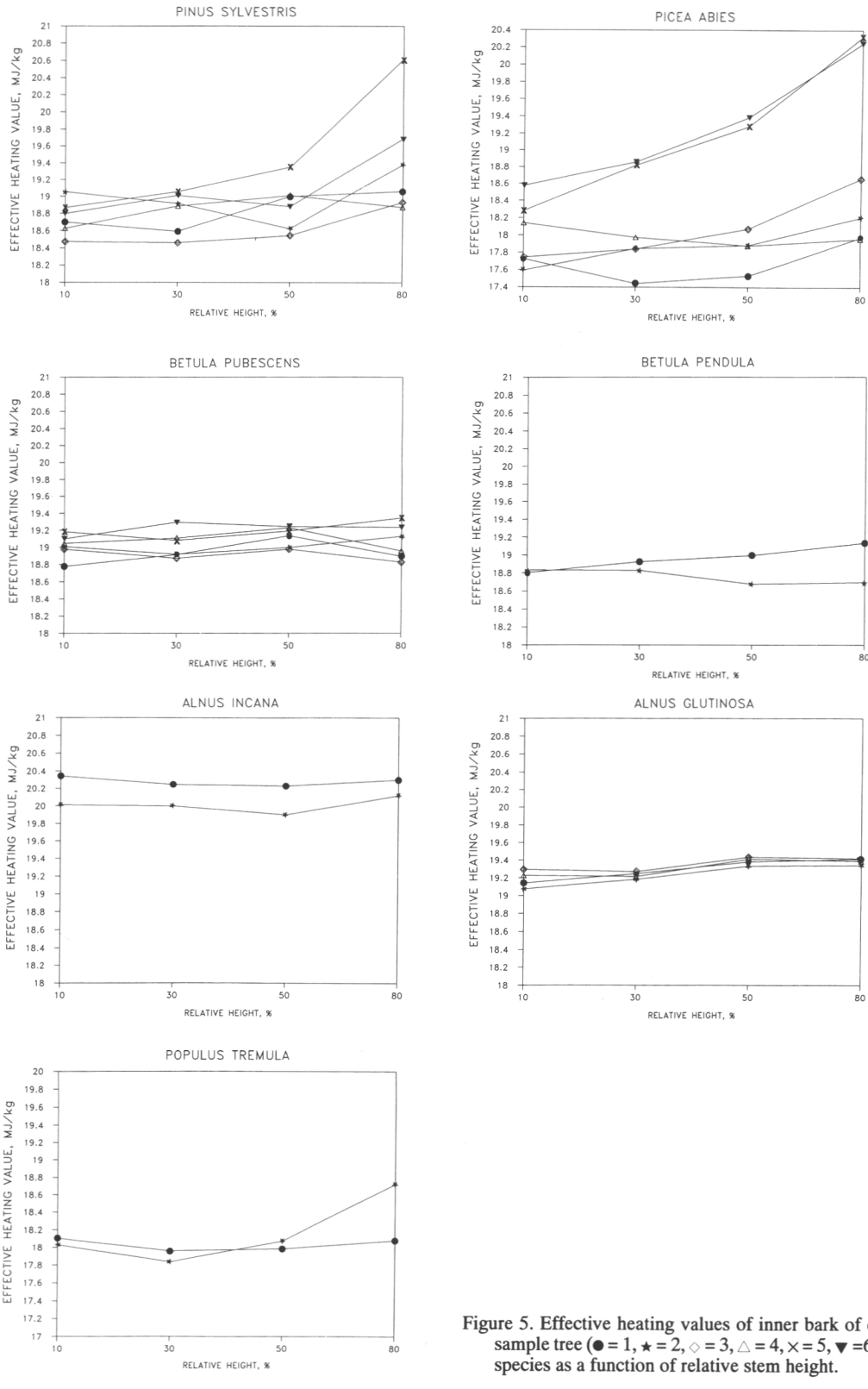


Figure 5. Effective heating values of inner bark of each sample tree (● = 1, ★ = 2, ◇ = 3, △ = 4, × = 5, ▼ =6) by species as a function of relative stem height.

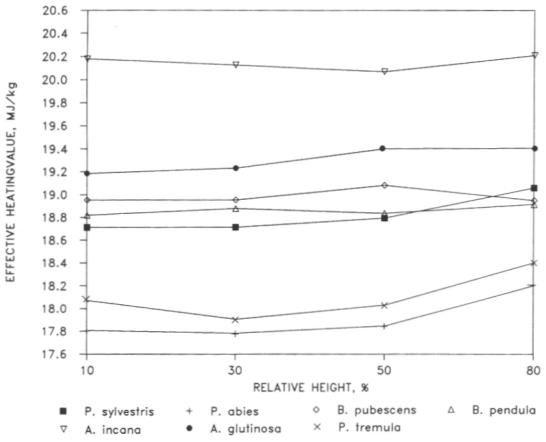


Figure 6. The average effective heating values of stem inner bark as a function of stem height for all species.

the H_0: ß≠0. Whereas with lignin and extractives soluble in organic solvents and hot water as dependent variables the model did not support the hypothesis.

3.1.2.2 Outer bark

Outer bark is a less important fuel than wood or inner bark when evaluated in terms of quantity. It makes up usually less than 5 % of the stem mass and no more than 10 % of the branch mass. It presents more variability between species in terms of chemical structure and heating value than the other two components. The within species variation of the heating values of outer bark is no greater than with wood but many species show a nonlinear trend along the stem. For the two birch species the trend is a decreasing and for black alder an increasing one. For other spe-

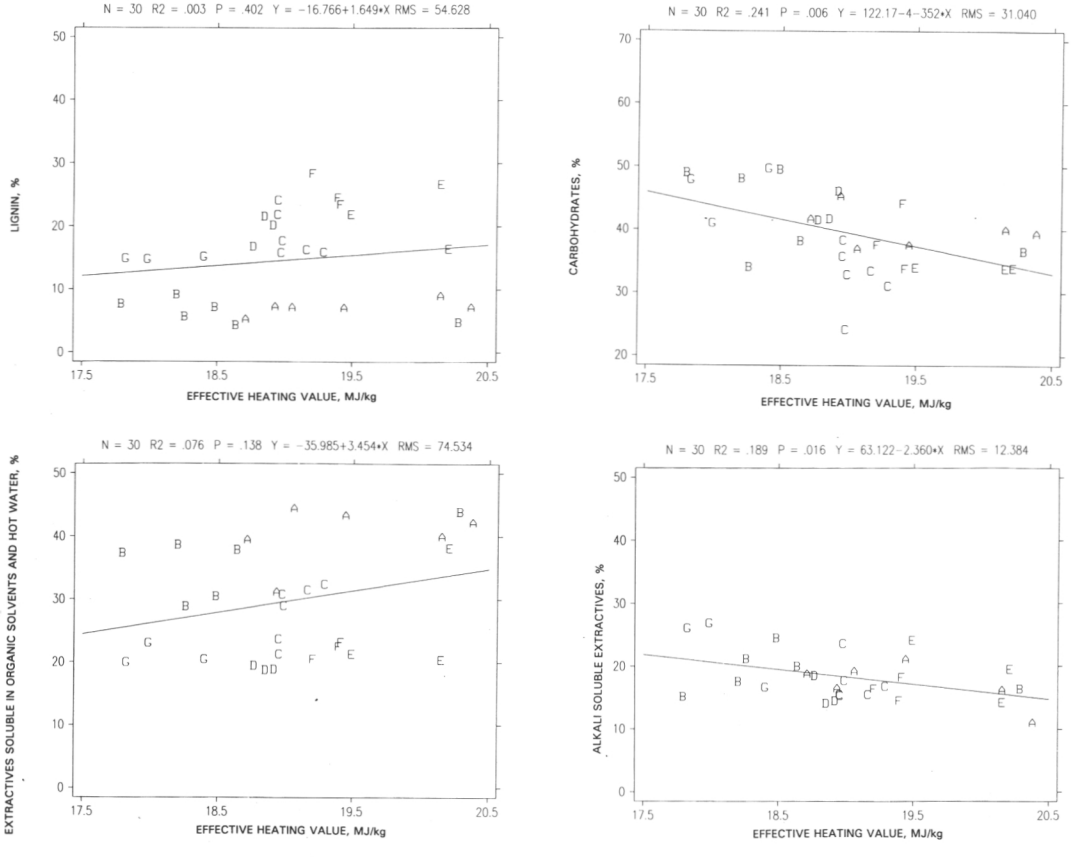


Figure 7. The chemical composition of inner bark as a function of effective heating value. Tree species A = *P. sylvestris*, B = *P. abies*, C = *B. pubescens*, D = *B. pendula*, E = *A. incana*, F = *A. glutinosa*, G = *P. tremula*.

cies the trend is intermediate (Figure 8).

The most noticeable change in q_v(net) is that of black alder. It increases 4 MJ/kg from the base to the top of the tree. This corresponds with an increase in content of alkali soluble extractives from 24.0 % at 20 % relative height to 32.2 % at 80 % height. The respective increase in organic and hot water extractives is from about 14.9 % to 22.2 %. At the same time lignin concentration drops from 32.0 % to 19.6 % (Appendix 1). As the extractives are higher in heating value than lignin the heating value of outer bark increases as the ratio between the two compounds changes in favour of extractives toward the top of the tree.

The outer barks of the two birch species have the highest q_v(net) of all species. This is caused by the high extractive concentration, mainly betulin (soluble in organic solvents) 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.

The results show that the q_v(net) of *Betula* sp. decrease with stem height which could be seen as a change in betulin and suberin content had they been analyzed separately from other extractives. Unfortunately this was not done. As a result the data on extractive content does not support the trends seen on Figure 8. However, it is known that outer bark derives its colour from betulin. A decrease in betulin can be seen as a colour change from white at the base (high q_v(net)) to black at the top (low q_v(net)).

The heating value of grey alder seems to peak at the centre part of the stem but there is no data on chemical structure available for that section. One would expect a higher heating value for the top part of the stem because of the increased extractive contents. Correspondingly lignin content drops from 26.0 % to 11.7 % and carbohydrate content from 20 % to 14.2 %. It is most likely that these trends counter balance each other as corresponding changes are not seen in the heating values.

A lesser trend is seen in pine where the heating value increases from the centre of the stem to the top. This reflects the increase in extractives and the decrease in lignin content. Aspen has a similar weak trend which is supported by a slight increase in alkali soluble extractives and a decrease in both lignin and carbohydrates.

It was hypothesised that soil type and latitude do not effect q_v(net). Table 2 shows that data do not support it. On average q_v(net) of pine, spruce and downy birch is lower when trees are growing on organic soils. The fact that latitude is shown to be a significant factor is caused by downy birch as its q_v(net) is almost 3 MJ/kg lower in the northern trees. Unfortunately the data on chemical components does not explain this difference.

Figure 9 shows the average q_v(net) as a function of stem height. The range of heating values is over 12 MJ/kg. This is much higher than with wood and inner bark components. The test statistics of analysis of variance shows species to be a highly significant factor (Table 6).

The heating values of the outer bark of branches over 5 mm in diameter are seen in Table 6. The species are in the same order of magnitude as the stem outer bark. The reasons for the order are the same as with stem outer bark, i.e. high energy alkali soluble, organic and hot water extractives as well as lignin in broad-leaved species overruling low energy carbohydrates. The ratio is the opposite in conifers causing them to

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

Whole-tree component	Latitude		Species							F-ratio
			Pinus sylvestris	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*	
Stem	South		20.309**a**	20.542**a**	31.433**b**	32.045**b**	28.900**d**	23.286**e**	21.202**c**	400.16***
		s=	0.624	0.448	3.035	3.972	3.944	2.537	0.697	
Branches >5 mm	-"-		21.166**a**	20.691**a**	27.580**bc**	28.548**c**	26.758**bd**	25.901**d**	21.886**a**	54.28***
		s=	0.295	0.107	1.025	2.810	0.009	0.615	0.319	
Stem	North		20.933**a**	20.771**a**	28.904**b**					2890.07***
		s=	0.434	0.207	1.024					
Branches >5 mm	-"-		21.947**a**	20.801**b**	26.479**c**					205.72***
		s=	0.359	0.049	0.119					

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

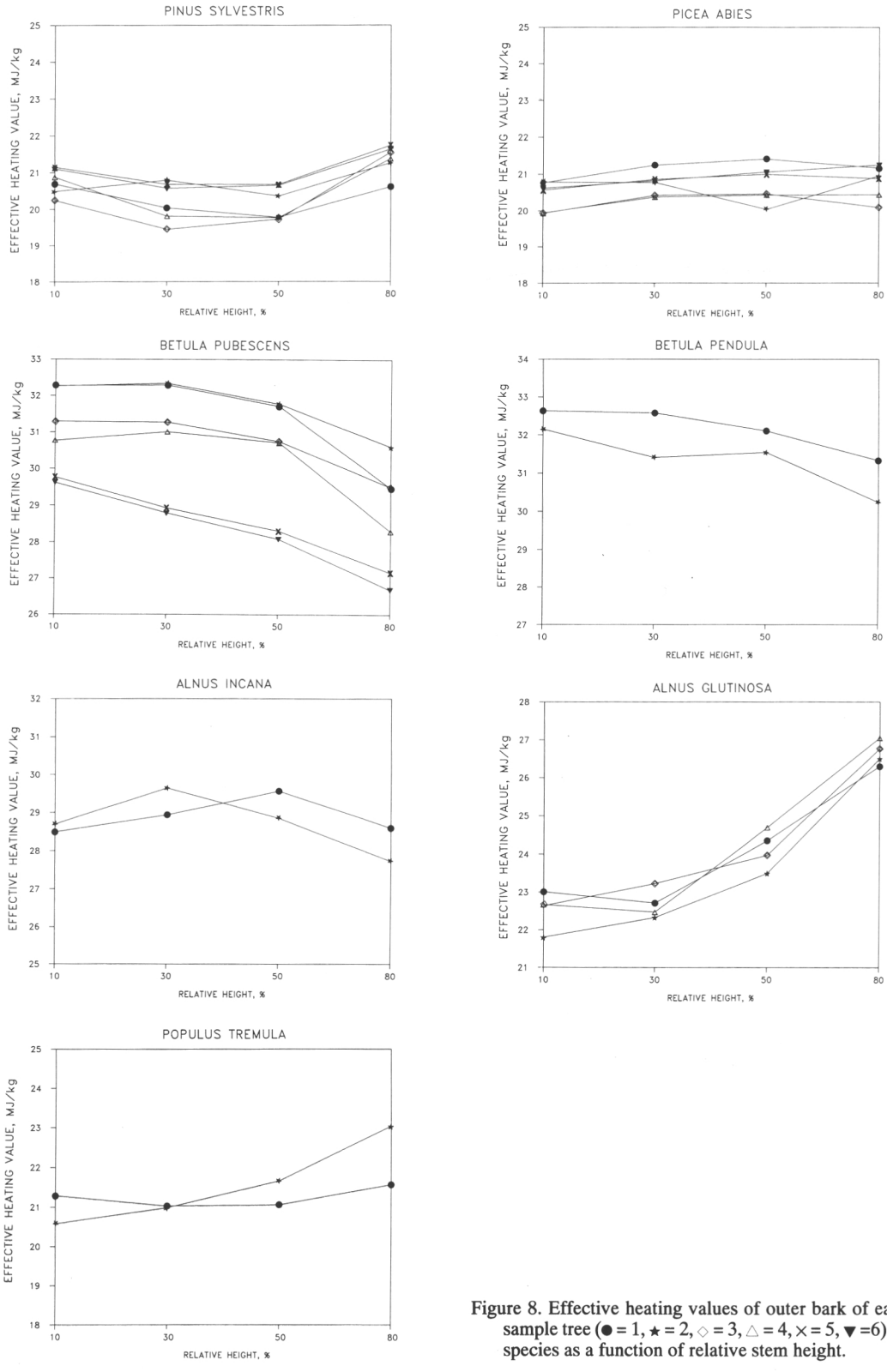


Figure 8. Effective heating values of outer bark of each sample tree (● = 1, ★ = 2, ◇ = 3, △ = 4, × = 5, ▼ =6) by species as a function of relative stem height.

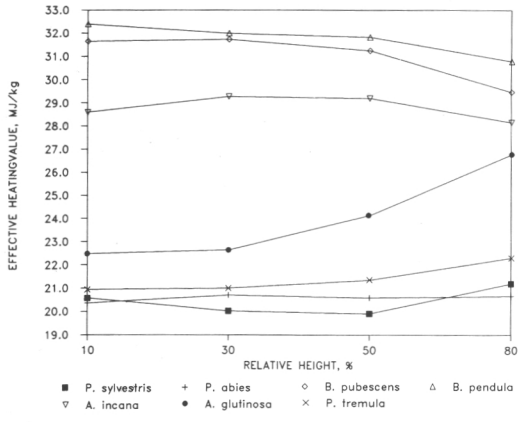


Figure 9. The average effective heating values of stem outer bark as a function of stem height for all species.

have the lowest heating values.

When the heating value of outer bark on stem and branches is compared the following observations are made. For pine and spruce outer bark has higher values in branches than in stems. For broad-leaved species the case is the opposite with the exception of black alder and aspen. The most likely explanation for conifers is the slightly higher extractive content in branch outer bark. It is more difficult to find an explanation for the behaviour in broad-leaved species. However, with birches, grey alder and aspen the amount of extractives soluble in organic solvents and hot water are lower in branches than in stems.

In Figure 10 the chemical components are regressed with heating value. All the regressions support the H_0: $\beta \neq 0$. For lignin and carbohydrates the slope is negative and positive for both categories of extractives.

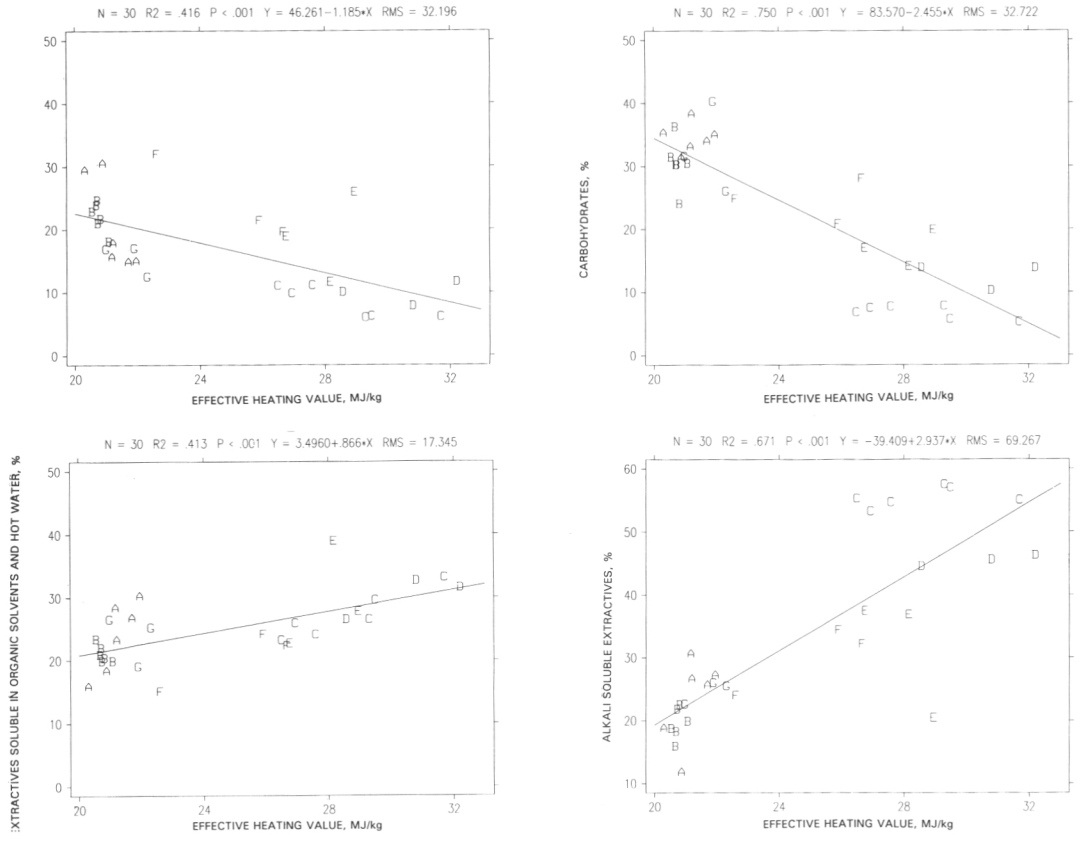


Figure 10. The chemical composition of outer bark as a function of effective heating value. Tree species A = *P. sylvestris*, B = *P. abies*, C = *B.pubescens*, D = *B. pendula*, E = *A. incana*, F = *A. glutinosa*, G = *P. tremula*.

Table 7. The effective heating values (MJ/kg) and test statistics for bark on branches less than 5 mm in diameter.

Latitude		Species *Pinus sylvestris*	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*	F-ratio
South		21.258**ab**	20.273**ac**	21.945**d**	20.815**c**	21.534**b**	21.024**ac**	17.983**e**	39.26***
	s=	0.156	0.287	1.515	0.152	0.255	0.660	0.038	
North		22.082**a**	20.593**a**	20.815**a**	..	..	..	..	4.80
	s=	0.602	0.252	0.068					

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

Table 8. The effective heating values (MJ/kg) and test statistics for foliage.

Latitude		Species *Pinus sylvestris*	*Picea abies*	*Betula pubescens*	*Betula pendula*	*Alnus incana*	*Alnus glutinosa*	*Populus tremula*	F-ratio
South		20.950**a**	19.400**cd**	19.550**cd**	19.700**cd**	20.600**ab**	20.100**bc**	19.200**d**	10.00**
	s=	0.127	0.195	0.265	0.088	0.401	0.048	0.322	
North		20.800**a**	19.300**b**	19.350**b**	..	..	..	..	96.78**
	s=	0.118	0.062	0.026					

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

3.1.2.3 Bark on small branches

Half of the dry mass of branches <5 mm in diameter is bark. The two bark components were not separated before the calorimetric and chemical analysis because of the small branch diameter. The heating values and test statistics are seen on Table 7. Species are shown to have a have a significant effect on the heating value which is supportive of the hypothesis.

Heating values are intermediate to those of inner and outer bark of branches over >5 mm in diameter. This is understandable as the bark component is a combination of these two barks and is also supported by the analysis on chemical composition (Appendix 1). This applies to all species except pine. Its q_v(net) is higher than the value of either inner or outer bark values of the larger branches. The only indication why this should be is that carbohydrate content is lower in the <5 mm than in either of the two bark components of >5 mm branches. This should give more room to the high energy compounds.

3.1.3 Foliage

The chemical composition of foliage is rather different in coniferous and broad-leaved trees. The results of the analysis of variance of heating values in Table 8 also suggest differences in chemical composition. Conifers are high in carbohydrates and extractives soluble in organic solvents and hot water. Broad-leaved species on the other hand are higher in lignin and alkali soluble extractives. This would indicate rather similar heating values within both subdivisions. This, however, is not the case. On the contrary the heating values of conifers and broadleaved species do overlap. Why for example pine and spruce have heating values of such a different magnitude can not be concluded on the basis of the chemical data. Olofsson reports a slightly smaller difference as his spruce had a higher q_v(net) than in this study.

The broad-leaved genera are in their own groups in terms of chemical composition. Birches have a higher content of extractives soluble in organic solvents and low lignin content. Alders, which are higher in heating value are lower in these extractives and higher in lignin. It seems that whatever the fraction composition of these extractives is they are lower in heating value than lignin. The genera seem to have similar compositions when concerning alcali soluble extractives and carbohydrates .

Aspen is lowest of all species in heating value. Lignin and carbohydrate content are the same as in other broad-leaved species. However, aspen has the lowest content of extractives soluble in

Table 9. The effective heating values (MJ/kg) of oven dry stem components.

Species	Latitude	Wood	Bark			Whole stem
			Inner	Outer	All bark	
P. sylvestris	south	19.308	18.758	20.309	19.529	19.333
	north	19.392	19.089	20.933	19.981	19.479
P. abies	south	19.048	17.844	20.542	18.803	19.022
	north	19.083	18.828	20.771	19.621	19.161
B. pubescens	south	18.617	18.965	31.433	22.745	19.187
	north	18.606	19.181	28.904	22.545	19.528
B. pendula	south	18.611	18.846	32.045	22.525	19.151
A. incana	south	18.670	20.141	28.900	21.566	19.000
A. glutinosa	south	18.883	19.262	23.286	21.438	19.305
P. tremula	south	18.668	18.049	21.202	18.574	18.652

organic solvents and highest alcali soluble extractive content. The composition of these extractive fractions are species specific but it seems that it is the extractives soluble in organic solvents that increase the heating value among broad-leaved species. The reason why this does not apply to spruce has to lie in the differences in the extractive composition.

3.2 The weighted heating values of stem, branch and whole-tree biomass

Stem biomass is composed of wood, inner bark and outer bark. The proportions of these 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.

Figure 11 shows that in all species and at any given stem height the heating value of outer bark is higher than the heating value of wood or inner bark. Furthermore, the heating value of combined inner and outer bark is higher than that of wood for all species except for aspen and southern sample trees of spruce (Table 9).

Musselman & Hocker (1981) and Singh & Kostecky (1986) found that North American species in genera *Pinus*, *Picea*, *Betula* and *Populus* had higher heating values in bark as well. Olofsson (1975) reports q_v(net) of pine, birch and spruce bark to be higher than of wood as well. His value for spruce bark is higher than what was determined in this study for the specimens either from southern or northern Finland. On the other hand, the heating values of pine, downy and silver birch bark of this study are higher than those given by Olofsson.

The average q_v(net) of stem biomass is the weighted mean of wood and bark values (Table 9). In spite of the large differences in proportions and q_v(net) of tree components the differences between species actually turn out to be very small on whole stem basis. This has also been earlier shown by Olofsson (1975). Although outer bark is higher in heating value than the other two components it makes a lesser contribution to the average heating value of stem biomass than the other two components. This is caused by the small quantity. For example the high qv(net) of the birch bark has relatively little effect on the weighted q_v(net) of stem biomass. This is also supported by Sandala et al. (1981) who report on the heating values of three broad-leaved species from the north eastern United States. It should also be noted that the stems of the northern specimens have a higher heating value than the southern ones. On a whole this is caused by the combined effect of higher component q_v(net) values and higher bark percentage (Appendix. 3). This holds also for the crown material.

The crown is formed by branches including wood, bark and foliage. Biomass studies referenced in appendix 3 show that bark accounts roughly for one third of the branch mass without foliage. This enhances the heating value of crown biomass as the heating value of bark is higher than of wood. A considerable amount of the live crown is made up by foliage. This is especially true in conifer stands (Hakkila 1991). Although the heating values of foliage are reported in Table 10 the values for crown do not include foliage. This is because most often whole-tree chips do contain little foliage as they are lost during

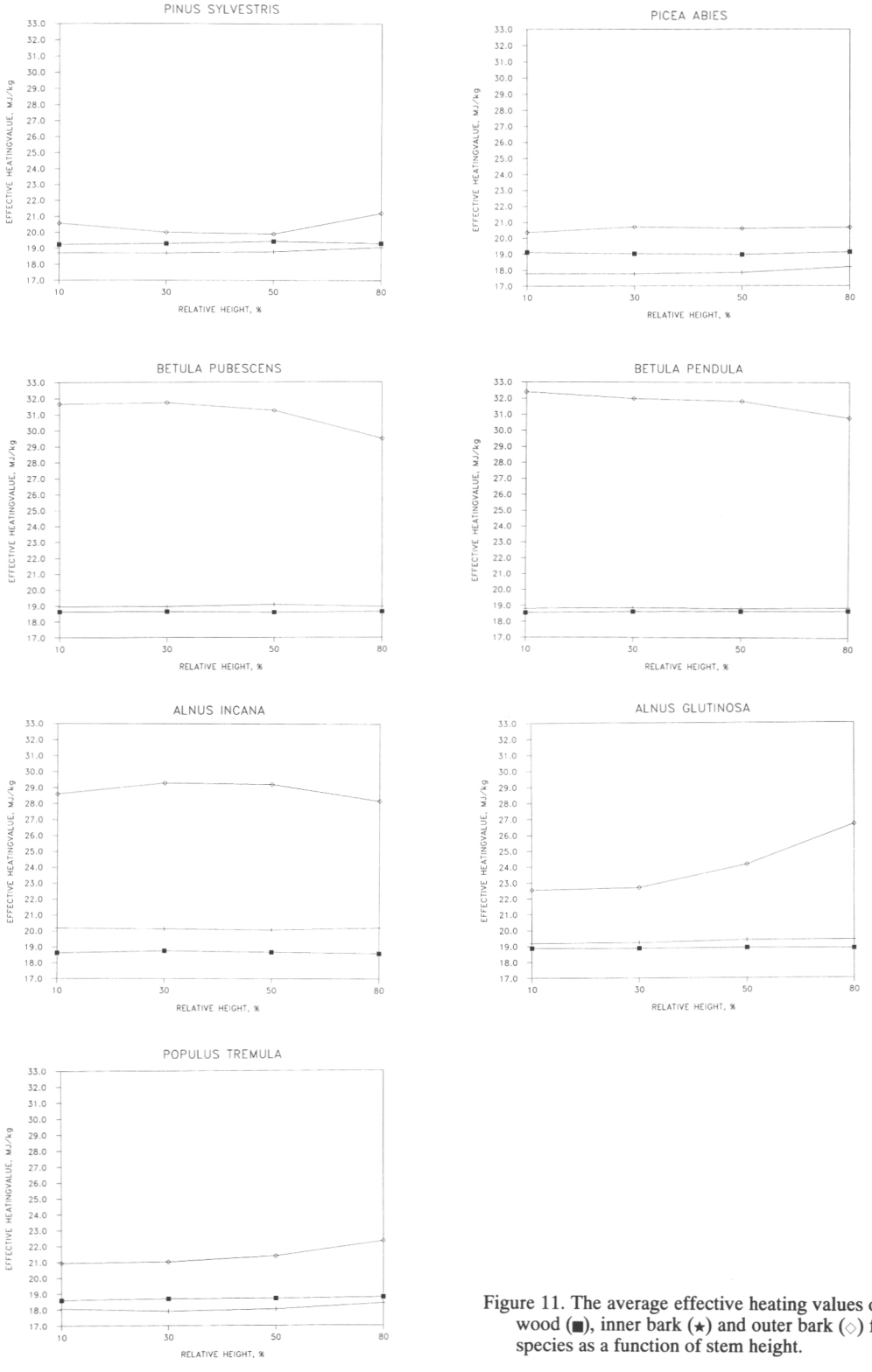


Figure 11. The average effective heating values of stem-wood (■), inner bark (★) and outer bark (◇) for each species as a function of stem height.

Table 10. The effective heationg values (MJ/kg) of wood, bark and foliage components of branches over and under 5 mm.

Species	Latitude	Wood			Bark				Foliage	Crown without foliage
		>5 mm	<5 mm	All branch	>5 mm Inner	>5 mm Outer	<5 mm	All bark		
P. sylvestris	south	19.796	20.150	19.970	19.441	21.166	21.258	20.668	20.996	20.234
	north	20.051	20.839	20.473	20.379	21.947	22.082	21.629	20.777	20.873
P. abies	south	19.627	19.793	19.734	18.481	20.691	20.273	19.830	19.224	19.772
	north	19.432	20.052	19.900	18.258	20.801	20.593	20.390	19.298	20.108
B. pubescens	south	18.672	18.885	18.734	18.985	27.580	21.945	22.294	19.766	19.944
	north	19.011	19.172	19.076	18.975	26.479	20.815	21.447	19.372	20.181
B. pendula	south	18.726	18.732	18.728	18.763	28.548	20.235	21.083	19.723	19.526
A. incana	south	18.935	19.035	18.962	19.491	26.758	21.534	21.676	20.571	20.029
A. glutinosa	south	18.725	18.875	18.769	19.413	25.901	21.024	20.383	20.080	19.365
P. tremula	south	18.790	18.763	18.786	17.822	21.886	17.983	18.280	19.180	18.613

seasoning and comminution. In addition the heating value of foliage is not very different from the rest of the crown. Its inclusion would make only a very small difference to the heating value.

Pine has the highest crown heating value. Next come alders, birches and spruce. Aspen has the lowest heating value which is about the same as for the stem (Table 10). Olofsson (1975) gives similar values for pine and spruce but, his value (20.28 MJ/kg) for birch branches is much higher than 19.526 MJ/kg determined in this study for silver birch.

Crown biomass is higher in heating value than stem biomass. This is a common phenomema in many genera (Hughes 1971). From the fuelwood point of view this is a positive aspect because branches are a low quality, low value and most often a totally unacceptable raw material for most sectors of the woodworking industry. When trees are harvested with branches intact not only will the amount of harvested biomass increase but the energy recovery will also increase per unit weight.

A whole-tree includes all the components of a tree above the stump cross-section (Hakkila 1989). Its heating value is somewhat dependent on the stem and crown biomass proportions. This in its turn is dependent on the stand history. The effect of latitude is also seen in the whole-tree heating values. This is natural as it has been shown to have an effect on the heating value of the components. On a whole-tree level this difference is to the advantage of the northern speciment.

The differences between species, however, are small at the whole-tree level. Pine has the highest and aspen the lowest q_v(net) by a margin of only 5 %. These differences may be so insignificant that they may not effect the pricing of fuelwood when purchased in the form of whole-trees. Even the errors of similar margin may take place in timber scaling, not to speak of the moisture variation within a fuelwood pile which has a much greater effect on the fuelwood value. In addition, it is interesting to see that inspite of the differences in materials and methods between this and Olofsson's study the heating values for pine (19.453 vs.19.59 MJ/kg), spruce (19.146 vs. 19.19 MJ/kg) and silver birch (19.049 vs. 19.04 MJ/kg) are almost the same. For practical purposes, tables of effective heating values of moist wood derived from Table 11 are given separately for southern and northern Finland for fixed moisture contents in Table 12. Those interested in other moisture contents should refer to the Formula [2] in Chapter 23.

Table 11. The effective heating values (MJ/kg) of stem, crown without foliage and whole tree biomass.

Species	Latitude	Stem	Crown	Whole-tree
P. sylvestris	south	19.333	20.234	19.525
	north	19.479	20.873	19.763
P. abies	south	19.022	19.772	19.286
	north	19.161	20.108	19.478
B. pubescens	south	19.187	19.944	19.301
	north	19.528	20.181	19.651
B. pendula	south	19.151	19.526	19.208
A. incana	south	19.000	20.029	19.182
A. glutinosa	south	19.305	19.365	19.314
P. tremula	south	18.652	18.613	18.647

Table 12. The effective heating values (MJ/kg) of wood fuel at different moisture contents in southern and northern Finland.

Tree part	Species	Moisture content, %						
		0	10	20	30	40	50	60
				SOUTHERN FINLAND				
Stem	*P. sylvestris*	19.333	19.061	18.721	18.283	17.700	16.883	15.658
	P. abies	19.022	18.750	18.410	17.972	17.389	16.572	15.347
	B. pubescens	19.187	18.915	18.575	18.137	17.554	16.737	15.512
	B. pendula	19.151	18.879	18.539	18.101	17.518	16.701	15.476
	A. incana	19.000	18.728	18.388	17.950	17.367	16.550	15.325
	A. glutinosa	19.305	19.033	18.693	18.255	17.672	16.855	15.630
	P. tremula	18.652	18.380	18.040	17.602	17.019	16.202	14.977
Crown without foliage	*P. sylvestris*	20.234	19.962	19.622	19.184	18.601	17.784	16.559
	P. abies	19.772	19.500	19.160	18.722	18.139	17.322	16.097
	B. pubescens	19.944	19.672	19.332	18.894	18.311	17.494	16.269
	B. pendula	19.526	19.254	18.914	18.476	17.893	17.076	15.851
	A. incana	20.029	19.757	19.417	18.979	18.396	17.579	16.354
	A. glutinosa	19.365	19.093	18.753	18.315	17.732	16.915	15.690
	P. tremula	18.613	18.341	18.001	17.563	16.980	16.163	14.938
Whole-tree	*P. sylvestris*	19.525	19.253	18.913	18.475	17.892	17.075	15.850
	P. abies	19.286	19.014	18.674	18.236	17.653	16.836	15.611
	B. pubescens	19.301	19.029	18.689	18.251	17.668	16.851	15.626
	B. pendula	19.208	18.936	18.596	18.158	17.575	16.758	15.533
	A. incana	19.182	18.910	18.570	18.132	17.549	16.732	15.507
	A. glutinosa	19.314	19.042	18.702	18.264	17.681	16.864	15.639
	P. tremula	18.647	18.375	18.035	17.597	17.014	16.197	14.972
				NORTHERN FINLAND				
Stem	*P. sylvestris*	19.479	19.207	18.867	18.429	17.846	17.029	15.804
	P. abies	19.161	18.889	18.549	18.111	17.528	16.711	15.486
	B. pubescens	19.528	19.256	18.916	18.478	17.895	17.078	15.853
Crown without foliage	*P. sylvestris*	20.873	20.601	20.261	19.823	18.475	17.658	16.433
	P. abies	20.108	19.836	19.496	19.058	18.548	17.731	16.506
	B. pubescens	20.181	19.909	19.569	19.131	18.548	17.731	16.506
Whole-tree	*P. sylvestris*	19.763	19.491	19.151	18.713	18.130	17.313	16.088
	P. abies	19.478	19.206	18.866	18.428	17.845	17.028	15.803
	B. pubescens	19.651	19.379	19.039	18.601	18.018	17.201	15.976

4 Conclusions

Species were found to have a significant effect on the heating value of wood, bark and foliage components. The heating value of wood is highest in the conifers. But, the heating value of the combined inner and outer bark is higher in the broad-leaved species. On the whole the combined bark has a higher heating value than wood. The heating value of crown material is higher than that of the stem. This means that those parts of the tree that are not wanted by the forest industry as a raw material, i.e. bark, crown and small whole-trees in general are actually the fuel-wood components of a tree with the highest heating values per unit weight. It should be noted, however, that unless some form of integrated harvesting is used the procurement of small trees and crown material may be to costly to carry out. Also, the conventional boilers with grates do require larger facilities when this low density fuel is burned. Fortunately floating bed instalations are invading the markets. They are more expensive to instal, but have the advantage of being much less sensitive to the fuel composition and quality than the conventional boilers. Furthermore, it is important to recognize that the heating value of the stem or whole-tree biomass

is very little affected by species. From the user point of view the moisture content and the quantity of fuelwood are much more important factors than the species.

It was hypothesised that there is a relationship between chemical composition heating value. The test statistics from the regression analysis do support the hypothesis of some chemical components being dependent on the effective heating value. The heating value of inner bark does not form good regressions with any of the dependent variables because of the variation in data. The best models for outer bark do result when carbohydrates and alkali soluble extractives are used as dependent variables. With wood the dependence of lignin and extractives soluble in organic solvents and hot water on heating value are stronger than that of carbohydrates on heating value. However, it seems that when regression analysis is focused on individual species rather than on pooled data heating value would give a good estimate of the carbohydrate content for coniferous species. A more detailed work would need to be carried out to find out wether this method could be used to determine carbohydrate contents.

Soil type has only a minor effect on the heating value of the individual components. Contrary to the hypothesis the results do suggest that latitude has a significant effect on most of the components. The results indicate that the heating value of stem, crown and whole-tree material is higher in the northern extent of the growing range than in the southern part of the country.

One of the aims of the study was to give practical information of the heating values to the fuelwood users. This is fulfilled by giving heating values of stem, crown and whole-tree biomass of seven indegenous species at varying moisture contents separately for the southern and northern parts of the country.

References

Ager, A., Rönnberg-Wästljung, A., Thorsén, J. & Sirén, G. 1986. Genetic improvement of willows for energy forestry in Sweden. Swed. Univ. Agric. Sci., Dept. of Ecology and Environmental Res. Sec. of Energy Forestry. Report 43. 47p.

Arola, R.A. 1977. Wood fuels — how do they stack up? In: Energy and the wood products industry: Proc. of a symposium, 1976 Nov. 15–17, Atlanta, GA. Madison, WI: For. Products Res. Soc. 34–45.

Björklund, T. 1984. Tervalepän biomassa. Summary: Biomass of black alder. Metsäntutkimuslaitoksen tiedonantoja 151. 71p.

— & Ferm, A. 1982. Pienikokoisen koivun ja harmaalepän biomassa ja tekniset ominaisuudet. Summary: Biomass and technical properties of small-sized birch and gray alder. Folia Forestalia 500. 37p.

Bureau of Analysed Samples Ltd. 1988. Certificate BCS-CRM No. 190p Bensoic Acid Thermochemical Standard (with Energy of Combustion certified by the University of Mancherster). 1p.

Bowersox, T.W., Blankenhorn, P.R. & Murphey, W.K. 1979. Heat of combustion, ash content, nutrient content and chemical content of Populus hybrids. Wood Science 11(4): 257–261.

Corder, S.E. 1973. Wood and bark as fuel. Res. Bull. 14. Corvallis, OR: Oregon State Univ., School of Forestry. 28 p.

Doat, J. 1977. Le pouvoir calorifique des bois tropicaux. Bois et Forets des Tropiques 172: 33–47.

Ekman, R. 1983. The suberin monomers and triterpenoids from the outer bark of Betula verrucosa Ehrh. Holzforschung 37: 205–211.

Energiakatsaus. 1992. KTM/Energiaosasto. No. 2. 40 p.

Fredrikson, H. & Rutegård, G. 1985. Lagring av småved och bränsleflis i binge. Summary: Storage of chunk wood and fuel chips in bins. Swed. Univ. Agric. Sci., Dept. of Forest Products. Research Notes No 151. 32p.

Fuwape, J.A. 1989. Gross heat of combustion of Gmelina (Gmelina arborea (Roxb)) Chemical Components. Biomass 19: 281–287.

Hakkila, P. 1967. Vaihtelumalleja kuoren painosta ja painoprosentista. Summary: Variation patterns of bark weight and bark percentage by weight. Communicationes Instituti Forestalis Fenniae 62(5). 37p.

— 1968. Geographical variation of some properties of pine and spruce pulpwood in Finland. Seloste: Eräitten mänty- ja kuusipaperipuun ominaisuuksien maantieteellinen vaihtelu Suomessa. Communicationes Instituti Forestalis Fenniae 66(8). 60p.

— 1970. Basic density, bark percentage and dry matter content of grey alder (Alnus incana). Seloste: Harmaalepän puuaineen tiheys, kuoriprosentti ja kuiva-ainesisältö. Communicationes Instituti Forestalis Fenniae 71(6). 27p.

— 1978. Pienpuun korjuu polttoaineeksi. Summary: Harvesting small-sized wood for fuel. Folia Forestalia 342. 38 p.

— 1989. Utilization of residual forest biomass. Springer Series in Wood Science. Springer-Verlag. 568 p.

— 1991. Hakkuupoistuman latvusmassa. Summary: Crown mass of trees at the harvesting phase. Folia Forestalia. 773. 24p.

— (ed.) 1992. Metsäenergia. Metsäntutkimuslaitoksen tiedonantoja 422. 51p.

— , Kalaja, H. & Mäkelä, M. 1975. Kokopuunkäyttö

pienpuuongelman ratkaisuna. Summary: Full-tree utilization as a solution to the problem of small-sized trees. Folia For. 240. 78p.
Harris, R.A. 1984. Fuel values of stems and branches in white oak, yellow poplar, and sweetgum. Forest Products Journal 34(3): 25–26.
— 1985. Fuel values of stems and branches in post oak and red maple. Forest Products Journal 35(4): 43–44.
Howard, E.T. 1973. Heat of combustion of various southern pine materials. Wood Science 5(3): 194–197.
Howard, J.O. 1988. Energy values for whole trees and crowns of selected species. USDA For. Serv., Research Note PNW-RN-480. 6 p.
Hughes, M.K. 1971. Seasonal calorific values from a deciduous woodland in England. Ecology 52: 923–926.
Koch, P. 1985. Utilization of hardwoods growing on southern pine sites: the raw material. U.S. Dept. Agr. For. Serv., Agr. Handbook 605. 1418 p.
Kollman, F. 1951. Technologie des Holzes und der Holzwerkstoffe I. Springer Verlag. 1050 p.
Kärkkäinen, M. 1980. Haapakokopuiden tekniset ominaisuudet. Summary: Technical properties of aspen whole trees. Manuscript at University of Helsinki, Department of forest technology.
Murphey, W.K. & Masters, K.R. 1978. Gross heat of combustion of northern red oak (Quercus rubra L.) chemical components. Wood Science 10(3): 139–141.
Musselman, K. & Hocker, Jr., H.W. 1981. Caloric values of eight New Hampshire forest tree species. Canadian Journal of Forest Research 11: 409–412.
Neenan, M. & Steinbeck, K. 1979. Caloric values for young sprouts of nine hardwood species. Forest Science 25(3): 455–461.
Olofsson, L. 1975. Värmevärden för olika delar av tall, gran och björk. Summary: Heating values for different parts of pine, spruce and birch. Dept. of Operational Efficiency. Research Notes 90. 39 p.
Report of the technical panel on fuelwood and charcoal on its second session. A/CONF. 100/PC/34, 25 February 1981.
Sandala, M.G., Blankenhorn, P.R. & Kline, D.E. 1981. Thermal analysis of white oak, northern red oak, and black cherry bark chemical components. Wood Science 13(3): 157–165.
Sastry, C.B.R. & Anderson, H.W. 1980. Clonal variation in gross heat of combustion of juvenile Populus hybrids. Canadian Journal Forest Research 10: 245–249.
Simola, P. 1977. Pienikokoisen lehtipuuston biomassa. Summary: The biomass of small-sized hardwood trees. Folia Forestalia 302. 16p.
Singh, T. & Kostecky, M.M. 1986. Calorific value variations in components of 10 Canadian tree species. Canadian Journal of Forest Research 16: 1378–1381.
Stringer, J.W. & Carpenter, S.B. 1986. Energy yield of black locust biomass fuel. Forest Science 32(4): 1049–1057.
Taras, M.A. 1978. Biomass of southern pines and their product yields. In: McMillin, C.W. (ed.). Complete tree utilization of southern pine. Forest Products Research Society Madison, 15–23.
Thörnqvist, T. 1985. Trädbränslekvalitet — vad är det? (Wood fuel quality — what is it?) Sveriges Lantbruksuniv. SIMS Uppsatser 14, 18 p.
Virtanen, P. 1963. Fuel properties of barking refuse from Finnish tree species. Pap. Puu 45: 313–330.
Voipio, R. & Laakso, T. 1992. Pienikokoisten puiden maanpäällisen biomassan kemiallinen koostumus. Summary: Chemical composition of the above ground biomass of small-sized trees. Folia Forestalia 789. 22p.
Wang, S., Huffman, J.B. & Littell, R.C. 1981. Characterization of Melaleuca biomass as a fuel for direct combustion. Wood Science 13(4): 216–219.
White, R.H. 1987. Effect of lignin content and extractives on the higher heating value of wood. Wood and Fiber Science 19(4): 446–452.
Zobel, B.J. & van Buijtenen, J.P. 1989. Wood variation Its causes and control. Springer Series in Wood Science. Springer-Verlag. 363p.

Total of 45 references

Appendix 1. The chemical composition of biomass components by species. The trees from the northern latitude are indicated with an asterisk (*).

A. The lignin content.

Tree species	Stem						Branches > 5mm			Branches < 5mm		
	20% height			80% height								
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	Foliage
P. sylvestris	25,5	5,3	29,5	27,0	7,2	17,9	29,7	7,1	15,7	27,8	10,5	9,8
	26,8	7,3	30,6	28,0	9,0	14,9	30,2	7,2	15,0	24,2	16,7	11,9
P. abies	27,8	7,7	22,9	28,2	9,2	23,9	31,7	7,2	24,7	30,2	18,7	11,5
	27,5	4,3	21,0	26,4	4,8	18,1	29,8	5,7	21,7	26,1	22,3	10,5
B. pubescens	22,2	24,2	6,2	21,5	21,9	6,3	21,5	17,7	11,2	22,5	14,1	14,6
	20,3	16,3	6,1	20,2	15,9	9,0	21,1	15,8	11,1	21,8	12,0	..
B. pendula	21,9	21,6	11,7	22,7	20,2	7,9	21,9	16,8	10,1	22,8	14,5	18,5
A. incana	23,0	26,7	26,0	22,4	16,4	11,7	23,8	21,9	18,9	26,5	19,0	21,5
A. glutinosa	24,8	28,4	32,0	25,2	24,6	19,6	25,9	23,5	21,4	27,5	22,0	25,0
P. tremula	20,1	14,8	16,9	19,8	15,2	12,5	18,4	14,9	17,0	21,2	17,5	18,6

B. The carbohydrate content.

Tree species	Stem						Branches > 5mm			Branches <5mm		
	20% height			80% height								
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	Foliage
P. sylvestris	69,6	41,8	35,4	66,1	37,0	38,4	56,6	37,6	33,2	51,6	31,1	37,4
	73,0	45,4	31,4	66,0	40,0	34,1	59,8	39,4	35,1	45,6	33,0	39,3
P. abies	78,9	49,1	31,5	74,5	48,2	36,3	66,2	49,6	30,3	63,3	36,5	31,7
	75,7	38,3	30,3	73,1	36,6	30,5	67,3	34,1	24,1	50,6	26 3	39,3
B. pubescens	67,0	38,4	5,3	65,3	35,8	5,8	64,2	32,9	7,8	60,0	23,4	20,1
	78,4	33,5	7,9	73,7	31,1	7,6	72,0	24,2	6,9	50,9	19,2	..
B. pendula	69,9	41,8	13,9	65,9	46,2	10,3	64,6	41,6	14,0	63,0	26,0	22,3
A. incana	69,0	33,8	20,0	62,6	33,9	14,2	63,0	34,0	17,1	55,0	28,3	20,4
A. glutinosa	69,8	37,6	24,9	64,8	44,2	28,1	63,9	33,8	20,9	57,0	25,9	23,8
P. tremula	74,6	41,1	31,6	69,1	49,8	26,1	69,3	48,0	40,3	58,8	38,5	24,8

C. The content of extractives soluble in organic solvents and hot water.

Tree species	Stem						Branches > 5mm			Branches < 5mm		
	20% height			80% height								
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	Foliage
P. sylvestris	5,0	39,5	15,9	5,4	44,4	23,3	9,1	43,3	28,4	14,1	38,2	40,6
	6,2	37,7	23,4	8,7	44,7	32,1	9,0	49,3	35,9	27,4	40,6	41,7
P. abies	3,5	37,4	23,4	4,9	38,7	20,9	5,2	30,5	22,0	9,6	26,4	43,3
	3,4	45,1	26,2	6,2	52,1	25,3	7,2	37,3	25,5	22,1	33,0	47,9
B. pubescens	4,4	21,3	33,2	5,8	23,7	29,6	6,8	29,0	24,1	9,1	23,9	32,5
	6,9	37,5	28,8	9,6	39,8	28,4	10,2	38,0	25,1	12,5	35,3	..
B. pendula	4,2	18,8	31,6	5,8	18,9	32,7	7,0	19,5	26,5	8,2	20,5	33,4
A. incana	4,4	20,4	27,8	7,5	38,2	39,0	8,2	21,3	22,7	11,3	22,5	28,3
A. glutinosa	5,1	20,5	14,9	6,2	22,4	22,2	8,3	23,5	24,1	9,8	21,1	27,6
P. tremula	4,5	23,1	26,5	6,1	20,5	25,2	8,6	20,0	19,0	14,8	19,5	25,4

D. The content of the alkali soluble extractives.

Tree species	Stem				Branches > 5mm		Branches < 5mm	
	20% height		80% height					
	Inner bark	Outer bark	Inner bark	Outer bark	Inner bark	Outer bark	All bark	Foliage
P. sylvestris	18,8	18,9	19,2	26,7	21,1	30,7	24,4	17,7
	16,5	12,0	16,2	25,7	11,0	27,3	20,3	15,1
P. abies	15,2	18,8	17,6	16,0	24,5	18,3	19,7	13,0
	20,0	21,8	16,4	19,9	21,2	22,6	21,7	11,1
B. pubescens	15,3	55,0	15,5	57,0	17,7	54,7	36,6	25,6
	15,6	57,6	14,5	53,3	19,5	55,3	36,9	..
B. pendula	14,1	46,3	14,5	45,6	18,5	44,6	33,0	23,9
A. incana	14,2	20,5	19,5	36,9	24,1	37,5	29,9	25,2
A. glutinosa	16,4	24,0	14,5	32,2	18,2	34,4	29,9	22,8
P. tremula	26,9	22,6	16,7	25,5	26,1	26,0	22,5	28,1

Appendix 2. The elemental composition of tree components by species**Appendix 1.** The chemical composition of biomass components by species. The trees from the northern latitude are indicated with an asterisk (*)..

Species	Wood			Inner bark		Outer bark		Bark	Foliage
	Stem	Branches > 5mm	Branches < 5mm	Stem	Branches > 5mm	Stem	Branches > 5mm	Branches > 5mm	
Carbon									
P. sylvestris	52.34	53.53	50.87	50.83	52.33	55.75	56.35	54.99	54.20
P. abies	52.43	53.36	50.37	49.70	50.20	55.56	56.10	54.02	51.30
B. pubescens	50.97	50.97	48.39	52.20	52.49	72.64	68.37	57.82	49.12
B. pendula	47.43	48.67	48.05	48.00	48.60	66.71	64.34	50.24	48.68
A. incana	49.09	48.21	49.17	49.67	48.34	64.09	60.58	51.53	49.75
A. glutinosa	46.64	47.90	48.45	50.29	50.09	58.52	62.06	53.97	50.95
P. tremula	46.21	46.84	50.23	48.95	47.81	52.71	52.94	48.05	48.23
Hydrogen									
P. sylvestris	6.09	6.03	5.23	6.17	6.36	5.68	6.12	6.70	6.82
P. abies	5.86	5.61	5.14	5.59	5.62	5.85	5.77	5.95	6.28
B. pubescens	5.86	5.80	5.15	5.79	6.10	9.37	8.43	6.55	6.13
B. pendula	5.22	5.25	5.18	5.10	5.01	9.41	8.40	5.33	6.08
A. incana	5.77	5.16	5.71	6.15	5.94	8.59	7.66	6.48	6.22
A. glutinosa	5.01	5.84	5.89	5.77	5.57	6.37	7.56	6.23	5.90
P. tremula	4.98	5.09	5.98	5.74	5.73	6.42	6.18	5.77	5.95
Nitrogen									
P. sylvestris	0.08	0.10	0.19	0.48	0.55	0.15	0.38	0.68	0.88
P. abies	0.01	0.03	0.14	0.47	0.52	0.33	0.43	0.74	0.79
B. pubescens	0.12	0.18	0.28	0.63	0.86	0.28	0.47	1.20	1.73
B. pendula	0.07	0.18	0.28	0.33	0.65	0.79	0.59	0.74	1.59
A. incana	0.44	0.59	0.83	1.49	1.74	1.28	1.23	1.72	2.79
A. glutinosa	0.20	0.46	0.62	1.06	1.26	1.15	1.06	1.33	2.22
P. tremula	0.15	0.29	0.61	0.84	1.30	0.59	0.88	1.00	2.50

Appendix 3. The 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.

A. Stem composition.

Species	Latitude	Bark division*)		Stem division		Literature source
		Inner	Outer	Wood	Bark	
		%		%		
P. sylvestris	south	50.5	49.5	88.9	11.1	1)
	north	54.7	45.3	85.2	14.8	*)
P. abies	south	64.7	35.3	87.9	12.1	1)
	north	60.0	40.0	85.5	14.5	*)
B. pubescens	south	69.4	30.6	86.2	13.8	1)
	north	65.0	35.0	76.6	23.4	*)
B. pendula	south	72.5	27.5	86.2	13.8	1)
A. incana	south	84.0	16.0	88.6	11.4	2)
A. glutinosa	south	45.8	54.2	83.5	16.5	3)
P. tremula	south	83.2	16.8	83.5	16.5	4)

1) Hakkila 1967
3) Björklund 1984
2) Hakkila 1970
4) Kärkkäinen 1980
*) data collected in this study

B. Crown composition

Species	Latitude	Branches > 5 mm*)				Branches*) < 5 mm		Total branch		Literature source
		Bark, %		Branch						
		Inner	Outer	Wood	Bark	Wood	Bark	Wood	Bark	
P. sylvestris	south	61.5	38.5	69.6	30.4	43.6	56.4	62.9	37.1	1)
	north	53.6	46.4	64.6	35.4	33.6	66.4	65.4	34.6	1)
P. abies	south	75.5	24.5	72.7	27.3	50.1	49.9	60.4	39.6	1)
	north	40.9	59.1	65.3	34.7	37.3	62.7	57.5	42.5	1)
B. pubescens	south	59.7	40.3	77.9	22.1	67.7	32.3	66.1	33.9	2)
	north	61.4	38.6	59.6	40.4	44.3	55.7	54.9	45.1	*)
B. pendula	south	73.2	26.8	73.9	26.1	54.4	45.6	66.1	33.9	2)
A. incana	south	69.2	30.8	71.1	28.9	52.1	47.9	60.7	39.3	2)
A. glutinosa	south	71.7	28.3	64.7	35.3	48.9	51.1	63.1	36.9	3)
P. tremula	south	87.4	12.6	70.7	29.3	39.1	60.9	65.9	34.1	*)

1) Hakkila 1991
3) Björklund 1984
2) Björklund & Ferm 1982
*) data collected in this study

C. Whole-tree composition.

Species	Latitude	Branches*)		Whole-tree		Literature source
		>5 mm	<5 mm	Crown	Stem	
P. sylvestris	south	50.8	49.2	21.3	78.7	1)
	north	46.4	53.6	20.4	79.6	1)
P. abies	south	35.4	64.6	35.2	64.8	1)
	north	24.4	75.6	33.5	66.5	1)
B. pubescens	south	69.4	30.6	15.1	84.9	1)
	north	59.8	40.2	18.9	81.1	1)
B. pendula	south	73.7	26.3	15.1	84.9	1)
A. incana	south	72.8	27.2	17.7	82.3	2)
A. glutinosa	south	70.7	29.3	15.8	84.2	3)
P. tremula	south	84.8	15.2	11.6	88.4	4)

1) Hakkila 1991
2) Simola 1977
3) Björklund 1984
4) Kärkkäinen 1980
*) data collected in this stydy

III

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Juha Nurmi

Heating Values of Mature Trees

The Finnish Society of Forest Science — The Finnish Forest Research Institute

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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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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 Mm^3/a (Metsätilastollinen vuosikirja 1995). The total growth of the above ground woody biomass, branches and foliage included is some 110 Mm^3/a. Of this volume 29 Mm^3/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 Mm^3 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 Mm^3 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.

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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

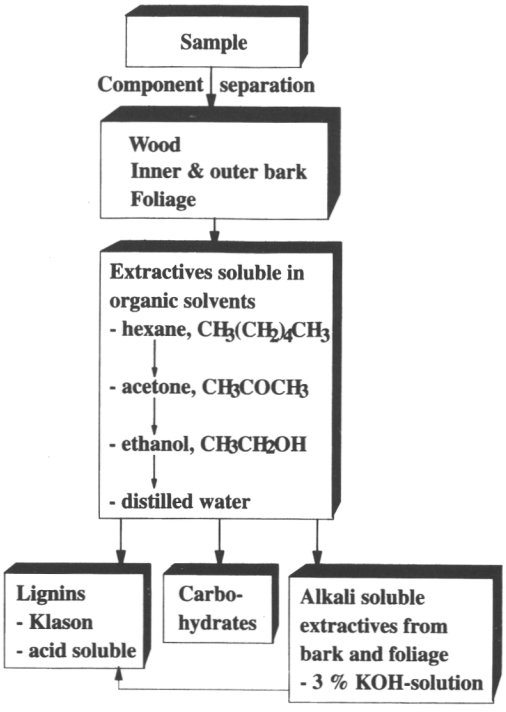


Fig. 1. Order of chemical analysis of the whole-tree components.

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:

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

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 heat-

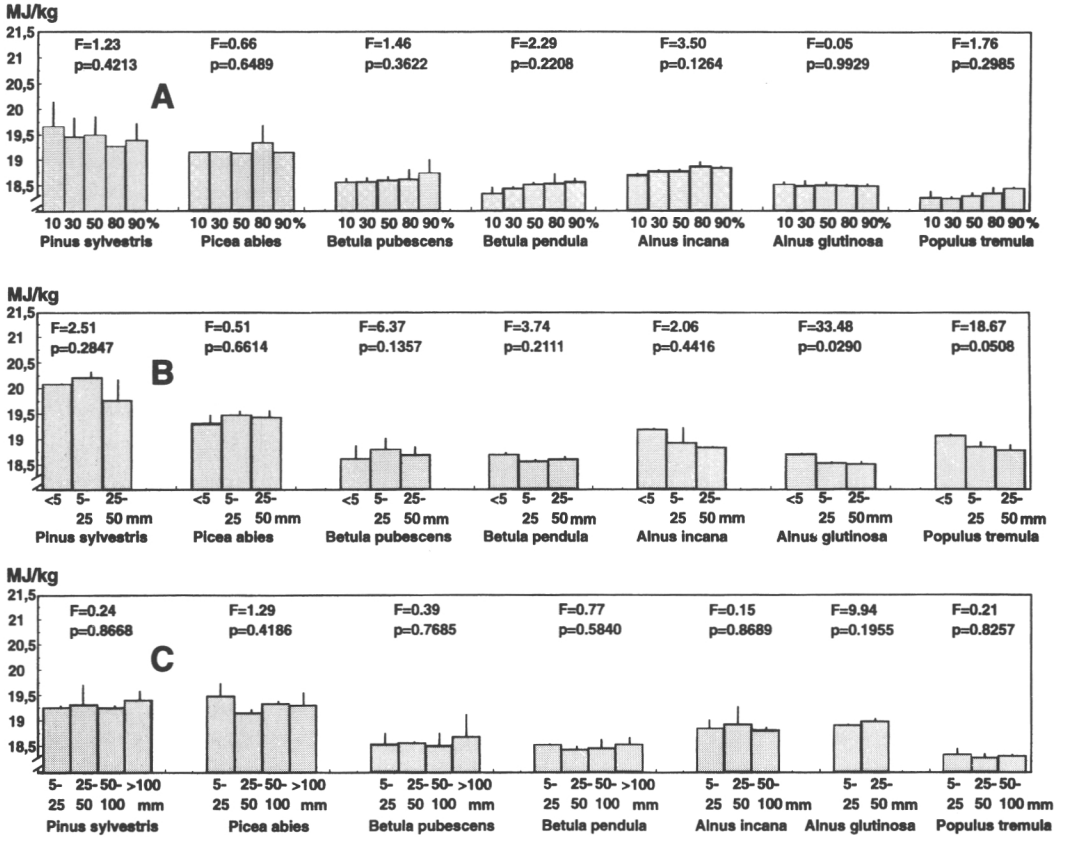


Fig. 2. Effective heating values (MJ/kg) of wood by species: (A) on the stemwood at different relative stem heights, (B) the branch wood in different diameter classes and (C) the root wood in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

ing 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).

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

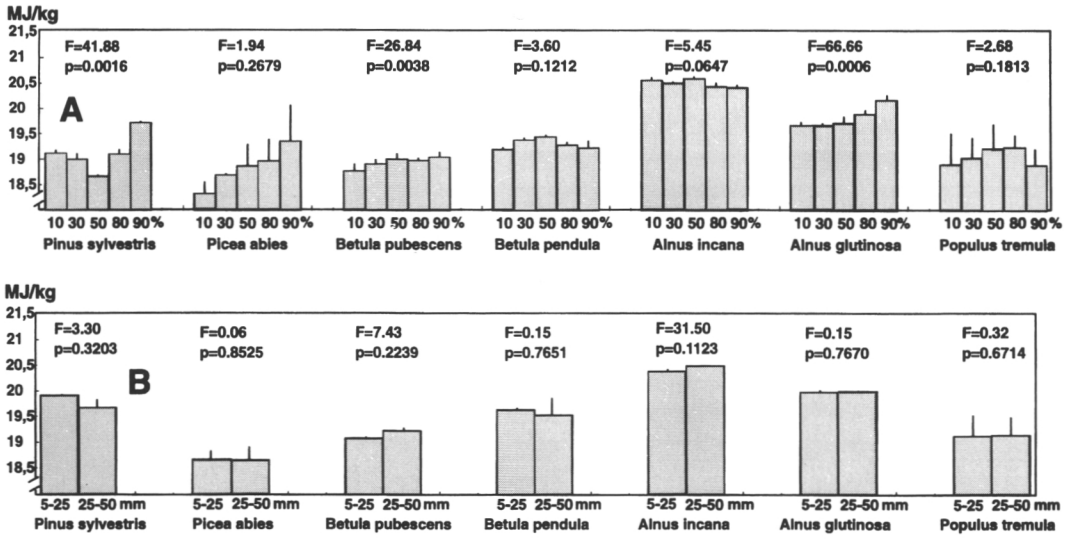


Fig. 3. Effective heating values (MJ/kg) of inner bark by species: (A) on the stem at different relative stem heights, (B) on the branch in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

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

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

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.

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

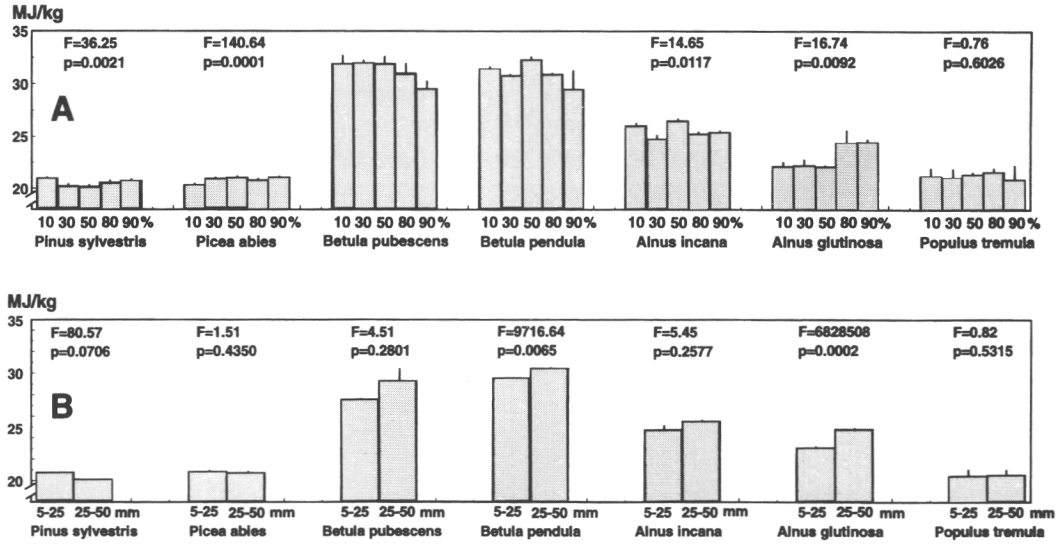


Fig. 4. Effective heating values (MJ/kg) of outer bark by species: (A) on the stem at different relative stem heights and (B) on the branch in different diameter classes. The statistical significance of relative stem height or diameter class shown above.

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

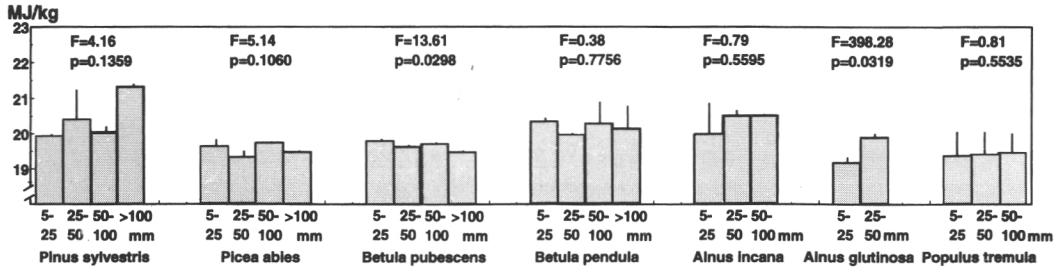


Fig. 5. Effective heating values (MJ/kg) of root bark by species in different diameter classes. The statistical significance of diameter class shown above.

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 prosess. 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.

References

Björklund, T. 1984. Tervalepän biomassa. Summary: Biomass of black alder. Metsäntutkimuslaitoksen tiedonantoja 151. 71 p.

Bureau of Analysed Samples Ltd. 1988. Certificate BCS-CRM No. 190p Bensoic Acid Thermochemical Standard (with Energy of Combustion certified by the University of Manchester). 1 p.

Doat, J. 1977. Le pouvoir calorifique des bois tropicaux. Bois et Forêts des Tropiques 172: 33–47.

Ekman, R. 1983. The suberin monomers and triterpenoids from the outer bark of Betula verrucosa Ehrh. Holzforschung 37: 205–211.

Elonen, J. & Korpilahti, A. 1996. Hakkuutähteen talteenoton vaikutus hakkuun ajanmenekkiin ja tuottavuuteen. Summary: The effect of recovery of logging residue on mechanised logging. Metsätehon katsaus 5/1996. 6 p.

Hakkila, P. 1967. Vaihtelumalleja kuoren painosta ja painoprosentista. Summary: Variation patterns of bark weight and bark percentage by weight. Communicationes Instituti Forestalis Fenniae 62(5). 37 p.

— 1975. Kanto- ja juuripuun kuoriprosentti, puuaineen tiheys ja asetoniuutteitten määrä. Summary: Bark percentage, basic density, and amount of acetone extractives in stump and root wood. Folia Forestalia 224. 14 p.

— 1989. Utilization of residual forest biomass. Springer Series in Wood Science. Springer-Verlag. 568 p.

— 1991. Hakkuupoistuman latvusmassa. Summary: Crown mass of trees at the harvesting phase. Folia Forestalia. 773. 24 p.

— & Fredriksson, T. 1996. Metsämme energian lähteenä. Metsäntutkimuslaitoksen tiedonantoja 613. 92 p.

— & Kalaja, H. 1983. Puu- ja kuorituhkan palauttamisen tekniikka. Summary: The technique of recycling wood and bark ash. Folia Forestalia 552. 37 p.

— & Mäkelä, M. 1974. Jatkotutkimuksia Pallarin kantoharvesterista. Summary: Further studies of the Pallari stumpharvester. Folia Forestalia 200. 15 p.

— , Kalaja, H. & Mäkelä, M. 1975. Kokopuunkäyttö pienpuuongelman ratkaisuna. Summary: Full-tree utilization as a solution to the problem of small-sized trees. Folia Forestalia 240. 78 p.

Kärkkäinen, M. 1980. Haapakokopuiden tekniset ominaisuudet. Summary: Technical properties of aspen whole trees. Manuscript at University of Helsinki, Department of Forest Technology.

Kollman, F. 1951. Technologie des Holzes und der Holzwerkstoffe I. Springer Verlag. 1050 p.

Metsätilastollinen vuosikirja. 1995. SVT Maa- ja metsätalous. Metsätilastollinen vuosikirja 25. Metsäntutkimuslaitos. Finnish Forest Research Institute. 354 p.

Musselman, K. & Hocker, H.W., Jr. 1981. Caloric values of eight New Hampshire forest tree species. Canadian Journal of Forest Research 11: 409–412.

Nurmi, J. 1993. Heating values of the above ground biomass of small-sized trees. Acta Forestalia Fennica 236. 30 p.

— 1994. Työtavan vaikutus hakkuukoneen tuotokseen ja hakkuutähteen kasautumiseen. Folia Forestalia – Metsätieteen aikauskirja 1994(2): 113–122.

— 1997. Hakkuutähteen metsäkuljetuksen tuottavuus päätehakkuukuusikoissa. Manuscript for Folia Forestalia at Finnish Forest Research Institute. 23 p.

Olofsson, L. 1975. Värmevärden för olika delar av tall, gran och björk. Summary: Heating values for different parts of pine, spruce and birch. Swedish University of Agricultural Sciences, Department of Operational Efficiency, Research Notes 90. 39 p.

Sandala, M.G., Blankenhorn, P.R. & Kline, D.E. 1981. Thermal analysis of white oak, northern red oak, and black cherry bark chemical components. Wood Science 13(3): 157–165.

Singh, T. & Kostecky, M.M. 1986. Calorific value variations in components of 10 Canadian tree species. Canadian Journal of Forest Research 16: 1378–1381.

Taras, M.A. 1978. Biomass of southern pines and their product yields. In: McMillin, C.W. (ed.). Complete tree utilization of southern pine. Forest Products Research Society Madison. p. 15–23.

Voipio, R. & Laakso, T. 1992. Pienikokoisten puiden maanpäällisen biomassan kemiallinen koostumus. Summary: Chemical composition of the above ground biomass of small-sized trees. Folia Forestalia 789. 22 p.

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		
	Inner	Outer	Wood	Bark	References
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		
	> 5 mm	< 5 mm	Crown	Stem	References
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

IV

FOLIA FORESTALIA 687

Metsäntutkimuslaitos. Institutum Forestale Fenniae. Helsinki 1987

Juha Nurmi

POLTTOHAKKEEN KUIVATUS TRAKTORIKONTEISSA

Drying of fuel chips and chunks in wooden bins

Approved on 10.4.1987

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NURMI, J. 1987. Polttohakkeen kuivatus traktorikonteissa. Summary: Drying of fuel chips and chunks in wooden bins. Folia Forestalia 687. 40 p.

Polttohakkeen kuivatusta 15 m^3:n puisissa traktorikonteissa tutkittiin viidellä Etelä-Suomen paikkakunnalla vuosina 1981 ja 1982. Tutkimuksessa selvitettiin hakkeen palakoon, kuivatuksen ajankohdan, rasiinkaadon, puulajin ja kontin mallin vaikutuksia. Kaikkiaan kuivatettiin noin 1100 i-m^3 haketta.

Palahake kuivui hienohaketta nopeammin. Kaatotuoreiden hakkeiden kuivumisnopeuksien ero oli 2—3-kertainen, kun haketta kuivattiin 20—30 %:n kosteuteen. Rasikuivatuksen ansiosta palakoon merkitys pieneni. Hienohakkeen keskimääräinen tehollinen lämpöarvo oli noin 2770 MJ/i-m^3 ja palahakkeen noin 2760 MJ/i-m^3. Lämpöarvon lisäys oli hienohaketta käytettäessä keskimäärin 1,3 % ja palahakketta käytettäessä 3,4 %.

Touko-elokuun välinen aika osoittautui parhaaksi kuivatuksen ajankohdaksi. Aikainen kevät sekä syksy ovat ilmaston takia huonoja ajankohtia. Alun perin vähäisemmän kosteutensa ansiosta pääsi rasipuista tehty hake ilman kanssa kosteustasapainoon kaatotuoreita hakkeita nopeammin.

Lepän ja koivun välisten puuteknologisten erojen ei havaittu vaikuttavan puun kuivumiseen. Verkkokontti sen sijaan osoittautui lautakonttia paremmaksi. Palakoon vaikutus näytti myös pienenevän verkkokonttia käytettäessä.

Drying fuel chips and chunks in 15 m^3 wooden bins was studied on five locations in Southern Finland in 1981 and 1982. The effects of particle size, season, leaf seasoning, bin type and tree species were observed. Altogether some 1100 loose m^3 of chips and chunks were dried.

Chunks dried faster than chips. Chunks made from freshly comminuted wood dried 2-3 times faster than chips to 20-30 % moisture content. However, the difference between chips and chunks decreased when leaf-seasoned trees were used in comminution. The mean effective heat value of chips was 2770 MJ/m^3 loose and 2760 MJ/m^3 loose for chunks. The net increase of heat value on actual gain basis was 1,3 % for chips and 3,4 % for chunks.

The period from May until the end of August proved to be the best drying season. Early spring and fall are not as good because of climatic reasons. Chips and chunks made from seasoned trees reached an equilibrium moisture content with the ambient air faster than chips and chunks made of fresh trees because of the lower starting moisture content.

The wood technological differences between alder and birch were not found to have any effect on drying. The wire mesh bin on the other hand turned out to be better than the wooden bin. The effect of particle size was also decreased when wire mesh bins were used.

Keywords: dry matter losses, heat value, fuelwood harvesting, leaf-seasoning, wood moisture content
ODC 831.1+861.0+847.1

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MERKKIEN SELITYKSET — KEY TO SYMBOLS

y = Hakkeen kosteus prosentteina tuorepainosta
Moisture content in green weight basis
x = Kuivatusaika viikkoina
Drying time in weeks
r^2 = Selitysaste
Coefficient of determination

Paikkakunnat — *Localities*
□ = Janakkala
× = Joroinen
○ = Hyrylä
△ = Ylihärmä
\+ = Pyhtää

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1. JOHDANTO

Polttohakkeen käyttö maassamme alkoi 1960-luvulla. Tällöin sen soveltuvuutta maatilojen ja pientalouksien käyttöön tarkastelivat mm. Jokihaara (1959) ja Heliövaara (1960, 1961). Käytön laajuutta koskevia selvityksiä tekivät Kantola (1961) ja erityisesti Anttila (1961). Kiinnostus polttohaketta kohtaan hiljeni kuitenkin vuosikymmenen ajaksi, mutta se alkoi uudelleen 1970-luvulla öljykriisin aikana. Sen tuloksena muodostettiin kansallinen energiapoliittinen ohjelma vuonna 1979, joka uusittiin 1983. Ohjelman olennaisena osana oli polttohakkeen käyttö. Aiheesta on syntynyt useita tutkimuksia ja tutkimuskokonaisuuksia, joista mainittakoon Kotimaisten... (1983), Hakkila (1984) sekä Immonen ja Seppälä (1984).

Puupolttoaineiden yhtenä erona fossiilisiin polttoaineisiin nähden on puun ominaisuuksien, mm. kosteuden ja tiheyden suuri vaihtelu. Puulajin ja kosteuden vaikutusta lämpöarvoon ovat tarkastelleet Heiskanen ja Jokihaara (1961), Lehtonen (1977) sekä Hakkila (1978). Lahovikaisuuden vaikutusta lämpöarvoon on tutkinut Salmi (1964). Yleiseltä kannalta ovat polttopuun ominaisuuksia käsitelleet Kärkkäinen (1977) ja Kofod (1983). Lisäksi Nylinder (1979) on selvitellyt polttoarvon riippuvuutta puun kosteudesta sekä puun kilpailukykyä polttoaineena öljyyn verrattuna. Vastaavasti Parikka (1984) on verrannut metsähakkeesta saatavan energian hintaa kivihiilen hintaan.

Puuaineen kosteus on tärkeä ominaisuus puun polton onnistumisen kannalta. Kosteus riippuu etupäässä puun käsittelystä ja varastoinnista. Pienpuualan toimikunnan aikana tehtiin useita polttohakkeen pien- ja suurkäyttöön kohdistuneita tutkimuksia (mm. Taipale 1960, 1962, 1963, Aittomäki 1963). Tämän vuosikymmenen puolella puhallusilmalla suoritettuja kuivatuskokeita ovat tehneet Gustafsson (1981), Thörnqvist (1982), Thörnqvist ja Gustafsson (1983), Gislerud (1983) sekä myös Nisula (ks. Hakkila ja Kalaja 1981, s. 14). Lampinen (1978) on tarkastellut savukaasujen käyttömahdollisuutta hakkeen kuivatuksessa. Muita kuivatustapoja ovat tutkineet Koch (1983) sekä Alestalo (1982).

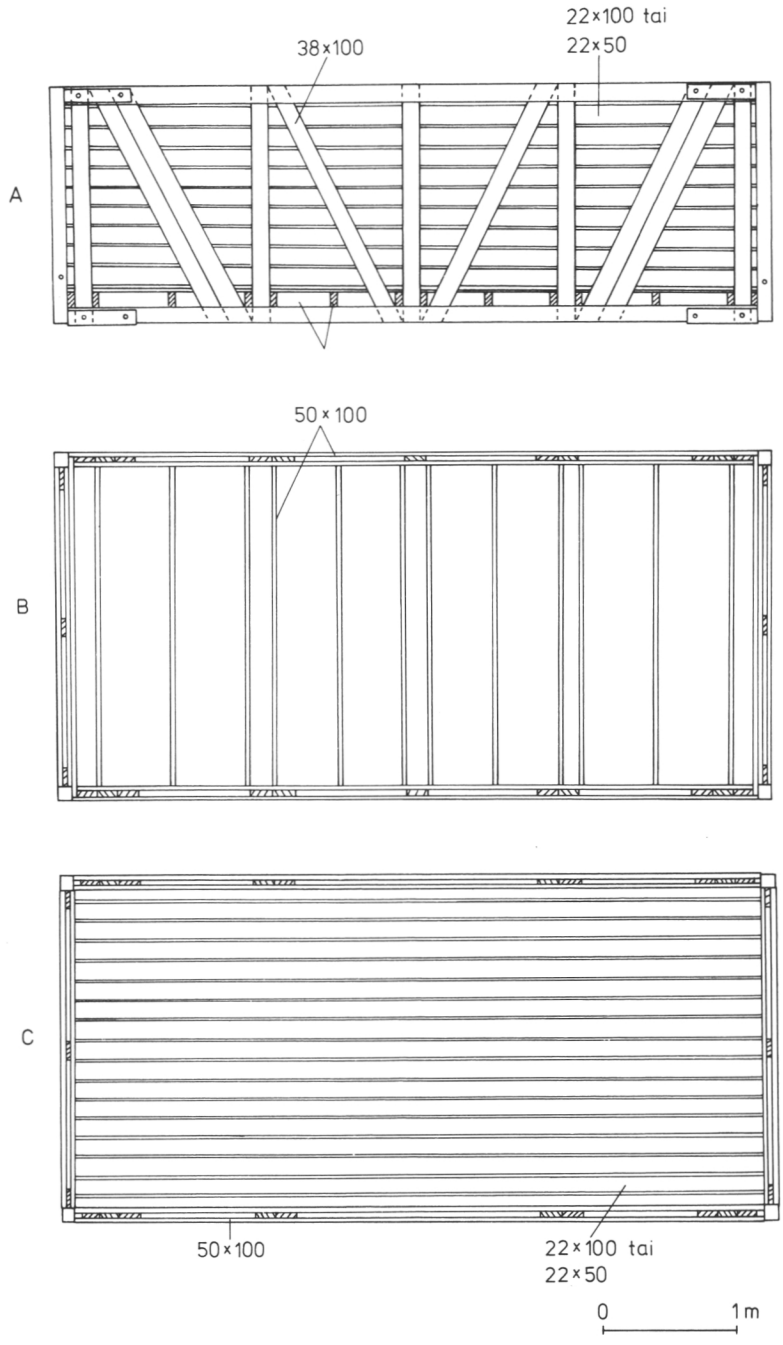
Vaikka hakkeen tai sen raaka-aineen kuivatus onkin yleinen ja tarpeellinen toimenpide pienkäytössä, se on usein kannattamatonta suurkulutuksessa. Tämän vuoksi useat teollisuuden piirissä tehdyt tutkimukset ovatkin keskittyneet varastointiin liittyviin kysymyksiin. Tällaisia tutkimuksia ovat tehneet mm. Immonen (1961), Håkansson ja Numminen (1963), Annergren ym. (1964), Hajny (1966), Bergman ja Nilsson (1966, 1967, 1968, 1971, 1974, 1979), Gislerud ja Grønlien (1977, 1978 a,b) sekä Gislerud (1978). Pienkuluttajien hakevarastoja on tutkittu enemmälti vasta kuluvalla vuosikymmenellä. Tämä johtunee lisääntyneestä mielenkiinnosta hakkeen varastoinnin mahdollisia terveyshaittoja kohtaan (Gislerud 1974, Thörnqvist 1980, 1983, Björklund 1982, 1983, White ym. 1983). Erityisesti hakkeen varastointiin liittyviä homepölyn aiheuttamia haittoja ovat tutkineet Smith ja Ofosu-Asiedu (1972), Høeg (1980, 1981), Thörnqvist ja Lundström (1980), Turkkila ja Knut (1982), Pesonen (1982), Pellikka (1983), Pellikka ja Kotimaa (1983) ja Belin (1984).

Polttohakkeen suurkuluttajien kannalta on edullisinta puuaineen kosteuden väheneminen ennen haketusta. Jo kauan käytössä ollut tapa kuivattaa kokonaisia puita rasissa tai kasoissa on edelleenkin tehokkain, ja siitä on olemassa lukuisia tutkimuksia (Jalava 1941, Heiskanen ja Hakkila 1960, Levanto 1961, Warsta 1961, Hakkila 1962, Simola ja Mäkelä 1976, Liss 1979, Faeste ja Johansson 1982, Uusvaara 1984). Puu kuivuu jonkin verran myös metsävarastoissa (Uusvaara 1984). Kärkkäinen (1981) on kehittänyt laskentamenetelmän rasiinkaadon taloudellisuuden arvioimiseksi.

Tämän tutkimuksen tarkoituksena on selvittää puisen traktorikontin soveltuvuus polttohakkeen kuivatukseen. Tutkimuksessa ei ole pyritty optimoimaan kontin rakennetta ja käsiteltävyyttä. Keskeistä on sen sijaan ollut hakkeen kuivuminen ja siihen mahdollisesti vaikuttavat tekijät kuten palakoko, kuivatusaika, rasimenetelmä ja puulaji.

Tutkimuksen kenttätöiden järjestelyissä avustivat Hannu Kalaja ja Tapio Nevalainen. Puhtaaksikirjoituksesta vastasivat Aune Rytkönen ja Maija Tuuri. Tulosten laskennasta ja grafiikasta vastasivat Hannu Aaltio ja Leena Muronranta. Käsikirjoituksen julkaisukuntoon saattamisessa avusti Raija Siekkinen. Englanninkielen tarkasti Elva Nurmi. Työn lukivat Pentti Hakkila, Olli Uusvaara ja Pertti Harstela. Kiitän kaikkia avusta.

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Kuva 1. Hakekontin rakenne. A) Sivulta, B) päältä ilman pohjalaudoitusta, C) päältä. Puutavaran mitat millimetreinä.

Fig. 1. Structure of the chip bin. A) Side view, B) top view without board cover, C) top view. Dimensions in millimeters.

2. TUTKIMUSMENETELMÄT JA AINEISTOT

21. Traktorikonttien rakenne

Konttia suunniteltaessa on pidetty tärkeänä sen taloudellisuutta ja käyttökelpoisuutta. Taloudellisuutta on pyritty edistämään rakennusmateriaalien valinnalla sekä aurinkoon ja tuuleen perustuvalla kuivatuksella. Vaikka metallinen kontti olisikin kestävämpi, se on erittäin kallis ja käytännössä raskas käsitellä. Lisäksi puisen kontin kokoaminen on paljon helpompaa kuin metallisen. On myös oletettu sahatavaraa olevan tiloilla helposti saatavilla.

Kontti on mitoitettu traktorin perävaunun mittoja vastaavaksi. Tämä mahdollistaa kontin siirtelyn haketus-, kuivatus- ja varastointipaikkojen välillä. Näin vältytään turhilta hakkeen kuormauksilta ja tyhjennyksiltä. Kuivatuksen ajaksi kontti voidaan myös laskea traktorin perävaunusta suhteellisen helposti tukien varaan. Ulkoisilta mitoiltaan kontti täyttää maantiekuljetukselle asetetut vaatimukset silloin, kun kontin päällä käytettävä katos ei ole paikoillaan.

Kontti koostuu seinärakenteista sekä niitä sitovista lattialaudoituksista. Ensin kootaan 2 kappaletta sivuseinärakenteita 38x100 mm ja 50x100 mm puutavarasta (kuva 1a). Haluttaessa voidaan käyttää pelkästään kokoa 50x100 mm. Toisena vaiheena yhdistetään sivuseinät toisiinsa lattian koolauksilla (kuva 1b).

Ilman esteetön pääsy hakkeeseen on konttikuivatuksen kannalta olennaista. Siksi verhoilulautojen väliin jätettiin rakoja. Rakojen leveys vaihtelee konteissa sen mukaan, kuivataanko niissä hienohaketta vai palahaketta. Hienohakkeen nimellispituus oli 20 mm ja palahakkeen 50—70 mm. Hienohake valmistettiin hakkureilla Junkkari HJ6 ja HJ10 sekä Hakki H-200. Palahakkeen valmistuksessa käytettiin Kopo PH-10 ja PH-15 -hakkureita.

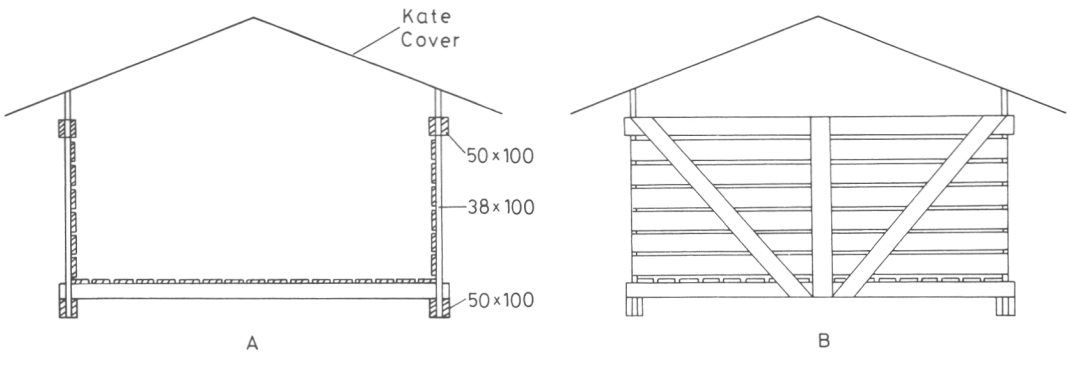
Varisemisen estämiseksi on hienohakekonttiin jäävien rakojen oltava palahakekontin rakoja pienemmät. Saman ilmakosketuspinta-alan saamiseksi on hienohakekontti verhoiltava kapeammalla laudalla rakojen määrän lisäämiseksi. Hienohakekonteissa käytettiin 22x50 mm:n rimaa 10 mm:n raotuksella ja palahakekonteissa 22x100 mm:n lautaa 20 mm:n raotuksella (kuva 1c). Samanaikaisesti sivuseinien ja pohjan verhoilun yhteydessä tehtiin kontin etuseinä tukineen (kuva 2).

Kontin perälevy on irrotettava. Tämä on välttämätöntä käytettiinpä kontin tyhjennykseen etukuormainta, kippausta tai lapiota. Perälevy kootaan samanlaiseksi rakenteeksi kuin sivuseinät ja verhoillaan tarvittavalla laudoituksella. Perälevy voidaan kiinnittää salpaamalla tai suoraan konttiin naulaamalla, mikä kuitenkin kuluttaa kontin puurakenteita. Suositeltavampi on kuvien 3a ja b esittämä kiinnitystapa, jossa perälevy roikkuu kontin sisäpuolelle sijoitetun tangon varassa. Lukitussalvat sijaitsevat kontin ulkopuolella alanurkissa. Mikäli tätä kiinnitystapaa käytetään, voidaan kontti kipata tyhjäksi ilman perälevyn irrottamista.

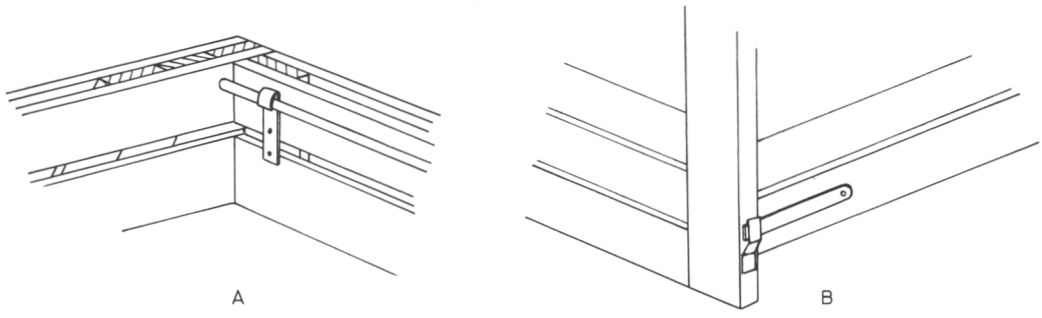
Paremman ilmankierron ja suuremman ilmakosketuspinnan aikaansaamiseksi rakennettiin Ylihärmään vuonna 1982 kaksi kappaletta ns. verkkokontteja (kuva 4). Niissä seinien lautaverhoilu korvattiin 20x20 mm:n silmäkoon teräsverkolla. Lisäksi kummankin kontin keskelle rakennettiin 0,55 m^3 tilava ilmakanava, joka kulkee pituussuunnassa koko kontin läpi lähes kontin korkuisena ja 10 cm:n levyisenä.

Konttien katokset rakennettiin v. 1981 kokeita varten 22x50 mm:n rimoista ja 0,15 mm:n paksuisesta muovista (kuva 5 alaosa). Pyhtäällä tosin käytettiin kuvan 5 yläosan osoittamia Eura-peitekatoksia ilman räystäitä. Muovi ja rimat osoittautuivat kuitenkin kestävyydeltään erittäin huonoiksi materiaaleiksi. Sadeveden paino venytti muovia muodostamalla katoksen päälle vesivarastoja. Veden paino puolestaan aiheutti kiinninaulattujen muovien repeilemisiä, jolloin hakkeen sekaan pääsi vettä. Tällaisen kiinteän katoksen nosto kontin päälle ja sen poistaminen oli erittäin vaikeata.

Katoksen mallia ja materiaaleja muutettiin vuoden



Kuva 2. A) Hakekontti takaa ilman perälautaa, B) edestä. Puutavaran mitat millimetreinä.
Fig. 2. A) Rear view of the bin without the rear gate, B) front view. Dimensions in millimeters.



Kuva 3. Perälaudan kiinnitys. A) Sisäpuoleinen ripustin ja B) ulkopuolinen salpa.
Fig. 3. Mounting of the rear gate. A) Inside support and B) outside latch.

1982 tutkimuksia varten. Katteena käytettiin tällöin Turo Oy:n valmistamaa 4x6 m:n kokoista pressua. Sen materiaalina on Vinyplan ja kudosaineena polyamidilanka. Pressu on tulen ja pakkasen kestävä ja painaa 680 g/m^2. Konttiin naulattiin kurkihirsi ja räystäät, joiden varaan pressu levitettiin. Tämä katemalli kesti erittäin hyvin tuulen ja sateen ja oli helppo koota. Pressujen eduksi on myös laskettava se, että niitä voidaan käyttää kuivatuskauden ulkopuolella moniin muihin kattamistarkoituksiin.

Konttien korkeus, leveys ja pituus olivat keskimäärin 130x230x500 cm ja tilavuus noin 15 m^3. Konttien mitat ja tilavuus vaihtelivat vain vähän paikkakunnasta ja rakentajasta riippuen.

Alla olevasta asetelmasta käy ilmi hieno-, pala- ja verkkokontteihin tarvittavien rakennusmateriaalien määrät ilman katoksia.

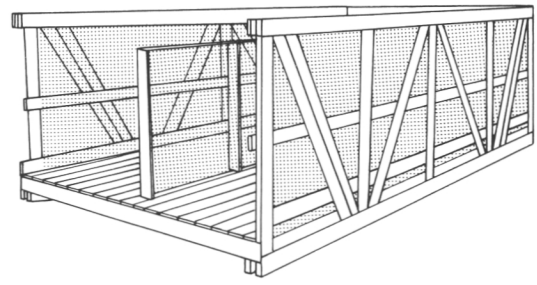
		Lautakontti		Verkkokontti	
Tavaralaji	Koko, mm	Hieno-hake	Pala-hake	Hieno-hake	Pala-hake
Sahatavara, m	22x50	520	—	180	—
-"-	22x100	—	260	—	90
-"-	38x100	60	60	60	60
-"-	50x100	90	90	90	90
Verkko, m^2	20x20	—	—	32	32

Kuivatustutkimus suoritettiin viidellä paikkakunnalla. Janakkalassa, Joroisissa ja Pyhtäällä kuivattiin leppähaketta, Hyrylässä ja Ylihärmässä koivuhaketta. Kullekin paikkakunnalle rakennettiin kuusi lautakonttia sekä Ylihärmään lisäksi kaksi verkkokonttia. Niissä kuivatettiin tutkimuksen aikana yhteensä 74 kontillista eli noin 1100 i-m^3 haketta. Paikkakuntakohtaiset hakkeen määrät ja painot on lueteltu taulukoissa 1a ja b.

22. Kuivumisen ajankohdat ja kesto

Kuivatustutkimus suoritettiin vuosien 1981 ja 1982 aikana neljässä eri erässä (kuva 6). Kaksi hake-eristä oli kaatotuoretta ja kaksi rasikuivattua. Kaatotuoreella hakkeella tarkoitetaan puun kaadosta kahden vuorokauden kuluessa tehtyä haketta. Rasikuiva hake tehtiin noin kuukauden rasissa kuivuneesta puusta.

Ensimmäinen erä tehtiin keväällä kaatotuoreesta lehdettömästä puusta. Vuonna 1981 tämän erän hakkeet tehtiin toukokuussa ja vuonna 1982 ne tehtiin maaliskuun vaihteessa. Täten ei eri tutkimusvuosien kevään kaatotuoreiden hakkeiden kuivumista voida pitää täysin vertailukelpoisina. Keväällä kaatotuoreena valmistetun hakkeen kuivatus loppui syyskuun alussa. Vuonna 1981 keskimääräinen kuivatusaika oli 16 viikkoa, ja vuonna 1982 se oli 22 viikkoa.



Kuva 4. Verkkokontti.
Fig. 4. A wire mesh bin.

Tutkimuksen *toinen erä* koostui kesä-heinäkuun vaihteessa kaatotuoreista lehdellisistä puista tehdyistä hakkeista. Tutkimuksen ajoittuminen oli molempina vuosina sama, mikä mahdollistaa niiden keskinäisen vertailun. Kuivatusta tosin jatkettiin vuonna 1981 aina talveen asti. Vuosina 1981 ja 1982 keskimääräiset kuivatusajat olivat 25 viikkoa ja 20 viikkoa.

Kolmas erä tehtiin rasikuivasta puusta samaan aikaan kesän kaatotuoreen erän kanssa, joten suora vertailu kaatotuoreen puun kuivumisen kanssa on mahdollista. Vuoden 1981 rasikuivatus kesti 5—11 viikkoa, keskimääräisen ajan oltua 7 viikkoa. Toisena tutkimusvuotena rasikuivatus kesti kaikilla paikkakunnilla 5 viikkoa.

Neljäs erä haketettiin syyskuussa rasikuivista puista, jotka kaadettiin rasiin elo-syyskuussa vuonna 1981 ja elokuussa vuonna 1982. Rasiajan ajoittumisessa ja pituudessa oli suuria vaihteluita vuonna 1981. Rasiajan pituus oli vuonna 1981 keskimäärin 4 viikkoa ja vuonna 1982 se oli 5 viikkoa.

Kuva 5. Kuivatuskoe käynnissä Pyhtäällä (yllä) ja Hyrylässä (alla).
Fig. 5. Drying experiment taking place in Pyhtää (above) and Hyrylä (below).





Taulukko 1a. Hakkeen paino- ja tilavuustietoja vuonna 1981.
Table 1a. Weight and volume data on chips and chunks in 1981.

Hake Chips/ chunks	Tekoaika *Season*	Paikkakunta *Location*	Kokonaispaino, kg *Total weight, kg* Lähtö *Start*	 Loppu *End*	Hakkeen tilavuus, m^3 *Volume, m^3*	Paino, kg/i-m^2 *Weight, kg/m^3 loose* Lähtö *Start*	 Loppu *End*
Tuore	Kevät	Janakkala	5280	3120	13,4	394	233
hienohake	*Spring*	Joroinen	4620	3172	14,9	310	213
Fresh		Hyrylä	4960	2840	14,5	342	196
chips		Ylihärmä	3960	3117	14,2	279	219
Tuore	Kevät	Janakkala	4980	2860	14,4	346	199
palahake	*Spring*	Joroinen	4200	2831	14,6	288	194
Fresh		Hyrylä	4320	2794	14,6	296	191
chunks		Ylihärmä	3600	2746	14,2	254	193
Tuore	Kesä	Janakkala	4220	2987	14,4	293	207
hienohake	*Summer*	Joroinen	3090	2375	10,3	300	231
Fresh		Hyrylä	4780	3245	14,4	332	225
chips		Ylihärmä	4420	3237	14,2	311	228
		Pyhtää	4690	3142	14,5	324	217
Tuore	Kesä	Janakkala	3800	2683	12,9	295	208
palahake	*Summer*	Joroinen	2700	1879	9,7	278	194
Fresh		Hyrylä	4320	2872	14,4	300	199
chunks		Ylihärmä	3590	2457	14,2	253	173
		Pyhtää	4690	3065	14,5	329	211
Rasikuiva	Kesä	Janakkala	3820	2906	15,5	246	187
hienohake	*Summer*	Joroinen	2870	2296	11,8	243	195
Seasoned		Hyrylä	4380	3204	14,4	304	223
chips		Ylihärmä	3710	3251	14,2	261	229
		Pyhtää	4470	3454	14,5	308	238
Rasikuiva	Kesä	Janakkala	3580	2703	15,4	232	176
palahake	*Summer*	Joroinen	2450	1999	9,5	258	210
Seasoned		Hyrylä	3860	3216	14,7	263	219
chunks		Ylihärmä	3900	3032	14,2	275	214
		Pyhtää	4270	3107	14,5	294	214
Rasikuiva	Syksy	Janakkala	3860	3380	13,4	288	252
hienohake	*Autumn*	Joroinen	3713	3438	14,6	254	235
Seasoned		Hyrylä	2635	2492	8,6	306	290
chips		Ylihärmä	4009	3596	14,2	282	253
Rasikuiva	Syksy	Janakkala	3500	2918	13,7	255	213
palahake	*Autumn*	Joroinen	3619	3157	14,9	243	212
Seasoned		Hyrylä	2373	2322	8,9	267	261
chunks		Ylihärmä	3744	3416	13,9	269	246

23. Kuivumisen seuranta

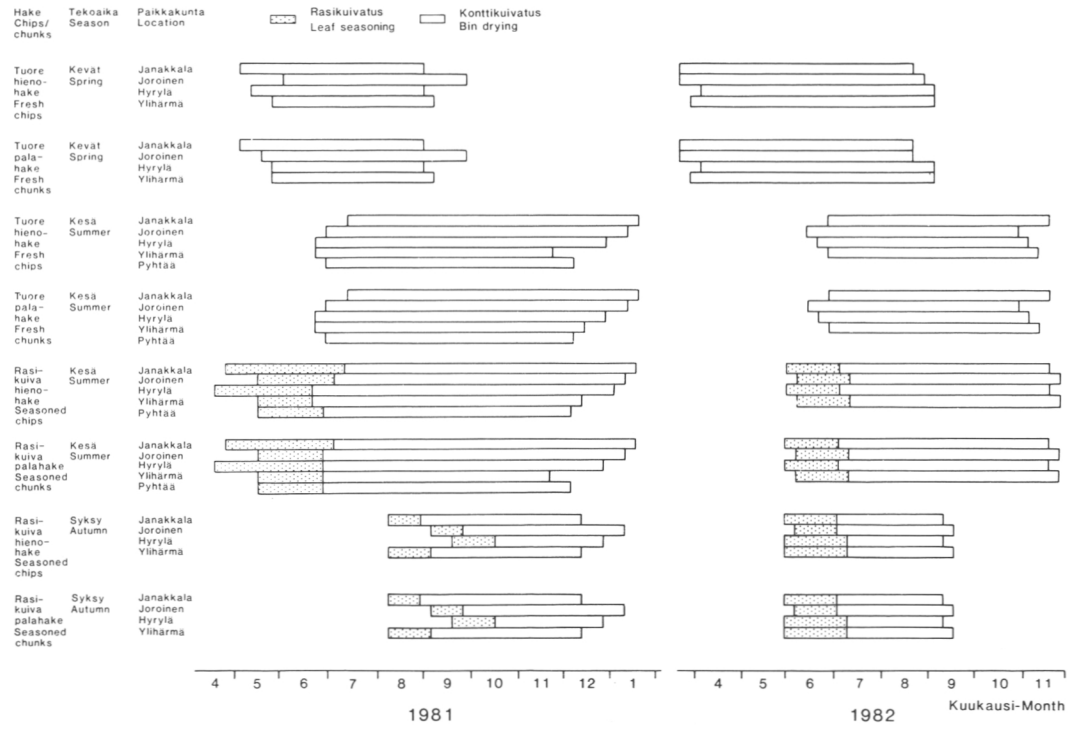
Tutkimuksen tavoitteen saavuttamiseksi oli välttämätöntä saada tietoja hakkeen kosteuden kehittymisestä tutkimusaikana. Kosteuden muutoksia ei voida seurata näytteitä ottamalla, sillä hakkeen kosteus vaihtelee epätasaisesti. Kosteuden kehitystä voidaan kuitenkin seurata hakemassan määräaikaisilla punnituksilla, mikäli hakkeen kosteus ja kuiva-aineen määrä on määritetty kokeen alussa. Menetelmä ei ota kuitenkaan huomioon kuivatuksen aikana tapahtuvia kuiva-ainetappioita, joten se liioittelee kuivumistuloksia. Virhettä voidaan kuitenkin korjata kokeen lopussa otettavien näytteiden perusteella.

Painomittauksen suorittamiseksi turvallisesti ja vähällä työvoimalla tilattiin Koatram Oy:ltä siirrettävä punnitusjärjestelmä. Järjestelmään kuuluu 3 kappaletta 2 tonnin tunkkiantureita, mittauslähetin sekä vaaka, joka sisältää elektroniikka- ja näyttöosat (kuva 7). Virtalähteenä käytettiin auton akkua. Laitteiden toimituksen viivästyttyä käytettiin tutkimuksen alkuvaiheessa vuonna 1981 hakkeiden punnitsemiseen autovaakoja.

Konttien punnitseminen tunkkiantureilla vaati joitakin normaalikuivatuksesta poikkeavia menettelytapoja. Sen sijaan, että kontit olisi jätetty korkealle ilmaan tukien varaan kuivumaan, ne täytyi laskea noin 40 cm:n korkeudelle maasta. Tältä korkeudelta tunkkien ulottuvuus oli vielä riittävä nostamaan kontin punnituksessa ilmaan. Kontteja punnittaessa yksi tunkki sijoitettiin koolauksien alle kontin etuosaan ja kaksi muuta taakse sivuille. Tunkkien sijoittelua seurasi laitteen taaraus, kontin nosto ja painon luku näyttöosasta. Kontin paino katoksineen oli määritetty aina ennen kontin täyttöä hakkeella. Vähentämällä laitteen osoittamasta lukemasta kontin ja katoksen paino saatiin hakkeen paino. Kontin ja katoksen painot määriteltiin myös kokeen lopussa, jotta niiden painonmuutokset eivät aiheuttaisi virheitä lopputuloksissa. Kaikki kontit pyrittiin punnitsemaan viikoittain. Painon muutosten hidastuttua punnitusväli pidennettiin kahteen tai useampaan viikkoon.

Taulukko 1b. Hakkeen paino- ja tilavuustietoja vuonna 1982.
Table 1a. Weight and volume data on chips and chunks in 1982.

Hake Chips/ chunks	Tekoaika *Season*	Paikkakunta *Location*	Kokonaispaino, kg *Total weight, kg* Lähtö *Start*	 Loppu *End*	Hakkeen tilavuus, m^3 *Volume, m^3*	Paino, kg/i-m^2 *Weight, kg/m^3 loose* Lähtö *Start*	 Loppu *End*
Tuore hienohake *Fresh chips*	Kevät *Spring*	Janakkala Joroinen Hyrylä Ylihärmä	4583 4662 4890 4678	2533 2983 2997 2848	13,5 14,7 13,3 14,3	339 317 368 327	188 203 225 200
Tuore hienohake verkkokontissa *Fresh chips in a wire mesh bin*	Kevät *Spring*	Ylihärmä	4074	2519	13,7	297	184
Tuore palahake *Fresh chunks*	Kevät *Spring*	Janakkala Joroinen Hyrylä Ylihärmä	4660 4905 3953 4233	2714 2945 2242 2647	14,6 14,6 11,0 14,3	319 336 350 296	186 202 204 185
Tuore palahake verkkokontissa *Fresh chunks in a wire mesh bin*	Kevät *Spring*	Ylihärmä	4639	2873	13,7	339	210
Tuore hienohake *Fresh chips*	Kesä *Summer*	Janakkala Joroinen Hyrylä Ylihärmä	4688 4709 4379 4327	3159 3028 2952 3224	14,1 14,1 14,6 14,3	332 334 300 303	224 215 202 226
Tuore palahake *Fresh chunks*	Kesä *Summer*	Janakkala Joroinen Hyrylä Ylihärmä	4468 4610 4074 4093	2914 2897 2679 2983	14,4 14,2 14,3 13,8	310 325 285 297	202 204 187 216
Rasikuiva hienohake *Seasoned chips*	Kesä *Summer*	Janakkala Joroinen Hyrylä Ylihärmä	3518 3805 3827 3476	2474 2946 3090 2940	14,1 14,5 14,1 14,9	250 262 271 233	175 203 219 197
Rasikuiva palahake *Seasoned chunks*	Kesä *Summer*	Janakkala Joroinen Hyrylä Ylihärmä	3446 3212 3395 3190	2364 2529 2862 2730	13,6 14,6 14,2 13,1	253 220 239 244	174 173 202 208
Rasikuiva hienohake *Seasoned chips*	Syksy *Autumn*	Janakkala Joroinen Hyrylä Ylihärmä	4145 4153 3759 4089	3561 3541 3239 3739	15,2 14,7 14,8 14,3	273 283 254 285	234 241 219 261
Rasikuiva hienohake verkkokontissa *Seasoned chips in a wire mesh bin*	Syksy *Autumn*	Ylihärmä	3958	3518	13,7	289	257
Rasikuiva palahake *Seasoned chunks*	Syksy *Autumn*	Janakkala Joroinen Hyrylä Ylihärmä	3665 4112 3268 3146	3057 3322 2690 2848	13,9 14,6 14,0 13,1	264 282 233 240	220 228 192 217
Rasikuiva palahake verkkokontissa *Seasoned chunks in a wire mesh bin*	Syksy *Autumn*	Ylihärmä	2970	2690	13,7	217	196



Kuva 6. Hakkeen ja rasipuiden kuivatuksen ajoittuminen eri paikkakunnilla 1981 ja 1982.
Fig. 6. Timing of drying and leaf seasoning in different localities in 1981 and 1982.

24. Näytteiden otto ja käsittely

Haketuksen yhteydessä otettiin kustakin kontillisesta näytteet hakkeen kosteuden, palakokojakauman ja home-itiöiden määrän määrittämiseksi. Konttien tyhjentämisen yhteydessä kerättiin uudelleen kosteus- ja homepölynäytteet. Hakkeesta otettiin vuonna 1982 homepölynäytteet myös kuivatusajan puolivälissä. Homepölyä koskevat tulokset on julkaistu aikaisemmin (Pellikka 1983, Pellikka ja Kotimaa 1983).

Hakkeen alkukosteus määritettiin hyvin sekoitetusta, vasta haketetusta materiaalista. Jokaisesta kontista määritettiin yksi 1—2 litran näyte, joka kuljetettiin kaksinkertaisessa muovipussissa laboratorioon käsiteltäväksi. Näytteistä otettiin tuorepaino saapumispäivän aikana. Mikäli uunikuivatusta ei voitu suorittaa heti, varastoitiin näytteet kylmäkaapissa. Kuivapainon määrittämiseksi näytteitä kuivattiin kaksi vuorokautta 102°C:n lämmössä.

Punnitusmenetelmän aiheuttamat virheet kosteus- ja kuiva-ainemäärissä pyrittiin korjaamaan konttien tyhjennyksen yhteydessä otetuilla näytteillä. Varastoidun hakkeen keskimääräisen kosteuden määrittäminen on kuitenkin vaikeata, sillä kosteus kerrostuu vyöhykkeiksi hakkeen sisällä.

Vuonna 1981 käytettiin näytteiden otannassa useita eri menetelmiä. On vaikeata arvioida kuinka erityyppiset otannat vaikuttavat laskettuihin keskiarvoihin. Näytteiden pieniä keskihajontoja voitaneen kuitenkin pitää osoituksena otannan onnistumisesta. Kustakin kontista otettiin 4—15 näytettä. Joissain tapauksissa otettiin sekoitettu näyte kontin poikkileikkauspinnalta metrin välein. Toisissa tapauksissa taas otettiin erilliset näytteet kontin pinta-, keski- ja pohjavyöhykkeistä. Taulukosta 2a ilmenevät myös kustakin kontista otettujen keräilynäytteiden lukumäärä, lasketut keskiarvot sekä painon perusteella lasketut loppukosteudet.

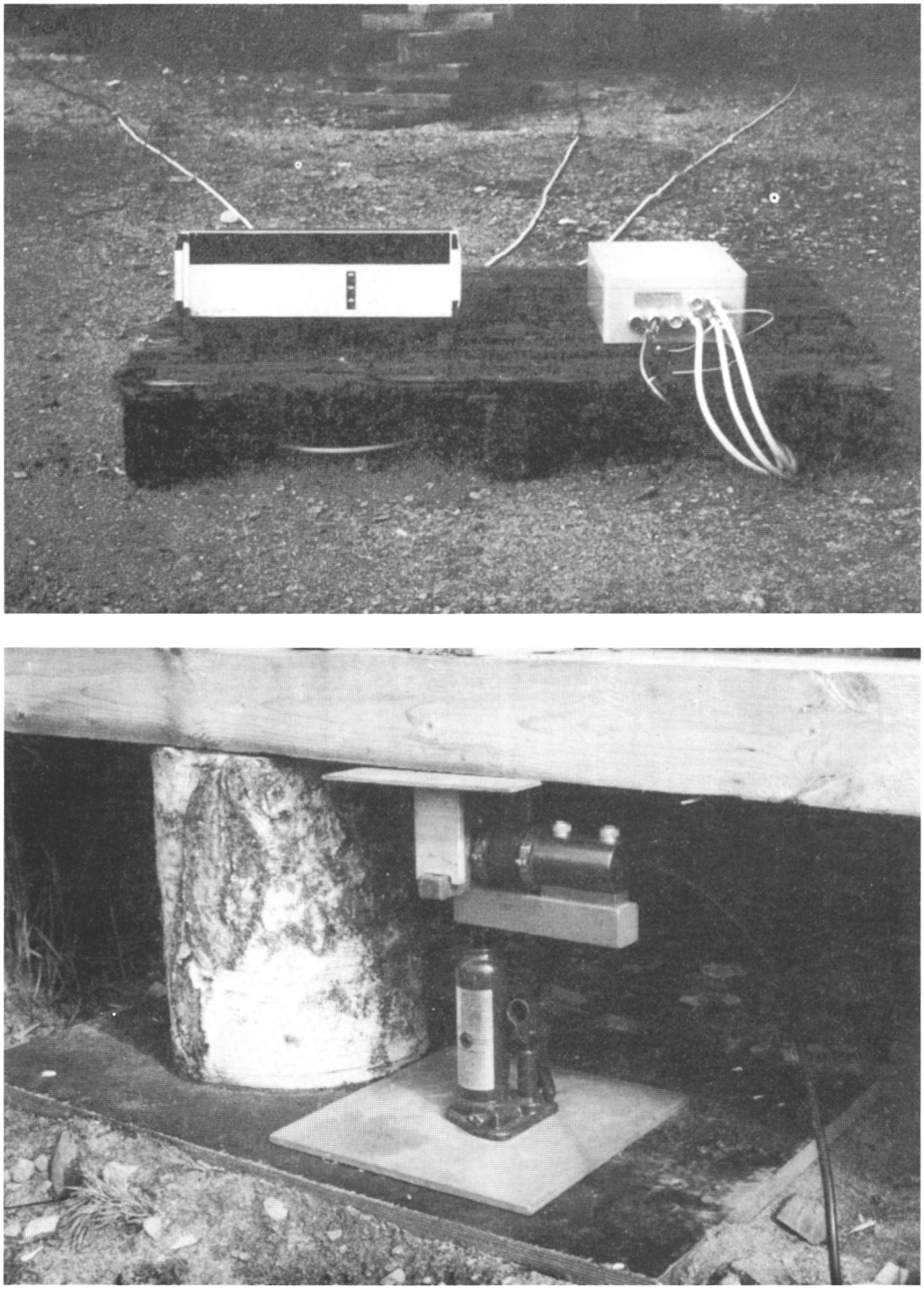
Vuonna 1982 käytettiin kaikkien konttien tyhjennyksessä samaa näytteiden otantamenetelmää. Kutakin kontin pituuden täyttä metriä kohti kerättiin 50—100 litraa haketta, josta otettiin kosteusnäyte sekoituksen jälkeen. Näin saatiin jokaisesta kontista viisi keräilynäytettä. Alku- ja loppukosteudet ilmenevät taulukosta 2b.

Jokaisesta kontista otettiin haketuksen yhteydessä seulontanäytteitä, joiden suuruus oli noin 10 litraa. Seulontatulokset osoittavat selvästi hieno- ja palahakkeen kokojakauman erot (kuva 8).

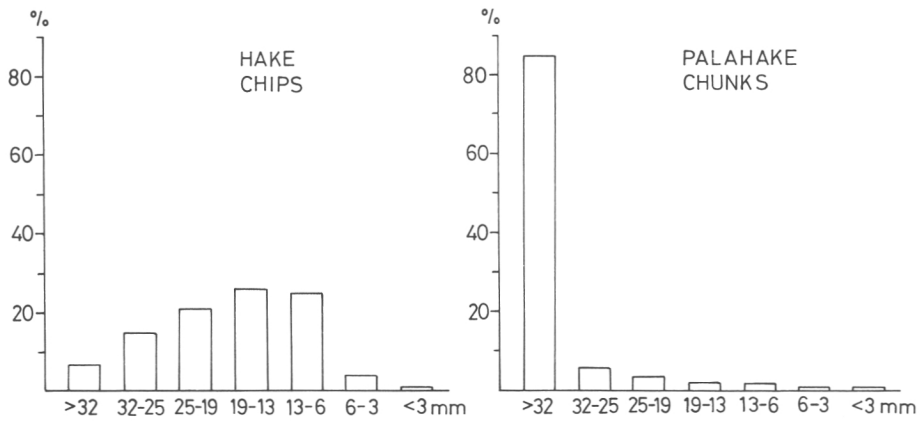
25. Ilmastolliset tilastot

Lämpötilan ja ilman suhteellisen kosteuden mittauksilla saatiin taustatietoa kuivatusoloista ja sään vaihteluista paikkakuntien ja koevuosien välillä. Kuivumisen riippuvuutta säästä ei kuitenkaan ole selvitetty tässä yhteydessä.

Kaikki oheisena esitetyt vuosien 1981 ja 1982 tilastot on saatu Ilmatieteen laitokselta. Tässä esiintyvät suureet lämpötila, ilman suhteellinen kosteus, tuulen nopeus ja kyllästyssuojaus on määritelty Tilastoja Suomen ilmastosta 1961-1980 -julkaisussa (Heino ja Hellsten 1983). Aineisto on koottu taulukkoon 3 sekä liitteisiin 1



Kuva 7. Yläkuvassa vaaka ja mittauslähetin. Alakuvassa tunkki antureineen.
Fig. 7. Electronic scale and amplifier above. The jack and load cell below.



Kuva 8. Hakkeen ja palahakkeen pituusjakaumat.
Fig. 8. Particle length distribution of chips and chunks.

Taulukko 2a. Hakkeen ja palahakkeen kosteudet vuonna 1981.
Table 2a. Moisture contents of chips and chunks in 1981.

Hake Chips/ chunks	Tekoaika *Season*	Paikkakunta *Location*	Lähtökosteus, % *Starting* m.c., %	Punnittu *Weight scale*	Loppukosteus — *Final m.c.*, % $\bar{x}$	Näytteet *Samples* s	n
Tuore	Kevät	Janakkala	55,4	24,6	37,2	—	—
hienohake	*Spring*	Joroinen	50,0	27,2	30,8	1,6	6
Fresh		Hyrylä	54,0	19,5	29,8	1,6	4
chips		Ylihärmä	39,6	23,3	18,2	0,3	10
Tuore	Kevät	Janakkala	56,2	23,7	28,0	—	—
palahake	*Spring*	Joroinen	50,7	26,8	29,9	5,6	6
Fresh		Hyrylä	41,9	11,8	20,0	1,9	4
chunks		Ylihärmä	39,9	21,2	14,4	0,3	6
Tuore	Kesä	Janakkala	55,4	37,0	—	—	—
hienohake	*Summer*	Joroinen	48,8	33,6	37,3	3,0	7
Fresh		Hyrylä	47,9	23,1	31,9	4,9	15
chips		Ylihärmä	43,7	24,6	27,9	5,5	15
		Pyhtää	50,3	25,8	38,3	2,3	9
Tuore	Kesä	Janakkala	57,8	40,4	—	—	—
palahake	*Summer*	Joroinen	51,3	29,9	30,0	3,6	15
Fresh		Hyrylä	50,7	25,6	26,5	3,3	15
chunks		Ylihärmä	40,7	16,2	23,5	2,6	15
		Pyhtää	54,3	29,9	35,1	4,9	7
Rasikuiva	Kesä	Janakkala	45,3	28,2	—	—	—
hienohake	*Summer*	Joroinen	41,0	26,5	26,7	3,3	11
Seasoned		Hyrylä	48,6	29,7	32,4	7,9	15
chips		Ylihärmä	32,6	22,5	21,9	1,5	15
		Pyhtää	47,7	32,4	37,0	1,2	10
Rasikuiva	Kesä	Janakkala	44,0	26,1	—	—	—
palahake	*Summer*	Joroinen	42,9	29,9	—	—	—
Seasoned		Hyrylä	39,5	27,4	25,8	3,7	15
chunks		Ylihärmä	33,6	14,6	20,1	1,3	15
		Pyhtää	45,4	24,8	27,8	3,5	10
Rasikuiva	Syksy	Janakkala	50,3	43,3	41,7	3,3	15
hienohake	*Autumn*	Joroinen	40,8	37,1	—	—	—
Seasoned		Hyrylä	47,9	44,8	43,2	9,4	12
chips		Ylihärmä	40,1	33,2	32,2	3,8	15
Rasikuiva	Syksy	Janakkala	47,5	36,8	39,6	3,8	15
palahake	*Autumn*	Joroinen	44,0	37,0	—	—	—
Seasoned		Hyrylä	41,0	39,7	36,8	5,6	12
chunks		Ylihärmä	37,0	30,1	29,5	1,8	15

Taulukko 2b. Hakkeen ja palahakkeen kosteudet vuonna 1982.
Table 2b. The moisture contents of chips and chunks in 1982.

Hake Chips/ chunks	Tekoaika *Season*	Paikkakunta *Location*	Lähtökosteus, % *Starting* m.c., %	Punnittu *Weight scale*	Loppukosteus — *Final m.c.*, % $\bar{x}$	Näytteet *Samples* s	n
Tuore	Kevät	Janakkala	54,3	15,3	26,8	2,9	5
hienohake	*Spring*	Joroinen	50,6	22,0	27,4	1,8	5
Fresh		Hyrylä	50,9	19,6	27,6	8,8	5
chips		Ylihärmä	45,9	11,5	17,3	1,9	5
Tuore	Kevät	Ylihärmä	45,6	14,3	15,6	3,5	5
hienohake	*Spring*						
verkkokontissa							
Fresh chips in							
a wire mesh bin							
Tuore	Kevät	Janakkala	53,1	18,5	24,5	9,2	5
hienohake	*Spring*	Joroinen	48,3	13,0	23,4	3,2	5
Fresh		Hyrylä	51,5	16,7	16,7	2,8	5
chips		Ylihärmä	45,0	12,8	16,5	4,3	5
Tuore	Kevät	Ylihärmä	47,6	16,0	18,8	1,3	5
palahake	*Spring*						
verkkokontissa							
Fresh chunks in							
a wire mesh bin							
Tuore	Kesä	Janakkala	53,8	32,9	35,0	7,9	5
hienohake	*Summer*	Joroinen	52,7	26,9	—	—	0
Fresh		Hyrylä	45,9	19,8	27,7	1,9	5
chips		Ylihärmä	43,9	25,8	26,3	2,4	5
Tuore	Kesä	Janakkala	50,9	26,6	31,8	2,8	5
palahake	*Summer*	Joroinen	52,4	24,8	—	—	0
Fresh		Hyrylä	49,3	22,5	24,2	3,4	5
chunks		Ylihärmä	39,8	18,6	22,8	2,0	5
Rasikuiva	Kesä	Janakkala	44,5	22,3	26,5	2,2	5
hienohake	*Summer*	Joroinen	44,0	28,3	27,4	3,0	5
Seasoned		Hyrylä	33,4	20,6	24,6	3,0	5
chips		Ylihärmä	32,9	24,3	21,5	1,7	5
Rasikuiva	Kesä	Janakkala	50,2	28,4	25,8	2,2	5
palahake	*Summer*	Joroinen	41,2	25,4	20,3	0,5	5
Seasoned		Hyrylä	31,9	21,3	20,1	0,8	5
chunks		Ylihärmä	31,2	22,9	19,8	1,4	5
Rasikuiva	Syksy	Janakkala	49,5	42,3	42,8	2,8	5
hienohake	*Autumn*	Joroinen	49,0	41,5	38,8	1,2	5
Seasoned		Hyrylä	36,2	27,4	33,0	2,5	4
chips		Ylihärmä	33,0	28,2	30,1	2,4	5
Rasikuiva	Syksy	Ylihärmä	33,0	27,6	27,4	5,8	5
hienohake	*Autumn*						
verkkokontissa							
Seasoned chips in a							
wire mesh bin							
Rasikuiva	Syksy	Janakkala	48,6	38,7	37,4	8,3	5
palahake	*Autumn*	Joroinen	46,3	35,2	34,7	1,8	5
Seasoned		Hyrylä	35,2	23,4	26,4	1,7	5
chunks		Ylihärmä	34,3	27,5	28,0	1,3	5
Rasikuiva	Syksy	Ylihärmä	34,3	29,3	27,8	3,5	5
palahake	*Autumn*						
verkkokontissa							
Seasoned chunks in							
a wire mesh bin							

Taulukko 3. Ilmastollisia tilastoja vuosilta 1981 ja 1982 (°C = ilman lämpötila, m/s = tuulen nopeus ja % = ilman suhteellinen kosteus).
Table 3. Weather data in 1981 and 1982 (°C = air temperature, m/s = wind speed and % = relative humidity).

Kuukausi *Month*	Muuttuja *Variable*	1981 Sääasema — *Weather station* Hattula	Varkaus	Kauhava	Ruotsinpyhtää	Hyrylä	1982 Sääasema — *Weather station* Hattula	Varkaus	Kauhava	Hyrylä
Huhtikuu	°C	1,3	0,2	0,5	1,4	1,8	2,6	1,6	1,1	2,9
April	m/s	..	..	4,0	3,3	3,9	3,5	..	3,4	4,1
	%	73	68	72	73	70	75	69	76	77
Toukokuu	°C	11,8	10,2	10,4	10,2	11,4	9,1	8,1	7,6	9,7
May	m/s	..	..	3,3	3,0	2,9	4,3	..	3,9	4,5
	%	65	63	65	68	62	71	66	72	68
Kesäkuu	°C	13,4	13,0	12,1	12,7	13,5	11,8	10,2	10,2	12,0
June	m/s	..	..	4,1	4,5	3,3	3,4	..	3,3	3,6
	%	79	78	77	80	76	66	63	61	66
Heinäkuu	°C	16,8	17,2	16,2	16,8	17,1	17,0	16,5	15,6	17,5
July	m/s	..	..	3,2	3,8	3,4	2,5	..	2,9	3,0
	%	79	74	80	77	74	65	62	66	64
Elokuu	°C	13,8	13,1	12,2	14,3	14,2	15,7	14,2	14,0	16,0
August	m/s	..	..	3,0	3,5	3,1	2,6	..	3,2	2,9
	%	83	82	86	82	74	74	76	76	76
Syyskuu	°C	9,9	8,6	8,4	10,5	10,4	9,9	7,8	8,5	10,5
September	m/s	..	..	2,6	2,9	2,2	3,2	..	3,4	2,4
	%	86	85	89	84	86	81	83	83	82
Lokakuu	°C	5,8	5,0	4,2	6,7	6,3	3,9	2,1	2,8	4,8
October	m/s	..	..	3,5	4,3	2,8	2,5	..	3,1	2,4
	%	91	90	93	86	90	88	87	88	85
Marraskuu	°C	-0,4	-1,7	-1,7	0,3	-0,1	3,0	1,4	1,5	3,7
November	m/s	..	..	4,0	3,0	3,3	4,9	..	4,0	4,7
	%	92	92	93	88	91	88	90	92	87
Joulukuu	°C	-7,5	-9,2	-10,7	-5,5	-6,7	-1,2	-3,4	-2,7	0,3
December	m/s	..	..	3,9	2,3	2,3	3,6	..	4,0	3,6
	%	90	86	89	86	89	89	90	91	90

ja 2. Koepaikkoja lähinnä olleet sääasemat olivat seuraavat:

Koepaikkakunta	Sääasema
Janakkala	Leteensuo, Hattula
Joroinen	Kuoppakangas, Varkaus
Hyrylä	Anttilan koetila, Hyrylä
Ylihärmä	Lentokenttä, Kauhava
Pyhtää	Ruotsinpyhtää

26. Kuiva-ainetappiot ja tehollinen lämpöarvo

Haketta varastoitaessa mikrobien toiminta aktivoituu. Mikäli ympäristöolot — lämpötila, kosteus, ravinto — ovat epäsuotuisat, on organismien hajotustoiminta hyvin hidasta tai sitä ei esiinny lainkaan. Aineen lämpötilan kohoaminen ja kuiva-aineen väheneminen ovat todisteita päinvastaisesta tilasta. Tämä on usein havaittavissa haketta kuivattaessa ja varastoitaessa (Aittomäki, 1963, Håkansson ja Numminen 1963, Bergman ja Nilsson 1967, 1979, Mihajlov 1971, Gislerud 1974, Gislerud ja Grønlien 1977 ja 1978a, b, Thörnqvist 1980, 1982, 1983).

Kuiva-ainetappioiden suuruus on laskettu tutkimuksen alussa ja lopussa määritettyjen kuiva-ainemäärien erotuksina. Koska laskenta perustuu kosteusnäytteistä saatuihin tuloksiin, haittaa otantaan liittyvä vaihtelu kuiva-ainetappioiden määritystä. Mittausmenetelmä voi jopa osoittaa kuiva-aineen lisääntyneen, minkä on katsottava johtuvan otannassa syntyneestä virheestä.

Tehollisten lämpöarvojen (MJ/i-m^3) laskemiseksi käytettiin Valtion polttoainekeskuksen kaupallisessa toiminnassa käyttämää yhtälöä koivu- ja leppäkokopuulle (Haapasalo, 1983). Käytetty yhtälö on muotoa $W_{eff} = 19.246—0.217$ K, missä K on hakkeen kosteus prosentteina tuorepainosta. Lämpöarvon muutos on ilmaistu prosentteina kokeen alussa saadusta lämpöarvosta. Hakkeen kuivuminen lisää ja kuiva-ainetappio vähentää tehollista lämpöarvoa. Muutoksen suunta riippuu näiden tekijöiden suhteesta.

27. Tilastollinen tarkastelu

Tuloksia tarkastellaan edellä mainittujen menetelmien lisäksi kuivumista kuvaavilla regressioyhtälöillä. Parhaan selitysasteen useimmille hake-erille antoi yhtälö $y_i = a + bx_i + cln\ (x_i)$, joten sen käyttöön päädyttiin kaikissa hake-erissä.

Selittävänä muuttujana (x_i) käytettiin kuivatusviikkojen määrää. Selitettäviä muuttujia (y_i) oli kolme: hakkeen kosteus prosentteina tuorepainosta (%), kosteuden väheneminen ja hakkeen irtokuutiometrin paino (kg/ i-m^3). Kosteuden vähenemisen laskemiseksi on kunkin

hake-erän lähtökosteudelle (%) annettu arvo 100, ja kaikki sitä seuraavat arvot on laskettu prosentteina lähtöarvoista. Näin on pyritty poistamaan paikkakuntien väliset lähtökosteuksien erot. Menettelyllä päästään parempiin selitysasteisiin varsinkin niiden hake-erien kohdalla, joissa lähtökosteuksien hajonta on suuri. Kosteuden vähenemistä osoittavan regressioyhtälön etuna on vielä se, että sitä voidaan käyttää joustavammin hakkeen kosteuden arvioimiseen kuin normaalia tuorepainoon perustuvaa kosteutta, koska lähtökosteusarvo ei tässä tapauksessa ole kiinteä.

Logaritmiselle yhtälölle saadaan määrittelemätön arvo selittävän muuttujan arvolla 0 viikkoa. Tämän vuoksi on yhtälöitä laskettaessa oletettu ensimmäisen punnituksen tapahtuneen kuivatuspäivänä 1. Tämä menettely ei kuitenkaan aiheuta suurta virhettä, sillä punnituslaitteiston siirtely paikkakunnalta toiselle siirsi punnituksen joissakin tapauksissa haketusta seuraavaksi päiväksi.

Hakkeen kosteuden (%) osoittavat regressioyhtälöt löytyvät kuvien 9—27 yhteydestä sekä taulukosta 7. Kosteuden vähenemisen yhtälöt löytyvät samoin taulukosta 7. Hakkeen painon kuvaajat ja yhtälöt on koottu liitteisiin 3—7.

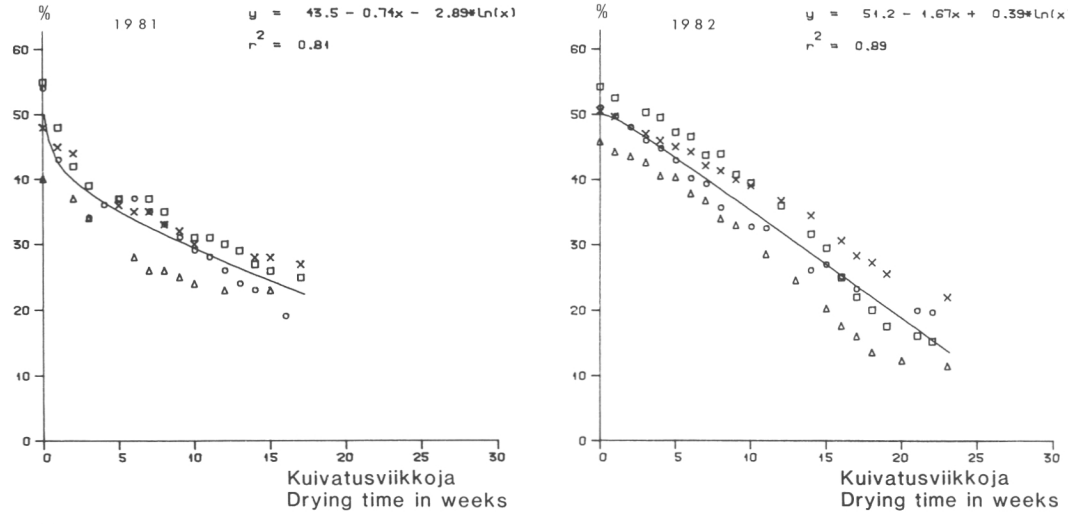
3. KUIVATUSKOKEEN TULOKSET HAKE-ERITTÄIN

31. Kevään kaatotuore hienohake

Kuivatuskokeen ensimmäiset hake-erät tehtiin jo keväällä ennen lehtien puhkeamista. Ensimmäisenä vuonna puut kaadettiin toukokuussa mutta toisena jo huhtikuussa. Sää oli suotuisampi vuonna 1981, koska kuivatus alkoi keskimäärin 8 viikkoa myöhemmin kuin vuonna 1982 (taulukko 3). Seuraava asetelma on tiivistelmä ensimmäisten kuivatuskuukausien säästä. Lukemat ovat sääasemilta saatuja keskiarvoja.

	Lämpötila °C	Tuuli m/s	Kosteus %	Kyllästysvajaus mb
1981 Toukokuu	10,8	3,1	65	7,1
1982 Huhtikuu	2,0	3,7	73	2,4

Huolimatta kuivatuksen alkamisesta eri aikoina olivat lähtökosteudet samat: 49,8 % (1981) ja 49,5 % (1982). Kuivuminen edistyi eri vuosina kuitenkin eri tavoin (kuva 9). Vuoden 1981 kosteuksia esittävä kuvaaja on selvästi muodoltaan logaritminen, kun taas vuonna 1982 kuivuminen on lähes lineaarista (kuva 9).



Kuva 9. Kevään kaatotuoreen hienohakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 9. Moisture content of chips made from fresh material in spring as a function of time in 1981 and 1982.

Taulukko 4. Hakkeiden loppukosteudet (%) vuosina 1981 ja 1982.
Table 4. The final moisture contents of chips and chunks in1981 and 1982.

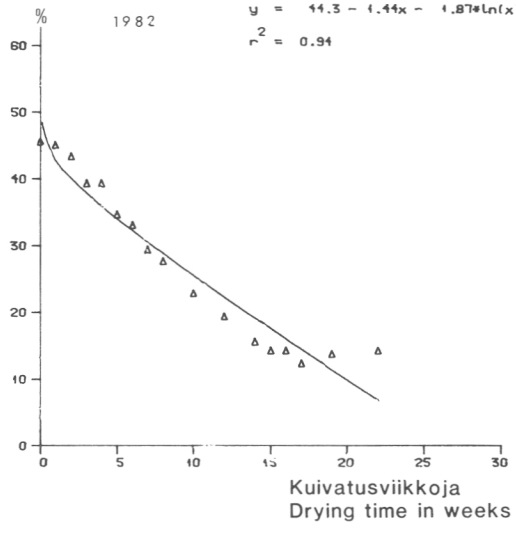
Tekoaika ja hake *Season and particle size*	Kontin tyyppi *Bin type*	1981 %	1982 %
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Puu — *Wooden*	29,0	24,8
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Verkko — *Mesh*		15,6
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Puu — *Wooden*	23,1	20,3
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Verkko — *Mesh*		18,8
Kesän kaatotuore hienohake *Summer chips from fresh trees*	Puu — *Wooden*	33,9	29,7
Kesän kaatotuore palahake *Summer chunks from fresh trees*	Puu — *Wooden*	28,8	26,3
Kesän rasikuiva hienohake *Summer chips from seasoned trees*	Puu — *Wooden*	29,5	25,0
Kesän rasikuiva palahake *Summer chunks from seasoned trees*	Puu — *Wooden*	24,6	21,5
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Puu — *Wooden*	39,0	36,2
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Verkko — *Mesh*		27,4
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Puu — *Wooden*	35,3	31,6
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Verkko — *Mesh*		27,8

Taulukoista 2a ja b ilmenevät punnitustuloksista sekä kosteusnäytteistä lasketut kosteusprosentit kokeen lopussa. Kosteusnäytteistä laskettu paikkakuntien keskiarvo oli vuonna 1981 29,0 % ja vuonna 1982 24,8 %. Kuiva-ainetappiot olivat vastaavasti kuukautta kohti keskimäärin 1,4 % ja 1,5 %. Hakkeen tehollinen lämpöarvo oli noussut hieman molempina vuosina. Keskimääräiset muutokset olivat +1,3 % (1981) ja +0,9 % (1982) (taulukot 4—6).

Hakkeen kosteuden selitysasteet olivat hyvät molempina vuosina. Kun valitaan kosteuden väheneminen selitettäväksi muuttujaksi, saadaan hieman korkeampia arvoja (taulukko 7).

Verkkokontissa kuivattavaa kesän kaatotuoretta haketta tutkittiin vain Ylihärmässä (kuva 10). Selitysaste (r^2 = 0,94) on hyvä, koska paikkakuntien välinen hajonta puuttuu.

Verkkokontissa kuivuneen hakkeen kuivumista on luonnollista verrata Ylihärmässä lautakontissa vuonna 1982 kuivuneeseen ha-



Kuva 10. Verkkokontissa kuivatun kevään kaatotuoreen hienohakkeen kosteuden muuttuminen vuonna 1982.
Fig. 10. Moisture content of chips made from fresh material in spring and dried in a wire mesh bin in 1982.

Taulukko 5. Hakkeen kuivatuksen aikana syntyneet kuiva-ainetappiot vuosina 1981 ja 1982.
Table 5. Dry matter losses during the drying experiment in 1981 and 1982.

Tekoaika ja hake *Season and particle size*	Kontin tyyppi *Bin type*	*Kokonaistappio* *Total losses*		Kuukausitappio *Monthly losses*	
		1981	1982	1981	1982
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Puu — *Wooden*	-5,1	-8,4	-1,4	-1,5
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Verkko — *Mesh*		-3,5		-0,7
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Puu — *Wooden*	-5,4	-6,0	-1,5	-1,2
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Verkko — *Mesh*		-4,0		-0,8
Kesän kaatotuore hienohake *Summer chips from fresh trees*	Puu — *Wooden*	-8,5	-4,6	-1,5	-1,2
Kesän kaatotuore palahake *Summer chunks from fresh trees*	Puu — *Wooden*	-4,6	-5,4	-0,7	-1,1
Kesän rasikuiva hienohake *Summer chips from seasoned trees*	Puu — *Wooden*	-2,0	-4,1	-0,4	-0,9
Kesän rasikuiva palahake *Summer chunks from seasoned trees*	Puu — *Wooden*	-2,0	-0,7	-0,4	+0,4
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Puu — *Wooden*	-0,4	-4,9	-0,1	-2,4
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Verkko — *Mesh*		-3,7		-1,6
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Puu — *Wooden*	-1,1	-2,0	-0,3	-1,0
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Verkko — *Mesh*		-0,5		-0,2

ke-erään, koska kokeet suoritettiin vierekkäisissä konteissa. Samasta lähtökosteudesta huolimatta kuivui verkkokontissa ollut hake nopeammin kuivatusjakson alussa. Molemmat Ylihärmän hakkeet saavuttivat tasapainokosteuden ilman kanssa noin 15—20 viikon kuluttua kuivatuksen alkamisesta. Tällöin myös niiden punnitustuloksista lasketut kosteudet olivat lähes samat.

Verkkokontissa kuivatun hakkeen loppukosteus oli 15,6 % ja Ylihärmän H1-hakkeen 17,3 %. Kuiva-ainetappiot olivat kuukautta kohti vastaavasti 0,7 % ja 1,3 %. Hakkeen tehollisen lämpöarvon muutos oli verkkokontissa + 5,1 % ja lautakontissa + 2,0 %.

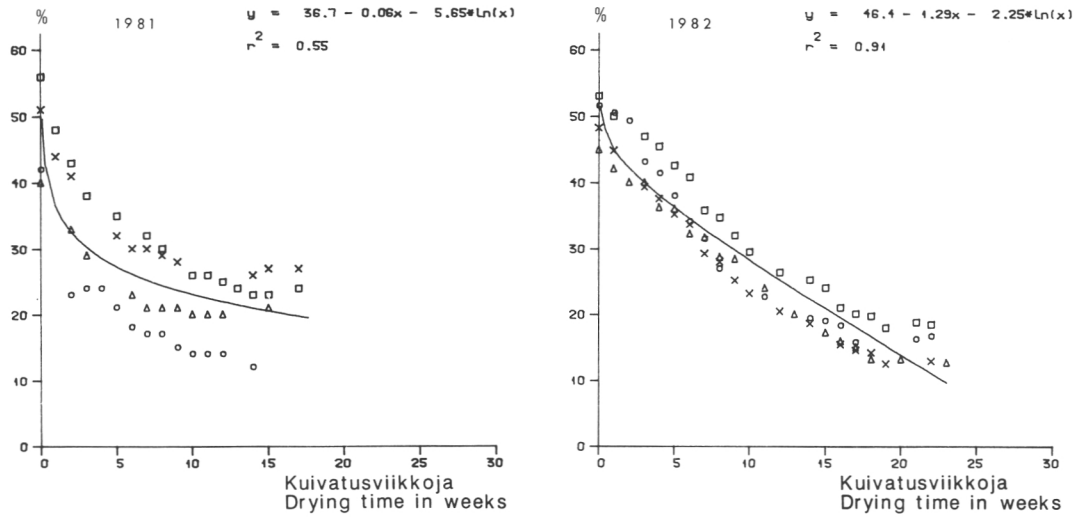
32. Kevään kaatotuore palahake

Palahakkeet kuivuivat kevään kaatotuoreita hienohakkeita nopeammin. Yhteistä pala- ja hienohakkeiden kuvaajille on kuitenkin kuivumiskokeen eriaikaisuudesta johtuva kuvaajan logaritmisuus vuonna 1981 ja lineaarisuus vuonna 1982.

Lähtökosteudet 47,2 % (1981) ja 49,1 % (1982) olivat jotakuinkin samat kuin hienohakkeiden. Kuusi viikkoa pidemmän kuivatusajan vuoksi vuoden 1982 kuivatustulos oli parempi. Keskimääräiset kosteudet kokeen lopussa olivat 23,1 % (1981) ja 20,3 % (1982). Kuiva-ainetappiot olivat vastaavasti kuukaudessa 1,5 % ja 1,2 %. Tehollisen lämpöarvon muutokset olivat positiiviset lukuun ottamatta Hyrylää (1981) ja Joroista (1982). Keskimääräiset muutokset olivat +5,2 % (1981) ja +4,5 % (1982) (taulukot 4—6).

Käytettäessä hakkeen kosteutta selitettävänä muuttujana saadaan erinomainen selitysaste (r^2 = 0,91) vuonna 1982 (kuva 11). Ensimmäisen tutkimusvuoden tulosta (r^2 = 0,55) heikentää parven suuri hajonta. Arvot paranevat, mikäli tasoerot poistetaan käyttämällä suhteellista kosteusprosenttia.

Verkkokontissa kuivatun palahakkeen kuivumisen kuvaaja osoittaa kuivumisen lä-



Kuva 11. Kevään kaatotuoreen palahakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 11. Moisture content of chunks made from fresh material in spring as a function of time in 1981 and 1982.

Taulukko 6. Hakkeen tehollinen lämpöarvo (MJ/i-m^3) kuivatuksen lopussa sekä kuivumisen ja kuiva-ainetappioiden aiheuttama lämpöarvon kokonaismuutos prosentteina (%).
Table 6. The effective heat value (MJ/m^3 loose) of chips and chunks at the end of the drying experiment; and the accumulative change of heat value effected by drying and dry matter losses.

Tekoaika ja hake *Season and particle size*	Kontin tyyppi *Bin type*	Lämpöarvo, MJ/i-m^3 *Heat value, MJ/m^3 loose*		Muutos, % — *Change, %*	
		1981	1982	1981	1982
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Puu — *Wooden*	2784	2827	+1,3	+0,9
Kevään kaatotuore hienohake *Spring chips from fresh trees*	Verkko — *Mesh*		2918		+5,1
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Puu — *Wooden*	2764	2885	+5,2	+4,5
Kevään kaatotuore palahake *Spring chunks from fresh trees*	Verkko — *Mesh*		3185		+5,4
Kesän kaatotuore hienohake *Summer chips from fresh trees*	Puu — *Wooden*	2683	2781	−2,5	+1,2
Kesän kaatotuore palahake *Summer chunks from fresh trees*	Puu — *Wooden*	2515	2733	+2,9	+0,9
Kesän rasikuiva hienohake *Summer chips from seasoned trees*	Puu — *Wooden*	2834	2745	+3,0	−0,3
Kesän rasikuiva palahake *Summer chunks from seasoned trees*	Puu — *Wooden*	3001	2765	+1,7	+6,7
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Puu — *Wooden*	2787	2726	+3,5	−1,7
Syksyn rasikuiva hienohake *Autumn chips from seasoned trees*	Verkko — *Mesh*		3418		−2,1
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Puu — *Wooden*	2789	2643	+3,8	+1,4
Syksyn rasikuiva palahake *Autumn chunks from seasoned trees*	Verkko — *Mesh*		2590		+1,1

Taulukko 7. Hakkeen kosteuden muuttuminen viikkoina mitatun kuivumisajan (x) pituudella selitettynä.
Table 7. Moisture content of chips and chunks as a function of drying time (x) measured in weeks.

Hake — *Chips/Chunks*	Kontti — *Bin*	Vuosi *Year*	Yhtälö — *Equation*	r^2	sy·x
	Hakkeen kosteus — *Moisture content*				
Kevään kaatotuore hienohake	Puu — *Wood*	1981	43,5−0,74x− 2,89 ln(x)	0,81	3,60
Spring chips from fresh trees		1982	51,2−1,67x+ 0,39 ln(x)	0,89	3,95
	Verkko — *Mesh*	1982	44,3−1,44x− 1,87 ln(x)	0,94	3,28
Kevään kaatotuore palahake	Puu — *Wood*	1981	36,7−0,06x− 5,65 ln(x)	0,55	6,88
Spring chunks from fresh trees		1982	46,4−1,29x− 2,25 ln(x)	0,91	3,66
	Verkko — *Mesh*	1982	46,7−1,50x− 1,23 ln(x)	0,96	2,45
Kesän kaatotuore hienohake	Puu — *Wood*	1981	40,0+0,03x− 5,41 ln(x)	0,61	5,68
Summer chips from fresh trees		1982	43,5−0,59x− 3,03 ln(x)	0,64	5,90
Kesän kaatotuore palahake	Puu — *Wood*	1981	40,0+0,20x− 6,29 ln(x)	0,39	9,08
Summer chunks from fresh trees		1982	38,7−0,24x− 4,69 ln(x)	0,71	5,30
Kesän rasikuiva hienohake	Puu — *Wood*	1981	33,5+0,35x− 4,93 ln(x)	0,38	6,18
Summer chips from seasoned trees		1982	31,2+0,13x− 3,66 ln(x)	0,61	3,98
Kesän rasikuiva palahake	Puu — *Wood*	1981	27,0+0,75x− 6.65 ln(x)	0,50	5,62
Summer chunks from seasoned trees		1982	29,8+0,30x− 4,26 ln(x)	0,44	5,59
Syksyn rasikuiva hienohake	Puu — *Wood*	1981	39,6+0,38x− 2,39 ln(x)	0,25	4,06
Autumn chips from seasoned trees		1982	38,0+0,06x− 1,51 ln(x)	0,09	7,30
	Verkko — *Mesh*	1982	28,8+0,23x− 1,81 ln(x)	0,94	0,68
Syksyn rasikuiva palahake	Puu — *Wood*	1981	37,4+0,27x− 2,29 ln(x)	0,36	3,36
Autumn chunks from seasoned trees		1982	35,1+0,28x− 2,41 ln(x)	0,22	6,08
	Verkko — *Mesh*	1982	29,6+0,41x− 2,04 ln(x)	0,83	1,18
	Kosteuden aleneminen — *Reduction of moisture content*				
Kevään kaatotuore hienohake	Puu — *Wood*	1981	88,0−1,64x− 5,63 ln(x)	0,84	6,80
Spring chips from fresh trees		1982	101,8−3,35x+ 0,77 ln(x)	0,94	5,80
	Verkko — *Mesh*	1982	97,1−3,16x− 4,10 ln(x)	0,94	7,20
Kevään kaatotuore palahake	Puu — *Wood*	1981	75,3−0,18x−11,06 ln(x)	0,74	9,61
Spring chunks from fresh trees		1982	94,1−2,64x− 4,48 ln(x)	0,94	5,65
	Verkko — *Mesh*	1982	98,2−3,16x− 2,57 ln(x)	0,96	5,14
Kesän kaatotuore hienohake	Puu — *Wood*	1981	80,6+0,09x−11,01 ln(x)	0,72	8,90
Summer chips from fresh trees		1982	87,1−0,99x− 6,58 ln(x)	0,81	7,54
Kesän kaatotuore palahake	Puu — *Wood*	1981	77,4+0,39x−12,35 ln(x)	0,57	12,49
Summer chunks from fresh trees		1982	79,5−0,35x−10,08 ln(x)	0,88	6,13
Kesän rasikuiva hienohake	Puu — *Wood*	1981	77,8+0,73x−11,24 ln(x)	0,60	9,35
Summer chips from seasoned trees		1982	80,1+0,51x− 9,67 ln(x)	0,80	6,16
Kesän rasikuiva palahake	Puu — *Wood*	1981	66,0+1,76x−16,33 ln(x)	0,64	10,47
Summer chunks from seasoned trees		1982	75,9+1,11x−11,58 ln(x)	0,84	5,33
Syksyn rasikuiva hienohake	Puu — *Wood*	1981	88,6+0,76x− 5,44 ln(x)	0,67	3,99
Autumn chips from seasoned trees		1982	94,4−0,54x− 2,44 ln(x)	0,59	4,83
	Verkko — *Mesh*	1982	87,4+0,71x− 5,50 ln(x)	0,94	2,04
Syksyn rasikuiva palahake	Puu — *Wood*	1981	88,5+0,62x− 5,34 ln(x)	0,65	4,37
Autumn chunks from seasoned trees		1982	88,7−0,09x− 4,78 ln(x)	0,69	5,63
	Verkko — *Mesh*	1982	86,2+1,20x− 5,94 ln(x)	0,83	3,45

hes yhtäläiseksi lautakonttien hakkeiden kanssa (kuva 12). Verkkokontin hake kuivui myös samalla nopeudella kuin Ylihärmän lautakontin hake.

Verkkokontin hakkeen loppukosteus oli yli kaksi prosenttiyksikköä suurempi Ylihärmän lautakontin hakkeen lukemaa: 18,8 % ja 16,5 %. Toisaalta verkkokontissa olleen hakkeen lähtökosteuskin oli suurempi. Koko kevään kaatotuoreen palahake-erän keskiarvokosteus vastaavana vuonna oli 20,3 %. Verkkokontin hakkeen kuiva-ainetappiot (0,8 %/kk) olivat jokseenkin samansuuruiset kuin Ylihärmän lautakontin hakkeessa (0,9 %/kk) ja koko palahake-erässä (1,2 %/kk). Tehollisen lämpöarvon muutos oli verkko-

kontissa +5,4 %, Ylihärmän lautakontissa +3,3 % ja koko erässä +4,5 %.

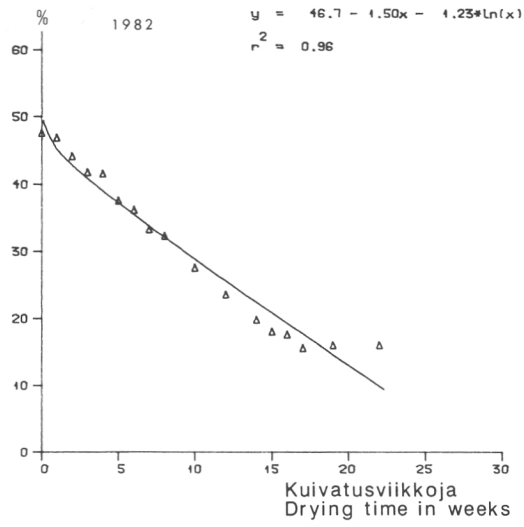
33. Kesän kaatotuore hienohake

Hakkeiden valmistus ajoittui molempina koevuosina kesä-heinäkuun vaihteeseen (kuva 6). Hakkeiden lähtökosteuksien keskiarvot olivat 49,2 % (1981) ja 49,1 % (1982). Kokeen alussa paikkakuntien välinen hajonta oli sama molempina vuosina (kuva 13). Kuivatuksen edistyessä hajonta kuitenkin lisääntyi jonkin verran. Näin oli etenkin vuonna 1981, jolloin Hyrylän hakkeen kuivuminen jatkui vielä joitakin viikkoja kuivumisen pysähdyttyä muilla paikkakunnilla.

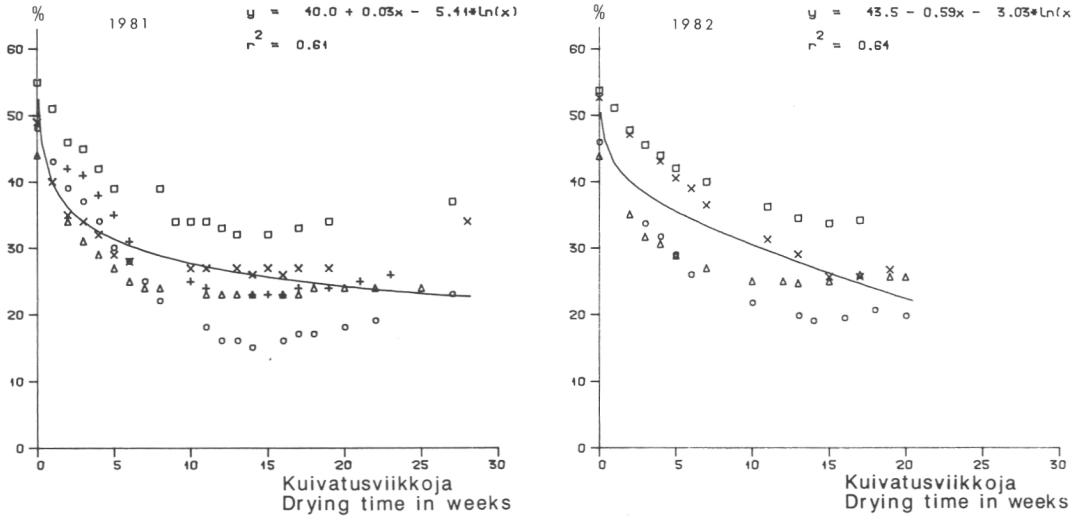
Hakkeiden keskimääräiset loppukosteudet ovat 33,9 % (1981) ja 29,7 % (1982). Vuoden 1981 suurempi arvo johtuu hakkeen kuivatuksen jatkumisesta talveen asti, jolloin hakkeeseen ehti imeytyä uutta kosteutta ilmasta. Kuiva-ainetappiot kuukautta kohti olivat 1,5 % (1981) ja 1,2 % (1982) (taulukot 4 ja 5).

Tehollisen lämpöarvon muutokset olivat molempien tutkimusvuosien välillä hyvin erilaiset. Erityisen huomionarvoinen oli vuosi 1981, sillä muutokset olivat negatiiviset kaikilla paikkakunnilla Janakkalaa lukuun ottamatta. Muutokset olivat keskimäärin −2,5 % (1981) ja +1,2 % (1982) (taulukko 6).

Kosteuden ollessa selitettävänä muuttujana saadaan kuivumisen yhtälölle tyydyttävät selitysasteet (taulukko 7). Vuoden 1981 alhaisempi selitysaste johtunee Hyrylän hakeerän poikkeavuudesta muihin paikkakuntiin nähden. Mikäli muuttujaksi valitaan kosteuden väheneminen, saadaan yhtälöille hieman paremmat selitysasteet.



Kuva 12. Verkkokontissa kuivatun kesän kaatotuoreen palahakkeen kosteuden muuttuminen vuonna 1982.
Fig. 12. Moisture content of chunks made from fresh material in spring and dried in a wire mesh bin in 1982.



Kuva 13. Kesän kaatotuoreen hienohakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 13. Moisture content of chips made from fresh material in summer as a function of time in 1981 and 1982.

34. Kesän kaatotuore palahake

Kesän kaatotuoreen palahakkeen kosteuden kuvaajia tarkasteltaessa kiinnittyy huomio heti suureen hajontaan vuonna 1981. Lähtökosteuksien suuren hajonnan lisäksi (40,7-57,8 %) hajonta vain lisääntyi kuivatuksen edistyessä. Paikkakuntien välinen järjestys ei kuitenkaan muuttunut kokeen aikana (kuva 14).

Kosteuden ollessa selitettävänä muuttujana saadaan selitysasteisiin selvät erot, r^2 = 0,39 (1981) ja r^2 = 0,71 (1982). Ylihärmän (1982) hakkeen vähäinen lähtökosteus aiheuttaa sen erottumisen muista paikkakunnista, vaikka kosteuden muuttuminen onkin ollut niiden kanssa samansuuntaista. Kun laskennassa käytetään suhteellista kosteutta, saadaan vuodelle 1981 kohtuulliset ja vuodelle 1982 hyvät selitysasteet (taulukko 7).

Hakkeiden lähtökosteuksien keskiarvot olivat 51,0 % (1981) ja 48,3 % (1982). Loppukosteuksiksi saatiin näytteiden perusteella vastaavasti 28,8 % ja 26,3 %. Hieman suurempi loppukosteus vuonna 1981 johtuu pitkästä kuivatusajasta aivan niin kuin saman vuoden hienohakkeiden loppukosteuskin.

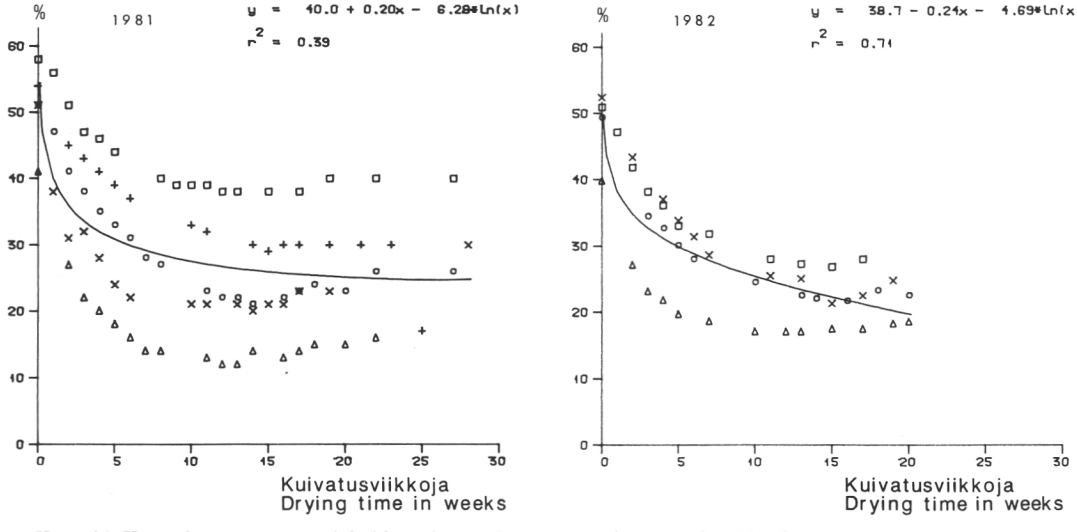
Kuiva-ainetappiot olivat kuukaudessa keskimäärin 0,7 % (1981) ja 1,1 % (1982). Kokonaistappiokin jäi pienemmäksi vuonna 1981 pitemmästä kuivatusajasta huolimatta. Tehollisen lämpöarvon muutoksiksi saatiin +2,9 % (1981) ja +0,9 % (1982) (taulukot 5 ja 6).

35. Kesän rasikuiva hienohake

Kesän rasikuivien hienohakkeiden kuivatus tapahtui samaan aikaan rasikuivien palahakkeiden sekä kesän kaatotuoreiden hakkeiden kanssa. Rasikuivatuksen pituus ja ajoittuminen vaihtelivat melko huomattavasti tutkimusvuosien välillä. Keskimääräiset kuivatusajat olivat 7,6 viikkoa (1981) ja 5,0 viikkoa (1982). Puut haketettiin ja hake kuivatettiin kuitenkin molempina vuosina lähes samaan aikaan. Kuivatus kesti kuitenkin huomattavasti pitempään vuonna 1981 kuin vuonna 1982 (kuva 15).

Rasikuivatus onnistui vuonna 1982 paremmin kuin vuonna 1981. Haketetun rasipuun keskimääräiset kosteudet kuivatuksen alussa olivat 43,0 (1981) ja 38,7 (1982). Puista ei otettu kosteusnäytteitä rasiinkaadon yhteydessä. Rasikuivatuksen onnistumisessa oli eroavaisuuksia myös paikkakuntien välillä erilaisten kuivatusolojen vuoksi. Konttikuivatuksen jälkeen hakkeiden loppukosteudet olivat 29,5 % (1981) ja 25,0 % (1982).

Molempina koevuosina kuivuminen edistyi lähes yhtä nopeasti. Lähtökosteuksien hajonta oli kuitenkin huomattavasti suurempi vuonna 1981, mikä johti alhaisempaan selitysasteeseen (r^2 = 0,38) kuin mitä saatiin vuoden 1982 hakkeille (r^2 = 0,61). Kun lähtökosteuksissa esiintyneet erot eliminoidaan käyttämällä kosteuden vähenemistä selittävänä muuttujana, saadaan selitysasteiksi 0,60 (1981) ja 0,80 (1982).

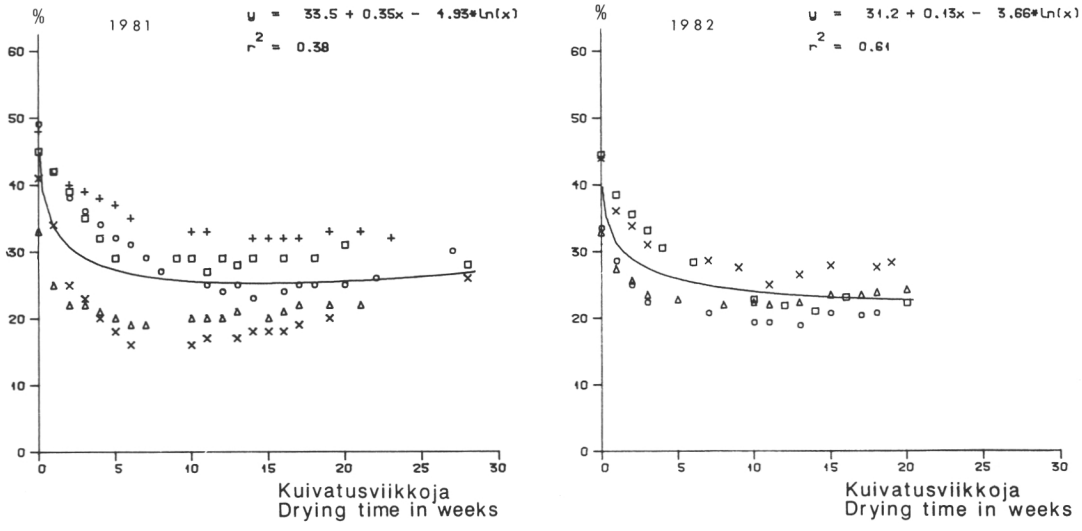


Kuva 14. Kesän kaatotuoreen palahakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 14. Moisture content of chunks made from fresh material in summer as a function of time in 1981 and 1982.

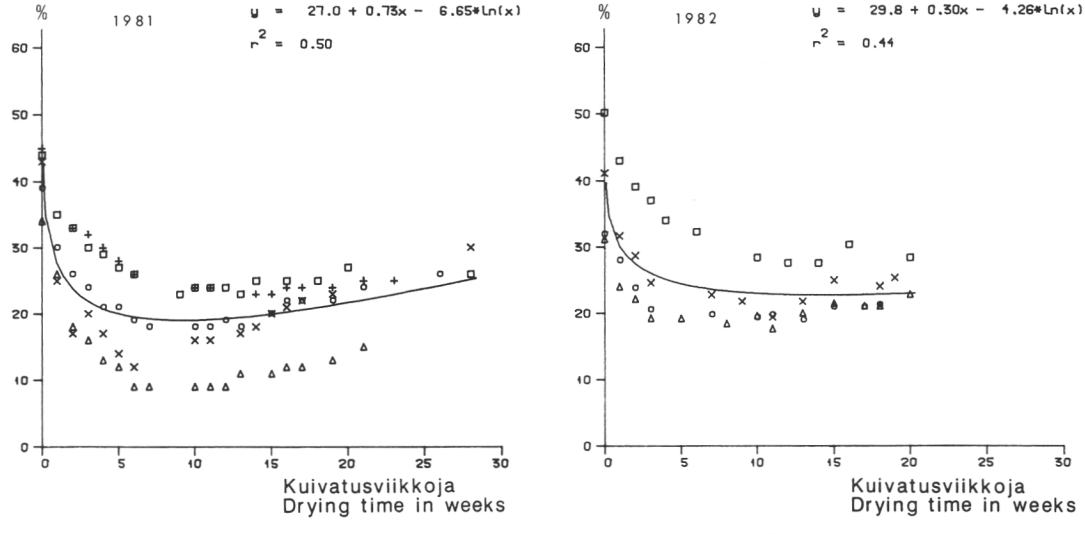
Kuiva-ainetappiot olivat kuukaudessa 0,4 % (1981) ja 0,9 % (1982). Pidemmästä kuivatusajasta huolimatta vuoden 1981 kokonaiskuiva-ainetappio (2,0 %) oli pienempi kuin vuoden 1982 (4,1 %). Tehollisen lämpöarvon muutokset olivat +3,0 % (1981) ja −0,3 % (1982) (taulukot 5 ja 6).

36. Kesän rasikuiva palahake

Vuosien 1981 ja 1982 kuvaajien välisenä erona on vuoden 1981 kuvaajan kääntyminen nousevaksi sen jälkeen, kun se on ohittanut pienimmän arvonsa noin yhdeksän viikon kuluttua kuivatuksen alusta (kuva 16).



Kuva 15. Kesän rasikuivan hienohakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 15. Moisture content of chips made from leaf-seasoned material in summer as a function of time in 1981 and 1982.



Kuva 16. Kesän rasikuivan palahakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 16. Moisture content of chunks made from leaf-seasoned material in summer as a function of time in 1981 and 1982.

Vuoden 1982 kuvaaja sen sijaan pysyy alhaisimmalla saavuttamallaan tasolla. Hakkeen kosteuden ja kosteuden vähenemisen ollessa selitettävinä muuttujina ovat selitysasteet samansuuruiset kuin hienohakkeilla.

Rasikuivien palahakkeiden lähtökosteudet, 41,1 % (1981) ja 38,6 % (1982), olivat noin 10 prosenttiyksikköä vastaavia kaatotuoreiden palahakkeiden kosteuksia pienemmät. Kuivatuksen lopussa otetuista näytteistä saatiin loppukosteuksiksi 24,6 % (1981) ja 21,5 % (1982).

Kuiva-ainetappiot olivat vuonna 1981 0,4 %/kk, mutta vuoden 1982 tulos selvitti kuiva-aineen lisääntyneen 0,4 %/kk. Tulos johtuu näytteen ottoon liittyvästä virheestä, sillä ainehan ei voi lisääntyä. Tehollisen lämpöarvon muutos oli kaikilla paikkakunnilla positiivinen vuoden 1981 Ylihärmän tulosta lukuun ottamatta. Lämpöarvojen muutosten keskiarvoiksi saatiin +1,7 % (1981) ja +6,7 % (1982) (taulukot 5 ja 6).

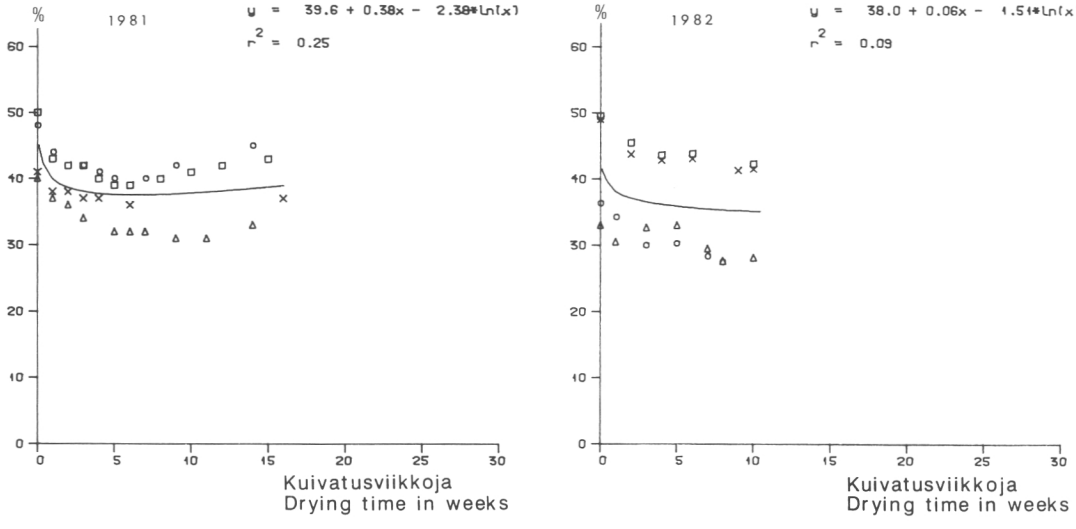
37. Syksyn rasikuiva hienohake

Rasikuivatuksen ajoittuminen vaihteli vuoden 1981 syksyllä paljon ja kuivatus erosi kestoajaltaan huomattavasti kesän rasikuivien puiden kuivatuksessa käytetystä ajasta. Vuoden 1982 kesän ja syksyn rasissaoloajat sen sijaan vastasivat pituudeltaan toisiaan (kuva 6). Hakkeen kuivatus kesti vuonna 1981 noin kuukauden kauemmin kuin vuonna 1982, ja hakkeen kuivatuksen alkamis- ja loppumisajankohdat vaihtelivat usean viikon verran.

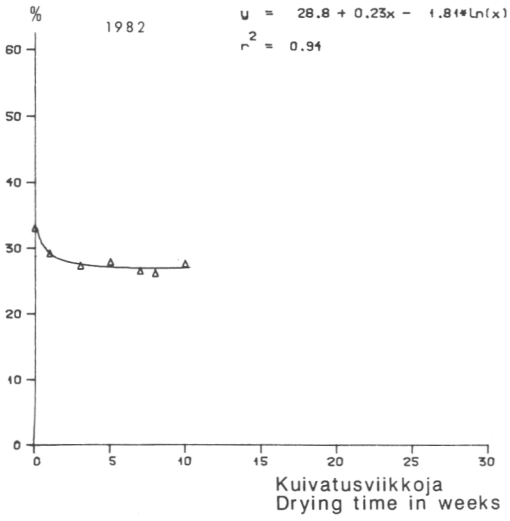
Eripituisten kuivatusaikojen vuoksi kuivumista esittävät kuvaajat eroavat toisistaan jonkin verran eri vuosina. Hakkeen kosteus on selvästi lisääntynyt vuonna 1981 kymmenen kuivatusviikon jälkeen, mikä aiheuttaa sen, että kuvaajan loppuosa nousee. Molemmille vuosille on olennaista tehokkaan kuivumisen rajoittuminen noin kahteen ensimmäiseen kuivatusviikkoon, joiden aikana tasapainotila ilman kosteuden kanssa on saavutettu (kuva 17).

Kuivumista kuvaaviin yhtälöihin liittyvät selitysasteet ovat huonot. Toisen vuoden kokeiden pienet selitysarvot johtuvat rasikuivatuksen vaihtelevasta onnistumisesta. Janakkalan ja Joroisten puiden rasikuivatus ei onnistunut toivotulla tavalla, sillä hakkeen alkukosteus jäi näillä paikkakunnilla 50 %:n tuntumaan. Selitysasteen pieni arvo johtuu toisaalta kuivatusajan lyhyydestä. Erityisesti vuoden 1982 kokeessa kuvaa heikkoa korrelaatiota havaintopisteiden muodostama lähes suorakaiteen muotoinen parvi. Selitysasteeksi saatiin vuonna 1981 $r^2 = 0{,}25$ ja vuonna 1982 $r^2 = 0{,}09$. Mikäli tasoerot poistetaan käyttämällä kosteuden vähenemistä selitettävänä muuttujana, saadaan selitysasteiksi vastaavasti 0,67 ja 0,59.

Hienohaketta kuivatettiin samaan aikaan lautakonteissa ja verkkokonteissa. Muodoiltaan kuivumista esittävät kuvaajat ovat mel-



Kuva 17. Syksyn rasikuivan hienohakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 17. Moisture content of chips made from leaf-seasoned material in autumn as a function of time in 1981 and 1982.



Kuva 18. Verkkokontissa kuivatun syksyn rasikuivan hienohakkeen kosteuden muuttuminen vuonna 1982.
Fig. 18. Moisture content of chips made from leaf-seasoned material and dried in a wire mesh bin in 1982.

kein identtiset (kuvat 17 ja 18). Kosteuseroa on kuitenkin noin kymmenen prosenttiyksikköä. Verrattaessa verkkokonttikuivatusta Ylihärmän lautakonttikuivatukseen havaitaan kosteuden vähentyneen molemmissa hakkeissa saman verran. Eroina ovat kuitenkin Ylihärmän hakkeen kosteuden lisääntyminen ja vähentyminen 3.—7. kuivatusviikkojen aikana. Vastaavia muutoksia ei havaittu verkkokontin hakkeessa.

Sää oli melko huono hakkeen kuivatukseen syys-lokakuun vaihteessa (taulukko 3). Ilman suhteellinen kosteus oli melko suuri ja sekä lämpötila että kyllästysvajaus olivat vähäiset. Ne vastannevat suurin piirtein huhtikuun oloja. Kuivumiselle on kuitenkin huomattavasti paremmat edellytykset keväällä, koska sää paranee kesän lähestyessä. Syksyllä taas tilanne on päinvastainen sään jatkuvasti heiketessä. Hakkeen kuivatuksen lisäksi heikkenee rasikuivatuksen käyttökelpoisuus.

Hakkeiden lähtökosteudet olivat vuosina 1981 ja 1982 44,8 % ja 41,9 % ja loppukosteudet vastaavasti keskimäärin 39,0 % ja 36,2 %. Molempina vuosina on siis tuloksena samansuuruinen kosteuden väheneminen. Kuukautta kohti lasketut kuiva-ainetappiot eroavat melko huomattavasti: 0,1 % (1981) ja 2,4 % (1982). Myös kokonaistappioissa oli selvä ero: 0,4 % (1981) ja 4,9 % (1982). Tähän ei vaikuttanut se, että kuivatus kesti kauemmin vuonna 1981. Tehollisen lämpöarvon muutoksiksi saatiin +3,5 % (1981) ja −1,7 % (1982) (taulukot 4-6).

Verkkokontissa vuonna 1982 kuivattu hake (27,4 %) saavutti vähäisemmän kosteuden kuin Ylihärmän hake (30,1 %) ja koko rasikuiva hake-erä (36,2 %). Kuiva-ainetappiot olivat verkkokontin hakkeessa (1,6 %/kk) jonkin verran Ylihärmän hake-erän (2,0 %/kk) ja kaikkien rasikuivien hake-erien keskiarvoja (2,4 %/kk) pienemmät. Tehollisen lämpöarvon muutos oli negatiivinen sekä verkkokontin hakkeessa (−2,1 %) että koko erässä (−1,7 %). Myös Ylihärmän erän lämpöarvo pieneni (−3,7 %).

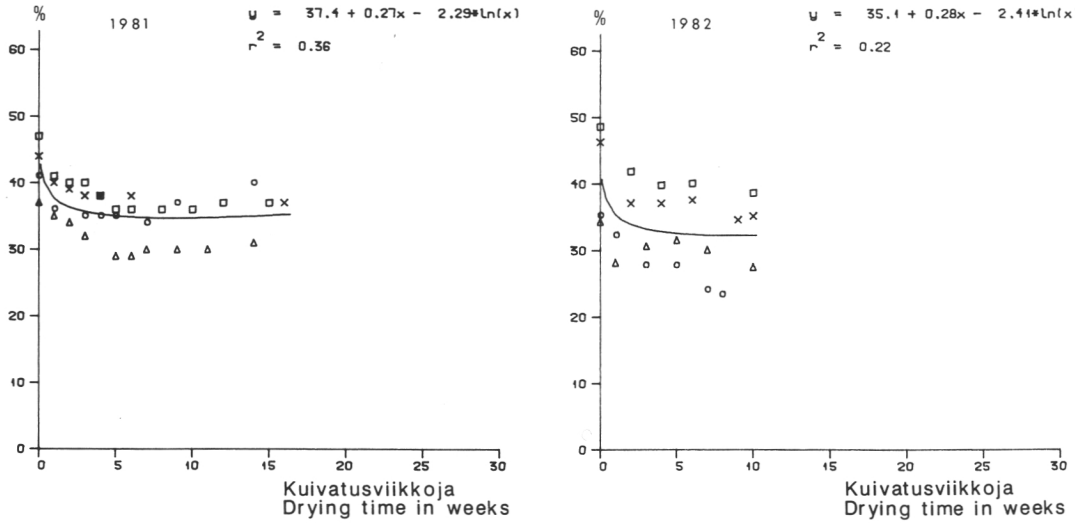
38. Syksyn rasikuiva palahake

Hakkeen kuivumista esittävät kuvaajat vuosilta 1981 ja 1982 ovat jokseenkin samanlaiset kuin vastaavan ajankohdan hienohakkeiden. Heti kuivatusajan alussa, 1—2 viikon aikana, kuivuminen on noin viiden prosenttiyksikön suuruista. Tämä koskee myös verkkokontissa kuivattua haketta (kuvat 19 ja 20).

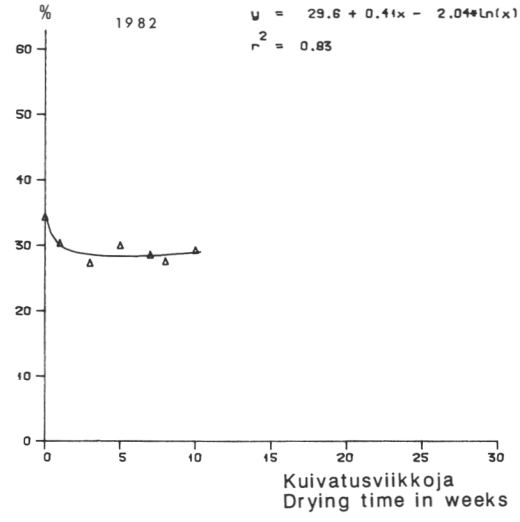
Laskettujen yhtälöiden selitysasteet ovat melko pienet molempina vuosina. Syyt heikkoihin selitysasteisiin ovat samat kuin hienohakkeenkin kohdalla. Selitysasteet paranevat huomattavasti, kun kosteuden väheneminen valitaan selitettäväksi muuttujaksi. Koska verkkokontteja oli vain yksi, hajonta oli pieni ja selitysaste pysyi samana, käytettiinpä selittäjänä kosteusprosenttia tai kosteuden vähenemistä (taulukko 7).

Palahakkeiden keskimääräiset alkukosteudet olivat 42,4 % (1981) ja 41,1 % (1982) ja loppukosteudet vastaavasti 35,3 % (1981) ja 31,6 % (1982). Kuiva-ainetappioiksi saatiin kuukautta kohti 0,3 % (1981) ja 1,0 % (1982). Kokonaistappiot olivat myös vuoden 1981 eduksi luvuin 1,1 % (1981) ja 2,0 % (1982). Tehollisen lämpöarvon muutokset olivat vastaavasti +3,8 % ja +1,4 % (taulukot 4—6).

Ylihärmän verkkokontin tulos (27,8 %) on saman suuruinen Ylihärmän lautakontin hakkeen kosteuden kanssa (28,0 %). Myös kuiva-ainetappiot olivat molemmilla hakkeilla vastaavasti samanlaiset: 0,2 %/kk ja 0,3 %/kk. Täten on luonnollista, että myös tehollisen lämpöarvon muutokset ovat lähellä toisiaan. Muutoksien suuruudet olivat +1,1 % verkkokontissa ja +0,9 % Ylihärmän lautakontissa.



Kuva 19. Syksyn rasikuivan palahakkeen kosteuden muuttuminen vuosina 1981 ja 1982.
Fig. 19. Moisture content of chunks made from leaf-seasoned material in autumn as a function of time in 1981 and 1982.



Kuva 20. Verkkokontissa kuivatun syksyn rasikuivan palahakkeen kosteuden muuttuminen vuonna 1982.
Fig. 20. Moisture content of chunks made from leaf-seasoned material in autumn and dried in a wire mesh bin in 1982.

4. HAKE-ERIEN VÄLISET EROT TEKIJÖITTÄIN

41. Hakkeen palakoon vaikutus

Tässä tarkastelussa on rajoituttu pelkästään hieno- ja palahakkeen välisiin kuivumiseroihin, eikä huomioon ole otettu kummankaan hakkeen sisäisen palakokojakauman vaihtelua. Kuva 8 esittää hakepalojen pituusjakauman, joka vastaa Hakkilan ja Kalajan (1981) sekä Heikan ja Piiraisen (1981) tuloksia. Palakokojakaumien suuret erot aiheuttavat myös huomattavia eroja hakkeen painossa ja tiiviydessä (taulukot 1a, b). Tämä puolestaan vaikuttaa hakkeen ilmanläpäisykykyyn. Gislerudin (1983) tekemissä puhalluskokeissa, joissa ilmanpaineen voimakkuus oli 500 Pa/m, palahakkeen massan läpäisseen ilman määrä oli nelinkertainen hienohakkeeseen verrattuna.

Kaatotuoreen palahakkeen kuivuminen on ensimmäisinä viikkoina aina hienohaketta nopeampaa. Rasikuivatuissa hakkeissa palakoon vaikutus ei ole yhtä olennainen, mikä johtunee rasihakkeiden vähäisestä lähtökosteudesta. Kuivattu palahake saavutti lautakonteissa aina noin 4—5 prosenttiyksikköä hienohaketta vähäisemmän kosteuden paikkakunnasta riippumatta (taulukot 1a,b ja 4).

Kun haketta kuivatettiin verkkokonteissa, palakoon vaikutus ei ollut yhtä selvä. Kevään kaatotuoreen palahakkeen kosteus kokeen lopussa oli 18,9 % ja hienohakkeen 15,6 %. Syksyn rasikuivien hakkeiden loppukosteus oli hienohakkeella 27,4 % ja palahakkeella 27,8 %.

Palakoolla ei ollut johdonmukaista vaikutusta kuiva-ainetappioiden määrään. Huomattavampia eroja syntyi ainoastaan vuoden 1981 kesän kaatotuoreiden hakkeiden välille sekä vuoden 1982 kevään kaatotuoreiden, kesän rasikuivien ja syksyn rasikuivien hakkeiden välille. Näissä tapauksissa palahakkeiden kuiva-ainetappiot olivat hienohakkeita pienemmät (taulukko 5). Erot muiden erien välillä olivat vähäiset. Verrattaessa hieno- ja palahakkeen yhteenlaskettujen kuiva-ainetappioiden kuukausittaisia keskiarvoja olivat palahakkeelle saadut arvot kumpanakin koevuotena hieman pienemmät. Tappioksi saatiin tällöin hienohakkeelle 0,9 % (1981) ja 1,5 % (1982) ja palahakkeelle 0,8 % (1981) ja 0,9 % (1982).

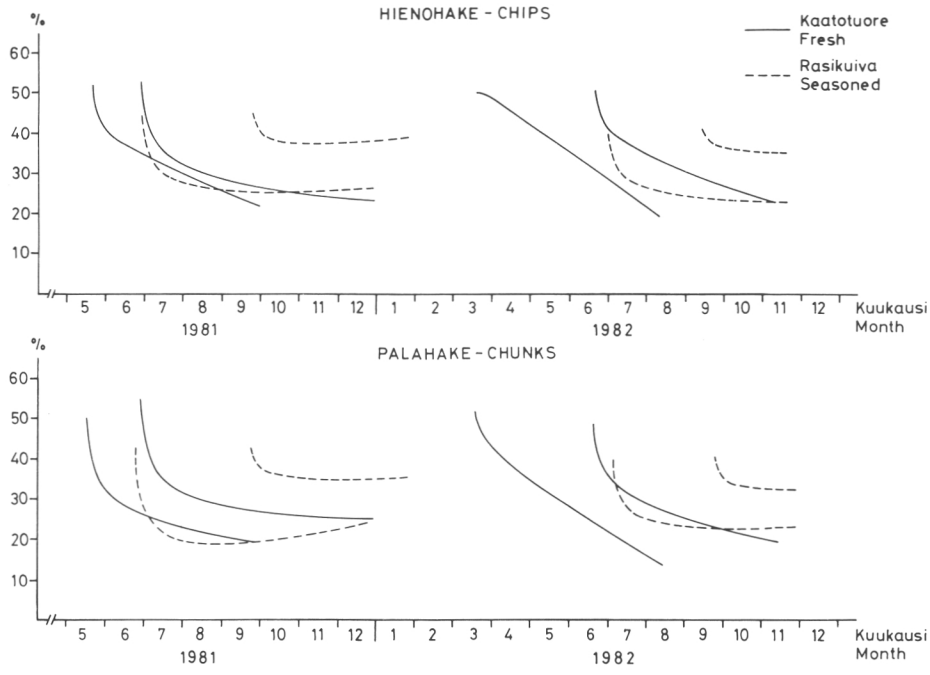
Palahakkeiden lämpöarvot (+3,4 % (1981), +3,4 % (1982)) suurenivat kuivatuksessa keskimäärin hienohakkeiden arvoja (+2,6 % (1981), +0,5 % (1982)) enemmän. Verkkokonteissa kuivattujen hakkeiden lämpöarvon muutokset olivat hyvin samanlaiset kuin lautakonteissa kuivatuilla hakkeilla. Hienohakkeiden keskimääräinen muutos oli +1,1 % ja palahakkeiden +3,4 %.

Hakeirtokuutiometrin sisältämän tehollisen lämpöarvon määrä (MJ/i-m^3) oli kokeen lopussa hienohakkeella jonkin verran palahaketta suurempi, mikä johtuu hienohakkeen suuremmasta massasta. Kuivatuksen jälkeen hienohakkeen irtokuutiometrin energiasisältö oli keskimäärin 2 772 MJ (1981) ja 2 770 MJ (1982). Palahakkeen arvot olivat 2 767 MJ (1981) ja 2 757 MJ (1982). Verkkokonteissa kuivuneelle hieno- ja palahakkeelle saatiin keskiarvoiksi 3 168 MJ ja 2 888 MJ.

42. Kuivatusajan vaikutus

Kuvista 21 ja 22 nähdään, että kuivatuksen ajankohdalla on huomattava vaikutus kuivumisen etenemiseen. Kuivuminen oli erityisen hidasta aikaisin keväällä (1982) tehdyillä hakkeilla. Muista vuodenajoista poiketen ei kuivatuksen alussa esiintynyt nopeata kosteuden vähenemistä, vaan kuivuminen oli tasaisen hidasta loppuun saakka. Kun kuivatus aloitettiin toukokuussa kuivui hake verraten nopeasti ensimmäisten viikkojen aikana. Kuivuminen tasaantui 10—15 viikon kuluttua kuivatuksen alusta, kun hakkeen kosteus lähestyi tasapainotilaa ilman suhteellisen kosteuden kanssa (Panshin ja de Zeeuw 1970).

Kesä-elokuun välinen aika on paras hakkeen kuivatukseen. Kaatotuoreesta puusta tehdyn hakkeen kosteus haihtui 10—20 prosenttiyksikköä parin ensimmäisen viikon aikana ja haihtuminen jatkui hitaampana vielä muutaman viikon ajan. Palakoosta riippuen



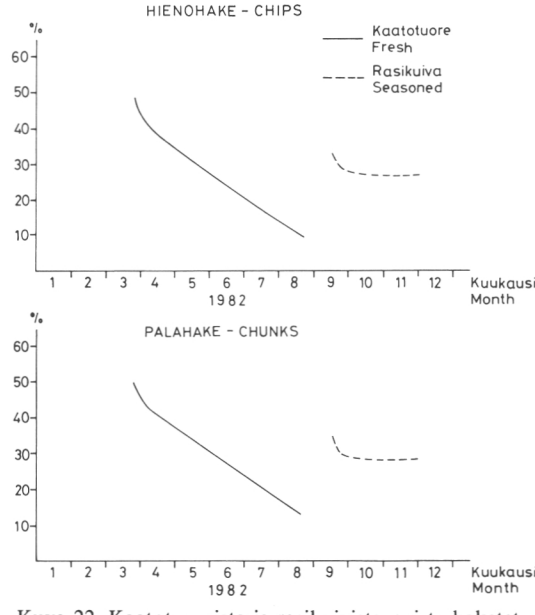
Kuva 21. Kaatotuoreista ja rasikuivista puista haketettujen hieno- ja palahakkeiden kuivuminen vuodenaikaan nähden.

Fig. 21. Drying of chips and chunks in relation to season when fresh and leaf-seasoned materials are used.

hake saavutti 30 %:n kosteuden 5—10 viikossa.

Kesällä rasikuivatuista puista tehdyn hakkeen kuivuminen edistyi samalla tavalla kuin kaatotuoreiden hakkeiden kuivuminen. Noin 10:tä prosenttiyksikköä pienemmän lähtökosteutensa vuoksi rasihakkeet pääsevät ilman kanssa kosteustasapainoon kaatotuoreita hakkeita nopeammin. Tehokas kuivatusaika kesti ainoastaan viitisen viikkoa ja saavutettu kosteus oli noin 25 %.

Hyvin lyhyeksi jäänyt tehollinen kuivumisaika ja vähäinen kosteuden haihtuminen olivat luonteenomaisia piirteitä syksyn rasikuivien hakkeiden kuivumiselle. Syyskuun huomattavasti kesäkuukausia pienemmän kyllästysvajauksen vuoksi ei ilma pystynyt ottamaan vastaan yhtä paljon vettä kuin kesällä. Rasikuivatus oli jo sitä paitsi vähentänyt puun kosteutta jonkin verran. Hakkeen kosteus väheni 2—3 viikon aikana noin 5 prosenttiyksikköä ja hake saavutti 35—40 %:n loppukosteuden. Pidennetty kuivatusaika johti kosteuden vähittäiseen lisääntymiseen (kuva 21).



Kuva 22. Kaatotuoreista ja rasikuivista puista haketettujen hieno- ja palahakkeiden kuivuminen verkkokonteissa vuodenaikaan nähden.

Fig. 22. Drying of chips and chunks in relation to season when wire mesh bins and fresh and leaf-seasoned materials are used.

Konttien tyhjennyshetkellä oli kevään kaatotuoreen hakkeen kosteus vähäisin. Kosteusjärjestyksessä seuraavina olivat kesän rasikuivat, kesän kaatotuoreet ja viimeisenä syksyn rasikuivat hakkeet. On kuitenkin otettava huomioon, että kyseessä oli koetilanne, jossa kevään kaatotuoreita hakkeita lukuun ottamatta hakkeiden loppukosteus ei ollut sama kuin pienin saavutettu kosteus. Hakkeen kosteuden keräämisen estämiseksi kontit tuleekin tyhjentää varastoon ajoissa.

Kuiva-ainetappiot ovat riippuvaisia sekä ajankohdasta että puutavaran tekotavasta. Kokonaistappiot olivat suurimmat kaatotuoreista puista tehdyissä erissä. Rasipuiden tappiot olivat huomattavasti niitä pienemmät, etenkin vuonna 1981. Myös kuukauden keskimääräiset tappiot antavat saman tuloksen (taulukko 5). Tutkimuksessa ei selvitetty, missä kuivatuksen vaiheessa kuiva-ainetappiot olivat suurimmat. Myöskään rasikuivatuksesta aiheutuvia tappioita ei tutkittu.

Hake-erien lämpöarvoissa ei ollut ajankohdan aiheuttamia johdonmukaisia eroja. Kuivan hakkeen lämpöarvot olivat enimmäkseen 2 700—2 800 MJ/i-m^3. Vuoden 1981 tuloksissa oli hieman enemmän vaihtelua kuin vuonna 1982 (taulukko 6).

43. Konttityypin vaikutus

Verkkopäällystetty kontti soveltuu kuivatustuloksiensa puolesta paremmin hakkeen kuivatukseen kuin lautakontti. Kun verrataan verkkokonteissa kuivuneita hakkeita muihin hakkeisiin voidaan päätellä seuraavaa. Kevään kaatotuoreen palahakkeen kuivuminen ei ollut sidoksissa konttityyppiin. Kevään kaatotuoreen hienohakkeen kuivumista on merkittävämmin edistänyt verkkokontti. Verkkokontteihin varastoitu hienohake saavutti seitsemän viikon kuivatuksen jälkeen noin 7 prosenttiyksikköä vähäisemmän kosteuden kuin lautakontissa olleet hakkeet. Ero säilyi aina siihen asti, kunnes kosteuden väheneminen pysähtyi 15—20 kuivatusviikon jälkeen.

	Ylihärmä	
	Lauta-kontti	Verkko-kontti
	Kosteus, %	
Kevään kaatotuore hienohake	17,3	15,6
Kevään kaatotuore palahake	16,5	18,6
Syksyn rasikuiva hienohake	30,1	27,4
Syksyn rasikuiva palahake	28,0	27,8

Myös kuiva-ainetappiot osoittavat verkkokontin toimineen hakkeen laadun kannalta hieman paremmin. Suurimmat erot syntyivät hienohaketta kuivattaessa. Kevään kaatotuoreita hienohakkeita käytettäessä kuiva-ainetappiot ovat olleet jopa kaksinkertaisia lautakontissa verkkokonttiin verrattuna.

	Kokonaistappio		Kuukausitappio	
	Lauta-kontti	Verkko-kontti	Lauta-kontti	Verkko-kontti
Kevään kaatotuore hienohake	7,0	3,5	1,3	0,7
" " palahake	5,1	4,0	0,9	0,8
Syksyn rasikuiva hienohake	4,6	3,7	2,0	1,6
" " palahake	0,8	0,5	0,3	0,2

Hakkeen kosteuksien ja kuiva-aineen määrien muutokset näkyvät selvästi tehollisen lämpöarvon muutoksina. Verkkokonteissa kuivuneen hakkeen todellinen lämpöarvon lisäys on noin kaksi kertaa lautakonttien haketta suurempi. Syksyn rasikuivien hienohakkeitten lämpöarvot (MJ/i-m^3) ovat tosin muista eristä poiketen pienentyneet.

	Lautakontti		Verkkokontti	
	MJ/i-m^3	%	MJ/i-m^3	%
Kevään kaatotuore hienohake	3098	+2,0	2918	+5,1
" " palahake	2898	+3,3	3185	+5,4
Syksyn rasikuiva hienohake	3318	-3,7	3418	-2,1
" " palahake	2858	+0,9	2590	+1,1

Verkkokonttien hake on kuivunut ja säilynyt jonkin verran paremmin kuin samaan aikaan lautakonteissa ollut hake. Vaikka tulokset rajoittuvat keväällä ja syksyllä tehtyihin hakkeisiin, on kuitenkin varsin luonnollista olettaa, että kesällä tehtyjen hakkeiden käyttäytyminen olisi samansuuntaista.

Vähäisen verkkokonttiaineiston perusteella on vaikeata tehdä varmoja johtopäätöksiä sen paremmuudesta lautakonttiin verrattuna. Tutkimustulosten perusteella on kuitenkin pääteltävissä palakoosta johtuvien kosteus- ja säilymiserojen menettävän merkitystään silloin kun haketta kuivataan verkkokonteissa.

44. Puulajin vaikutus

Leppä- ja koivuhakkeiden eroja on tarkasteltu ajankohdittain, kuitenkin niin että hieno- ja palahakkeiden tulokset on yhdistetty (taulukko 8). Leppähakkeiden lähtö- ja lop-

Taulukko 8. Koivu- ja leppähakkeiden kosteus-, kuiva-ainetappio- ja lämpöarvotietoja, kun hakkeen ja palahakkeen tiedot on yhdistetty.
Table 8. Data on moisture content, dry matter losses and heat values of birch and alder when data from chips and chunks are conbined.

		Haketus — *Comminution*							
		Kevään kaatotuore *Freshly comminuted in spring*		Kesän kaatotuore *Freshly comminuted in summer*		Kesän rasikuiva *Seasoned and comminuted in summer*		Syksyn rasikuiva *Seasoned and comminuted in autumn*	
		Leppä *Alder*	Koivu *Birch*	Leppä *Alder*	Koivu *Birch*	Leppä *Alder*	Koivu *Birch*	Leppä *Alder*	Koivu *Birch*
		Hakkeen kosteus, % *Moisture content, %*							
Lähtö	1981	53,1	43,9	53,0	45,8	44,4	38,6	45,7	41,5
Start	1982	51,6	48,3	52,5	44,7	45,0	25,1	48,4	34,7
Loppu	1981	31,5	20,6	35,2	27,5	26,9	32,4	38,6	35,4
End	1982	25,5	19,5	30,3	25,3	25,0	21,5	38,4	29,4
		Kuiva-ainetappiot, %/kk *Dry matter losses, %/month*							
	1981	−2,0	−0,8	−0,6	−1,3	−0,4	−0,5	−0,6	+0,1
	1982	−1,7	−1,0	−1,0	−1,1	+0,2	−0,6	−0,6	−2,7
		Tehollinen lämpöarvo, MJ/i-m^3 *Effective heat value, MJ/m^3 loose*							
1981	lähtö — *start*	2566	2811	2343	2771	2672	2979	2419	2866
	loppu — *end*	2594	2953	2396	2729	2707	3054	2462	3016
	muutos — *change, %*	+1,1	+5,1	+2,3	−1,5	+1,3	+2,5	+1,8	+5,2
1982	lähtö — *start*	2640	2921	2528	2830	2330	3016	2413	2969
	loppu — *end*	2670	3042	2552	2860	2501	3009	2515	2855
	muutos — *change, %*	+1,1	+4,1	+1,0	+1,1	+7,4	−0,2	+4,2	−3,9

pukosteudet olivat aina koivuhakkeiden arvoja suurempia. Koivuhakkeen lähtökosteus oli erästä riippuen noin 3—14 prosenttiyksikköä leppähaketta vähäisempi. Kokeen lopussa ero oli 2—11 kosteusprosenttia.

Leppähake kuivui rasissa huomattavasti huonommin kuin koivuhake. Tähän saattoivat olla syynä koivujen paremmat kuivatusolot, sillä Hakkilan (1962) tutkimuksessa rasissa kuivuneiden leppien ja koivujen erot olivat vain noin kaksi kosteusprosenttia. Hakkeen kuivatuksen aikana ovat rasikuivattujen leppä- ja koivuhakkeitten kosteudet hieman lähentyneet toisiaan. Kaatotuoreissa hake-erissä ei lähentymistä juuri ole.

Kuiva-ainetappiot olivat jokseenkin samat molemmilla puulajeilla, n. 1 %/kk. Arvot vaihtelivat kuitenkin melko suuresti hake-erästä ja vuodesta riippumatta. Lepästä ja koivusta tehtyjen rasihakkeiden kuiva-ainetappiot olivat kaatotuoreita hakkeita pienemmät (taulukko 8).

Koivuhakkeen lämpöarvo on suuremman painon ja vähäisemmän kosteuden vuoksi tilavuusyksikköä kohti laskettuna lepän lämpöarvoa suurempi kaikkina ajankohtina. Ero oli kokeen lopussa keskimäärin noin 14 %. Kuivan leppähakkeen lämpöarvo oli 2462—2707 MJ/i-m^3 ja koivuhakkeen 2729—3054 MJ/i-m^3. Puulajien väliset erot eivät siis johtuneet konttikuivatukseen liittyvistä tekijöistä vaan pikemminkin puulajien sisäisistä ominaisuuksista.

5. TULOSTEN TARKASTELU

Tutkimuksen aineistoa voitaneen pitää riittävänä antamaan kuva hakkeen kuivumisesta traktorikonteissa. Esimerkiksi Gislerudin (1983), Kochin (1983) ja Aittomäen (1963) tutkimukset hakkeen kuivumisesta koostuvat huomattavasti pienemmistä ja suppeammista aineistoista. Eri vuodenajat ja kokeiden maantieteellinen kattavuus ovat yleensä saaneet osakseen vain vähän huomiota hakkeen kuivatustutkimuksissa. Tämän tutkimuksen sijoittaminen viidelle Etelä-Suomen paikkakunnalle sekä lähes koko vuodelle ajoittuneet kokeet lisäävät tulosten luotettavuutta sekä yleistettävyyttä.

Tutkimuksessa käytetty hakkeen punnitusmenetelmä soveltui hyvin tarkoitukseensa, sillä luotettavien tietojen saanti hakkeen kosteuden muutoksista olisi ollut mahdotonta näytteitä ottamalla. Menetelmä tosin antoi hieman optimistisia kosteusarvoja kuiva-ainetappioiden vuoksi. Punnitustuloksista saatujen aikasarjojen perusteella laskettiin kullekin hake-erälle regressioyhtälöt. Lähtökosteuksissa esiintynyt vaihtelu paikkakuntien välillä aiheutti huomattavaa hajontaa joidenkin erien kohdalla. Hajonnan pienentämiseksi käytettiin selittävänä muuttujana hakkeen kosteuden lisäksi kosteuden vähenemistä. Näin saatiin myös selitysasteet paremmiksi.

Käytetty menetelmä osoitti, että palakoolla, kuivatuksen ajankohdalla ja kontin mallilla oli vaikutuksensa hakkeen kuivumiseen. Niiden vaikutuksista voidaan tehdä seuraavat johtopäätökset:

— Palahakkeen tärkeimmiksi ominaisuuksiksi voidaan lukea sen hienohaketta nopeampi kuivuminen sekä suuremmat lämpöarvon lisäykset. Vuodenajasta ja vuodesta riippuen hienohakkeen kuivuminen 20—30 % kosteuteen traktorikonteissa saattaa viedä 2—3 kertaa palahaketta kauemmin. Palakoon merkitys on suurin kaatotuoreita hakkeita käytettäessä.

— Touko-elokuun välinen aika osoittautui parhaaksi kuivatuksen ajankohdaksi. Hake voidaan kuitenkin tehdä jo aikaisemmin kevättalvella, jolloin yksi erä ehtii kuivua ennen parasta kuivatuskautta. Myöhään syksyllä olosuhteet ovat niin huonot, että kuivatuksessa päästään vain tyydyttävään tulokseen.

— Rasipuista tehty hake kuivuu kesällä muita hakkeita nopeammin vaatien vain muutaman viikon kuivatusajan. Rasimenetelmän käyttökelpoisuutta lisää se, että sitä voidaan käyttää keväästä syyskesään asti (Hakkila 1962). Rasimenetelmän lisäetuna pidettäköön myös palakoon pienenevää merkitystä hakkeen kuivatuksessa.

— Rasikuivien hakkeiden kuiva-ainetappiot olivat muita hakkeita vähäisemmät. Rasikuivatuksen aikana tapahtuvan tappion mahdollisuutta ei otettu huomioon, koska on ilmeistä, että rasiaikana kuiva-ainetappioita tapahtuu vain lehtien varisemisena (Simola ja Mäkelä 1976).

— Verkkokontin tärkeimpänä ominaisuutena on pidettävä palakoon merkityksen häviämistä. Tämän vuoksi saavutettu kosteus oli lähes sama molemmilla palakoilla. Myös kuivumisen kuvaajat ovat lähes identtiset. Vähäisen kosteuden ja pienten kuiva-ainetappioiden vuoksi verkkokonttien hakkeiden lämpöarvon lisäykset olivat lautakonttien hakkeita suuremmat.

Hakkuri (palakoko), puulaji ja kontin rakentamiseen saatavilla olevat materiaalit ovat yleensä olosuhteiden sanelemia. Hakepuun teon ja hakkeen kuivatuksen ajoittamiseen sen sijaan voidaan aina vaikuttaa. Koska myöhäinen syksy ja talvi eivät sovellu hakkeen kuivatukseen kontteja käytettäessä, on työt keskitettävä erityisesti kesän ajalle. Työmäärän ja kustannusten rajoittamiseksi tulee hakkeen kuivatukselle laatia aikataulu sekä valita edullisimmat menetelmät. Suositeltavana vaihtoehtona on pidettävä hakkeen kuivatuksen keskittämistä kesä-elokuun ajalle. Hake tulisi tällöin tehdä rasissa kuivuneesta puusta. Tällöin on tarvittava kuivumisaika 2—3 viikkoa yhtä konttia kohti.

Ensimmäistä rasihake-erää varten tulee puut kaataa toukokuun alussa. Noin kolmen viikon kuluttua voidaan kuivunut hake tyhjentää kontista ja hakettaa uusi erä tilalle. Mikäli tässä kolmen viikon rytmissä pysytään, voidaan yhdellä 15 i-m^3:n kontilla kuivata kesä-elokuun aikana neljä erää eli 60 i-m^3 haketta.

Vaikka kesä onkin paras kuivatusaika ei kuivatuksen aloittamiselle jo keväällä ennen rasiinkaatokauden alkua ole estettä. Näin meneteltäessä voidaan kaatotuoreesta tai

vaikkapa pinossa varastoidusta puusta tehdä haketta jo esimerkiksi maalis-huhtikuun vaihteessa. Hakkeen annetaan kuivua konteissa kahden kuukauden ajan siihen asti, kunnes kesäkuussa alkaa rasissa kuivatetuista puista tehtävän hakkeen kuivatus. Hakkeen kuivuminen on tosin keväällä hidasta, eikä 30 %:n kosteutta ehkä ehditä saavuttaa. Kuivatuskautta voidaan pidentää myös syksyyn, jolloin rasipuusta tehty hake vieläkin kuivuu nopeammin kuin kaatotuore puu keväällä. Yhdistämällä siis eri vuodenaikoina tapahtuva rasi- ja kaatotuoreen hakkeen kuivatus voitaneen yhdessä lautakontissa kuivata noin 90 i-m^3 haketta yhden kuivatuskauden aikana.

Kuivattaessa pelkästään kaatotuoretta haketta saadaan kuivaa haketta koko kuivatuskautena vain kolme erää (45 i-m^3). Nämä erät jakautuvat huhti-kesäkuun, kesä-elokuun ja elo-syyskuun ajalle. Jotta kaatotuoretta haketta saataisiin kuivatuksi yhtä paljon kuin rasihaketta, on käytössä oltava siis kaksinkertainen konttimäärä.

KIRJALLISUUS — REFERENCES

Aittomäki, S. 1963 Tutkimuksia polttohakkeen ja pilkkeiden kuivatuksesta ulkoilman avulla. Pienpuualan Toimikunnan julkaisu 151. 38 s.

Alestalo, A. 1982. Kuoren ja muun biopolttoaineen kuivaus aurinkoenergialla. Tutkimusseloste. Diario 235/881/80 KTM. Enso Gutzeit Oy. Julkaisematon. 44 s.

Annergren, G., Dillen, S. & Wardheim, S. 1964. On outside storage of sprucewood chips for sulphite pulping. Svensk Papperstidning (67)4:125—145.

Anttila, R. 1961. Hakkeen käyttö yleistyy maatiloilla. Pienpuualan Toimikunnan tiedotus 40.

Belin, L. 1984. Allergic alviolitisfungal spores. Teoksessa: Gislerud, O. & Heding, N. Storing, drying and internal handling of wood fuels. Proceedings of a conference held by the International Agency (IEA) Forestry Energy Programme Group C on June 22, 1984 in Copenhagen, Danmark. Danish Institute of Forest Technology. s. 12—15.

Bergman, Ö. & Nilsson, T. 1966. Studier över utomhuslagring av tallvedsflis vid Lövholmens Pappersbruk. Summary: On Outside Storage of Pine Chips at Lövholmen's Paper Mill. Institutionen för virkeslära, Skogshögskolan. Rapporter 53. 83 s.

— & Nilsson, T. 1967. Studier över utomhuslagring av aspvedsflis vid Hörnefors Sulfitfabrik. Institutionen för virkeslära, Skogshögskolan. Rapporter 55. 105 s.

— & Nilsson, T. 1968. Studier över utomhuslagring av björkvedsflis vid Mörrums Bruk. Summary: On Outside Storage of Birch Chips at Mörrum's Sulphate Mill. Institutionen för virkeslära, Skogshögskolan. Rapporter 60. 104 s.

— & Nilsson, T. 1971. Studies on outside storage of sawmill chips. Sammanfattning: Studier över utomhuslagring av sågverksflis. Institutionen för virkeslära, Skogshögskolan. Uppsatser R71. 102 s.

— & Nilsson, T. 1974. Studies on wood deterioration in outside storage of a commercial pine chip pile. Sammanfattning: Studier över vednedbrytning vid utomhuslagring av en tallflisstack. Institutionen för virkeslära, Skogshögskolan. Rapporter R93. 75 s.

— & Nilsson, T. 1979. An experiment on outdoor storage of whole-tree chips. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport R109. 21 s.

Björklund, L. 1982. Lagring av bränsleflis i fraktionen 25—30 mm. Summary: Storage of fuelwood chips in fraction 25—30 mm. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Uppsatser 115. 26 s.

— 1983. Lagring av helträdsflis av olika trädslag samt i olika fraktioner. Summary: Storage of whole-tree chips of different species and in different fractions. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 143. 50 s.

Energiapoliittinen ohjelma 1983. Hyväksytty valtioneuvostossa 24.2.1983. Helsinki. 34 s.

Faeste, I. & Johansson, K.J. 1982. Tørkeforløp i syrefelte traer under forskjellige lagringsforhold. Zusammenfassung: Trocknungsverlauf bei ungeasteten Bäumen unter verschiedenen Lagerungsverhältnissen. Norsk Institutt for Skogforskning. Rapport 2. 32 s.

Gislerud, O. 1974. Heltreutnyttelse V. Lagring av heltreflis. Summary: Whole tree utilization V. Storing of whole tree chips. Norsk Institutt for Skogforskning. Rapport 5. 29 s.

— 1978. Lagring av lauvtreflis. Et lagringsforsøk med Sande Paper Mill A/S. Norsk Institutt for Skogforskning. Rapport 9. 37 s.

— 1983. Experimental drying and storing of fuel chips. NISK. IUFRO -moniste. 5 s.

— & Grønlien, H. 1977. Lagring av heltreflis. Et lagringsforsøk med flis fra tynningsvirke ved Norsk Wallboard A/S, Gjøvik. Summary: Storage of whole-tree chips. A storage experiment with chips from thinnings at Norsk Wallboard A/S, Gjøvik. Norsk Institutt for Skogforskning. Rapport 1. 34 s.

— & Grønlien, H. 1978a. Lagring av or. Et lagringsforsøk ved Meraker Smelteverk A/S. Summary: Storage of whole-tree chips of gray alder. A storage experiment at Meraker Smelteverk A/S. Norsk Institutt for Skogforskning. Rapport 1. 36 s.

— & Grønlien, H. 1978b. Lagring av lauvtreflis. Norsk Institutt for Skogforskning. Rapport 9. 77 s.

Gustafsson, G. 1981. Grundläggande studier av torkning och lagring av bränsleflis — Etappraport 2. Nämnden för Energiproduktions forskning. NE/Bio-81-18.

Haapasalo, P. 1983. Puun polttoarvo ja siihen vaikuttavat tekijät. Moniste. VAPO. Jyväskylä. 24 s.

Hajny, G. 1966. Outside storage of pulpwood chips.

Tappi (49) 10, 97—105.
Hakkila, P. 1962. Polttohakepuun kuivuminen metsässä. Summary: Forest seasoning of wood intended for fuel chips. Communicationes Instituti Forestalis Fenniae 54(4). 82 s.
— 1978. Pienpuun korjuu polttoaineeksi. Summary: Harvesting small-sized wood for fuel. Folia Forestalia 342. 32 s.
— 1984. Metsähakkeen hankinta lämpölaitosten polttoaineeksi. SITRA. Tutkimusraportti 33. 121 s.
— & Kalaja, H. 1981. KOPO palahakejärjestelmä. Summary: KOPO block chip system. Folia Forestalia 467. 24 s.
Heikka, T. & Piirainen, K. 1981. Pienhakkureiden voimankäyttö. Summary: Power consumption of small chippers. Folia Forestalia 496. 22 s.
Heino, R. & Hellsten, E. 1983. Tilastoja Suomen ilmastosta 1961—1980. Liite Suomen meteorologiseen vuosikirjaan. Ilmatieteenlaitos. 560 s.
Heiskanen, V. & Hakkila, P. 1960. Polttohakepuun kuivuminen rasissa. Pienpuualan Toimikunnan tiedotus 17. 6 s.
— & Jokihaara, L. 1961. Puupolttoaineiden lämpöarvosta. Pienpuualan Toimikunnan tiedotus 33. 5 s.
Heliövaara, T. 1960. Polttoaineen ja keskuslämmityskattilan valintaan vaikuttavista tekijöistä. Hake puntarissa. Maaseudun Tulevaisuus 19.4.1960.
— 1961. Hakelämmitys käytäntöön sovellettuna. Koneviesti 5/1961.
Høeg, H. 1980. Forekomst av soppsporer i forbindelse med flisfyringsanlegg og lagring av flis. Norsk Institutt for Luftforskning. Oppdragsrapport 29. 36 s.
— 1981. Forekomst av soppsporer med flisfyringsanlegg og lagring av flis. II. Norsk Institutt for Luftforskning. Oppdragsrapport 26. 16 s.
Håkanson, K. & Numminen, J. 1963. Tutkimus hakkeen polttoarvon muutoksista sitä varastoitaessa. Imatran Voima Oy. Julkaisematon raportti. 41 s.
Immonen, K. & Seppälä, R. 1984. Polttopuun ja palaturpeen alueittainen tuotanto, jakelu ja käyttö. SITRA. Sarja B:76. 164 s.
Immonen, V. 1961. Hakkeen varastointia ja halkojen laatua koskevia tutkimuksia Turengin Sokeritehtaalla v. 1958 ja 1959. Summary: Studies of the storage chips and quality of split fuelwood at Turenki sugar mill in 1958 and 1959. Pienpuualan Toimikunnan julkaisu 96. 30 s.
Jalava, M. 1941. Rasiin kaadettujen puiden kuivumisesta. Metsätaloudellinen Aikakauskirja 58(6):173—176.
Jokihaara, L. 1959. Hakkeella helpompaan ja halvempaan lämmitykseen. Maaseudun Tulevaisuus 133.
Kantola, M. 1961. Polttohakkeen nykykäyttö keskuslämmitysrakenteissa. Summary: The Use of Wood Chips as Fuel in Central Heating Plants. Työtehoseuran Julkaisuja 93.
Koch, P. 1983. Moisture changes in oak and hickory fuel chips on roofed and unroofed Louisiana air-drying grounds as affected by pile depth and turning of chips. Forest Products Journal 33(6):59—61.
Kofod, E.O. 1983. Biologiske og kemiske processer i braendsels flislagre. Torstoftab, udtorring og sundhedsrisici. Skovteknisk Institut. The Danish Institute of Forest Technology. 19 s.
Kotimaisten polttoaineiden tuotanto- ja käyttöpotentiaali. 1983. Ekono Oy. Kauppa- ja teollisuusministeriö, energiaosasto. Sarja D:23:1—37.
Kärkkäinen, M. 1977. Puu — sen rakenne ja ominaisuudet. Helsinki. 442 s.
— 1981. Polttopuun rasiinkaadon ja muiden kuivatusmenetelmien perusteet. Summary: Foundations of leaf-seasoning and other drying methods of fuelwood. Folia Forestalia 459. 15 s.
Lampinen, K. 1978. Hakkeen kuivaus savukaasulla. LAKA-vuosikirja. s. 35—41.
Lehtonen, I. 1977. Puu polttoaineena. Kirjallisuuteen perustuva tarkastelu. Abstract: Wood as a fuel. A study based on literature. Folia Forestalia 293. 16 s.
Levanto, S. 1961. Tutkimuksia 2-metrisen koivupolttopuun hakkuusta kesällä sekä rasiinkaatoa käytettäessä. Summary: Studies on summer felling and preparation of 2-metre birch fuelwood. Pienpuualan Toimikunnan julkaisu 130. 54 s.
Liss, J-E. 1979. Syrfällning. Institutionen för Skogsteknik, Skogshögskolan. Garpenberg. Stencil 73. 20 s.
Mihajlov, G.M. 1971. Hakkeen varastoiminen avoimissa kasoissa. Teoksessa: Koperin, F.I. et al. (toim.) Hakkeen valmistus puunkorjuutiloilla. Proizvodstuo tehnologitseskoj sepy v lespromhozah. Izd. les. prom. Moskova. s. 171—175.
Nylinder, M. 1979. Relationstal Träbränslen — Olja. Summary: Conversion factors Fuelwood — Oil. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 110. 51 s.
Panshin, P.J. & de Zeeuw, C. 1970. Textbook of Wood Technology. Vol. 1. McGraw-Hill Book Company. 705 s.
Parikka, M. 1984. Värmeproduktionskostnad för skogsbränsle i jämförelse med kol. Sveriges Lantbruksuniversitet, Skoglig marknadsinriktning. Rapport 3. 78 s.
Pellikka, M. 1983. Homepölyaltistus polttohakkeen käsittelyn yhteydessä. Metsäntutkimuslaitoksen tiedonantoja 81. 76 s.
— & Kotimaa, M. 1983. Polttohakkeen käsittelystä aiheutuva ilman homepölypitoisuus sekä siihen vaikuttavat tekijät. Summary: The mould dust concentration caused by the handling of fuel chips and its modifying factors. Folia Forestalia 563. 18 s.
Pesonen, M. 1982. Homepölyaltistus maatiloilla hakkeen käytön yhteydessä. Emissio 1/82. s. 19—21.
Salmi, J. 1964. Lahovikaisuuden vaikutus koivupuun lämpöarvoon. Summary: The influence of decay on the heat value of birch wood. Pienpuualan Toimikunnan julkaisu 168. 27 s.
Smith, R.S. & Ofosu-Asiedu, A. 1972. Distribution of thermophilic and thermotolerant fungi in a sprucepine chip pile. Canadian Journal of Forest Research 2:16—26.
Simola, P. & Mäkelä, M. 1976. Rasiinkaato kokopuiden korjuussa. Summary: Leaf-seasoning method in whole-tree logging. Folia Forestalia 273. 18 s.
Taipale, A. 1960. Tutkimuksia polttohakkeen varastoinnista. Summary: Studies of the storage of fuel chips. Pienpuualan Toimikunnan julkaisu 100. 47 s.
— 1962. Sahanhakkeen kuivuminen avokeossa ja katetussa varastossa. Summary: Seasoning of chips made of sawmill waste in uncovered stack and covered store. Pienpuualan Toimikunnan julkaisu 141. 27 s.
— 1963. Sahanhakkeen kuivumisesta varastossa. Teho 3.
Thörnqvist, T. 1980. Lagring av bränsleflis i perforerade plastsäckar. Summary: Storing of fuel chips in perforated plastic bags. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 115. 50 s.
— 1982. Torkning av bränsleflis med solfångaruppvärmd luft. Summary: Drying of fuel chips with

solar panel warmed air. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 126. 56 s.
— 1983. Bränsleflis förändring under ett års lagring. Summary: Fuel chips change during one year of storage. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 148. 65 s.
— & Gustafsson, G. 1983. Kalluftstorkningens betydelse för bränsleflisens lagringsbarhet. Summary: The importance of air drying for the storing property of fuel chips. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 142. 75 s.
— & Lundström, H. 1980. Svampförekomst vid bränsleflis hantering i mindre anläggningar. Summary: Factors affecting the occurrence of fungi in fuel chips for domestic consumption. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 117. 38 s.
Turkkila, K. & Knut, S. 1982. Homeiden määrä ja laatu maatilojen hakkeessa. Summary: The amount and species of the moulds in the chips of farms. Työtehoseuran metsätiedotus 344. 4 s.
Uusvaara, O. 1984. Hakepuun kosteuden alentaminen ennen haketusta korjuuseen ja varastointiin liittyvin toimenpitein. SITRA. Tutkimusraportti 35. 30 s.
Warsta, O. 1961. Rasiin kaadetun koivun ja lepän kuivumisesta. Pienpuualan Toimikunnan tiedotus 43. 8 s.
White, M.S., Curtis, M.L., Sarles, R.L. & Green, D.W. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part 1. Moisture content and temperature. Forest Products Journal 33(6):31—38.

Total of 73 references

SUMMARY

Drying of fuel chips and chunks in wooden bins

Small scale drying of whole tree fuel chips was studied at the Finnish Forest Research Institute during 1981 and 1982. The effects of particle size, season, bin type and tree species were studied.

Particle sizes were divided into chips (20 mm) and chunks (50—70 mm). Chipping was done with Junkkeri HJ-6 and HJ-10, and Hakki H-200 chippers. Kopo PH-10 and PH-15 were used for chunking. All the machinery was farm tractor driven.

The experiment was carried out in four stages and on five locations during both years. The drying seasons are listed below according to the particle size. (See also Figure 6 for the drying schedule.)

— Spring chips made from freshly cut trees
— Summer chips made from freshly cut trees
— Summer chips made from leaf-seasoned trees
— Autumn chips made from leaf-seasoned trees
— Spring chunks made from freshly cut trees
— Summer chunks made from freshly cut trees
— Summer chunks made from leaf-seasoned trees
— Autumn chunks made from leaf-seasoned trees

To carry out the experiment 30 wooden bins were built. They measured 130 x 230 x 500 cm and had a volume of 15 m^3 (Fig. 1—5). To enhance air circulation space was left between each lining board. Plastic roofings of various kinds were used. In 1982 two additional bins were constructed with a wire mesh lining instead of board. These bins also had an air canal in the bin (Fig. 4). All the bins were designed so that they would fit to a farm tractor trailer and met traffic regulations. A total of 74 bins (over 1000 m^3 loose) of chips and chunks were dried.

To record the moisture changes in the bins a portable electronic scale was used to weigh the bins (Fig. 7). Each bin was weighed once a week. The drawback of this system was that it did not take dry matter losses into consideration. This led to slightly optimistic results over a long period. Fortunately this could be compensated for at the end of the experiment by sampling. This approach was taken because proper moisture sampling from the bins is impossible.

On the basis of the weighing results regression equations were calculated for each particle size and season (Table 7). Locations were combined. Moisture content on green weight basis (%) was used as a dependent variable. Drying time in weeks was used as an independent variable. In addition to moisture content (%) also decrease of moisture content was used. In this case the starting moisture content was given a value of 100 and all the subsequent values are expressed as a percentage of the starting moisture content. This was done to decrease dispersion between locations and to improve coefficients. These equations are also more flexible to use as they are not tied to a specific moisture content.

In Figures 9—19 we can see that generally speaking the progress of drying was very similar, i.e. logarithmic in all the seasons both with chips and chunks. The common feature was the rapid drying during the first few weeks followed by a relatively slow drying over several weeks as the moisture content approached equilibrium state with the ambient air. On the other hand many differences also occurred.

The drying rate of chunks was found to be faster than of chips. This was most significant with freshly comminuted material where chunks dried faster by a factor of two. The differences were a lot less pronounced with material comminuted from leaf-seasoned trees. Also the final moisture contents of chunks were lower (Table 4). It should be noted, however, that the final figures are not the same as the lowest figures because of the increased moisture content during the fall.

The season of drying was found to be the most significant factor affecting drying (Fig. 21 and 22). As was expected, summer was the best season. Drying was further enhanced by using leaf-seasoned trees. It took the freshly comminuted material three times longer to

reach the moisture content of leaf-seasoned material. The difference was of the same order for both chips and chunks.

Drying is slow when started early in the spring (1982) and continues at a steady rate well into the summer. Rates do improve, however, if drying is postponed until May (1981).

The drying capacity of the bins becomes very limited in the fall. Leaf-seasoned material lost only 5 %-units of moisture over 2-3 weeks and stayed at the reached level for the rest of the experiment.

Dry matter losses were about 1,0 % per month (Table 5). It was also found that the losses of fresh material were higher than of seasoned material. The losses were also slightly higher for chips than for chunks.

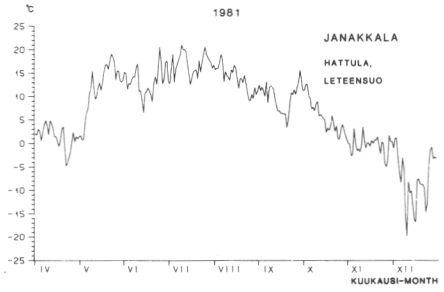
The accumulative effect of drying and dry matter losses is seen on the changes of heat values (Table 6). Because of the better drying characteristics chunks had a higher net gain than the chips. However, the heat values per unit volume were of the same magnitude because of the higher bulk density of chips.

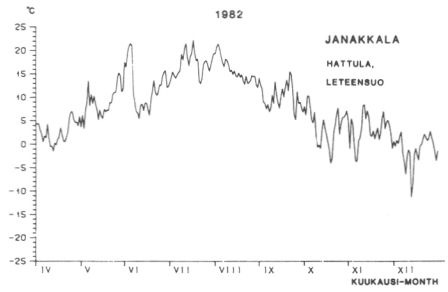
The wire mesh bins turned out to be equal to or better than the wooden bins. The major difference between the bin types was that with the wire mesh bin the particle size seemed to lose its importance. The chips and chunks also reached a lower moisture content in these bins and had a higher net gain of heat value. Dry matter losses were also lower.

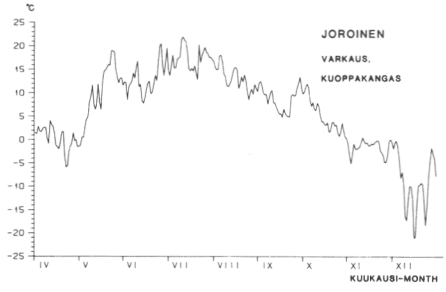
No major differences were found between alder and birch. Nevertheless, it should be noted that the starting and final moisture contents of birch were always lower. Most often the difference maintained its magnitude until the end of the experiment. Dry matter losses were of the same magnitude but not consistent. Because of the higher basic density and lower moisture content the heat values (MJ/m^3 loose) of birch chips and chunks were always greater than the heat values of alder. At the end of the experiment the difference was about 14 % on average.

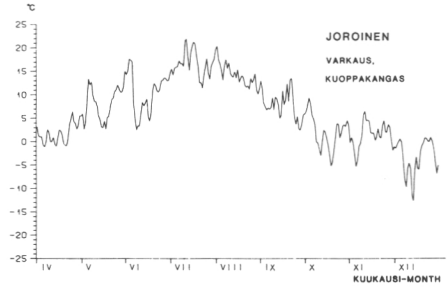
Drying was extended to several months in the study. In practice, however, the drying time should be optimized so that a maximum amount of chips or chunks can be dried per season.

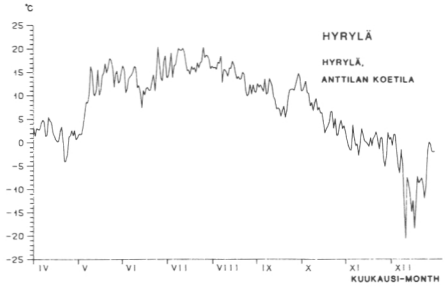
Drying of chips and chunks made of fresh material in spring will take 10-15 weeks. If comminution is done in summer the corresponding time is 5-10 weeks. Leaf-seasoned material will take about 5 weeks. Hence, if drying is optimized we can dry about 90 m^3 of chips or chunks per year in one bin. This is possible by drying one batch of fresh material in the spring, four batches of seasoned material in the summer and one batch of seasoned material in the fall.

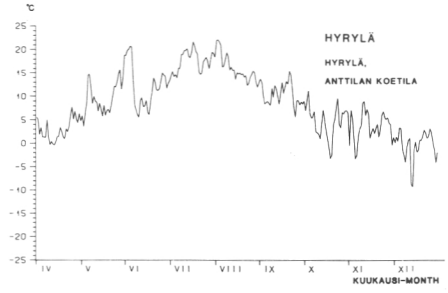


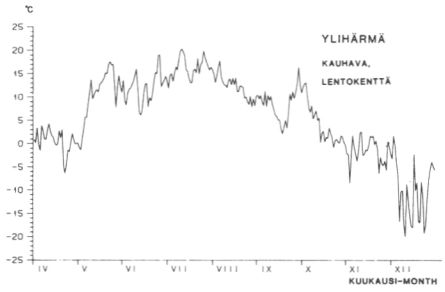


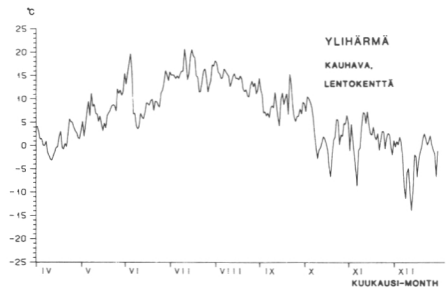


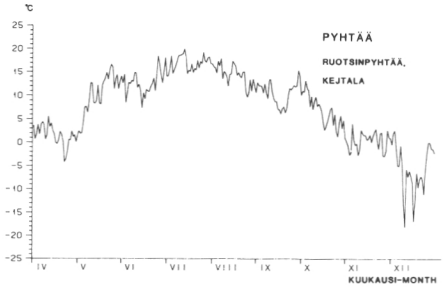




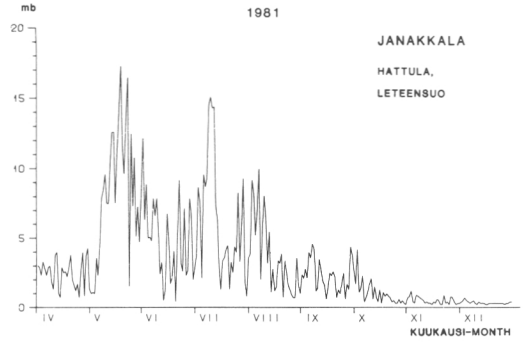


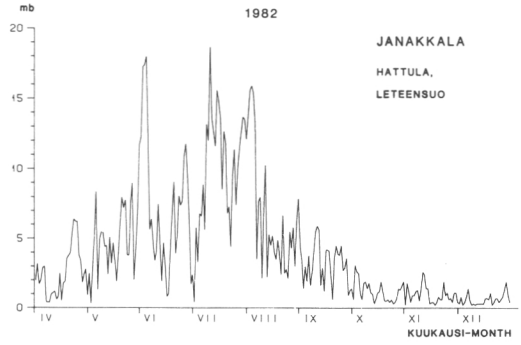


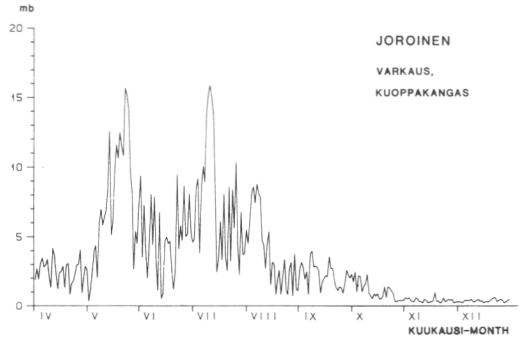


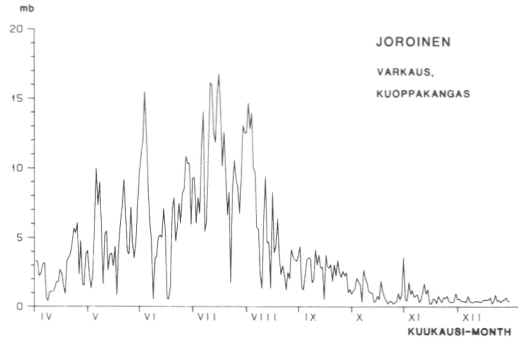


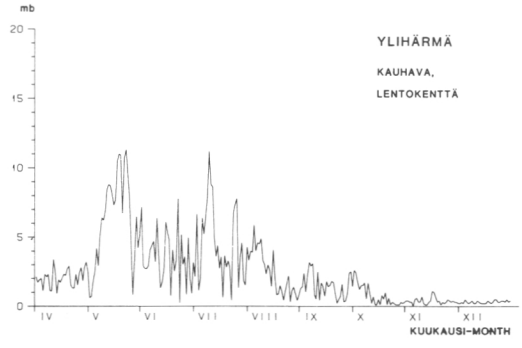
Liite 1. Ilman keskilämpötilat paikkakunnittain vuosina 1981 ja 1982.
Appendix 1. Mean daily temperatures in 1981 and 1982.

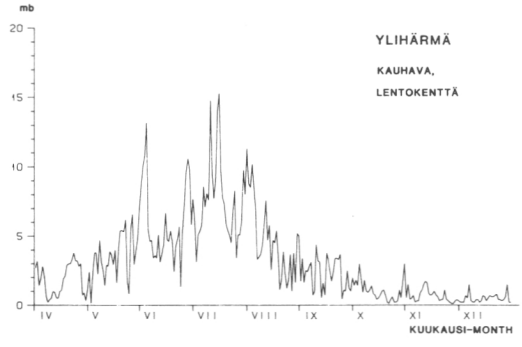


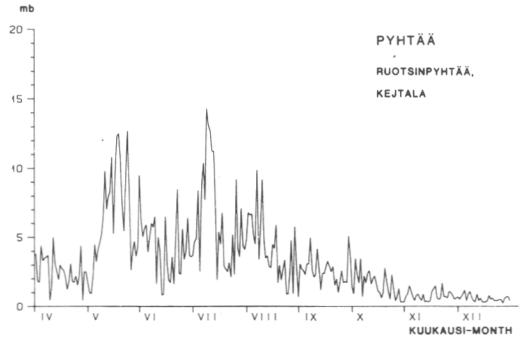




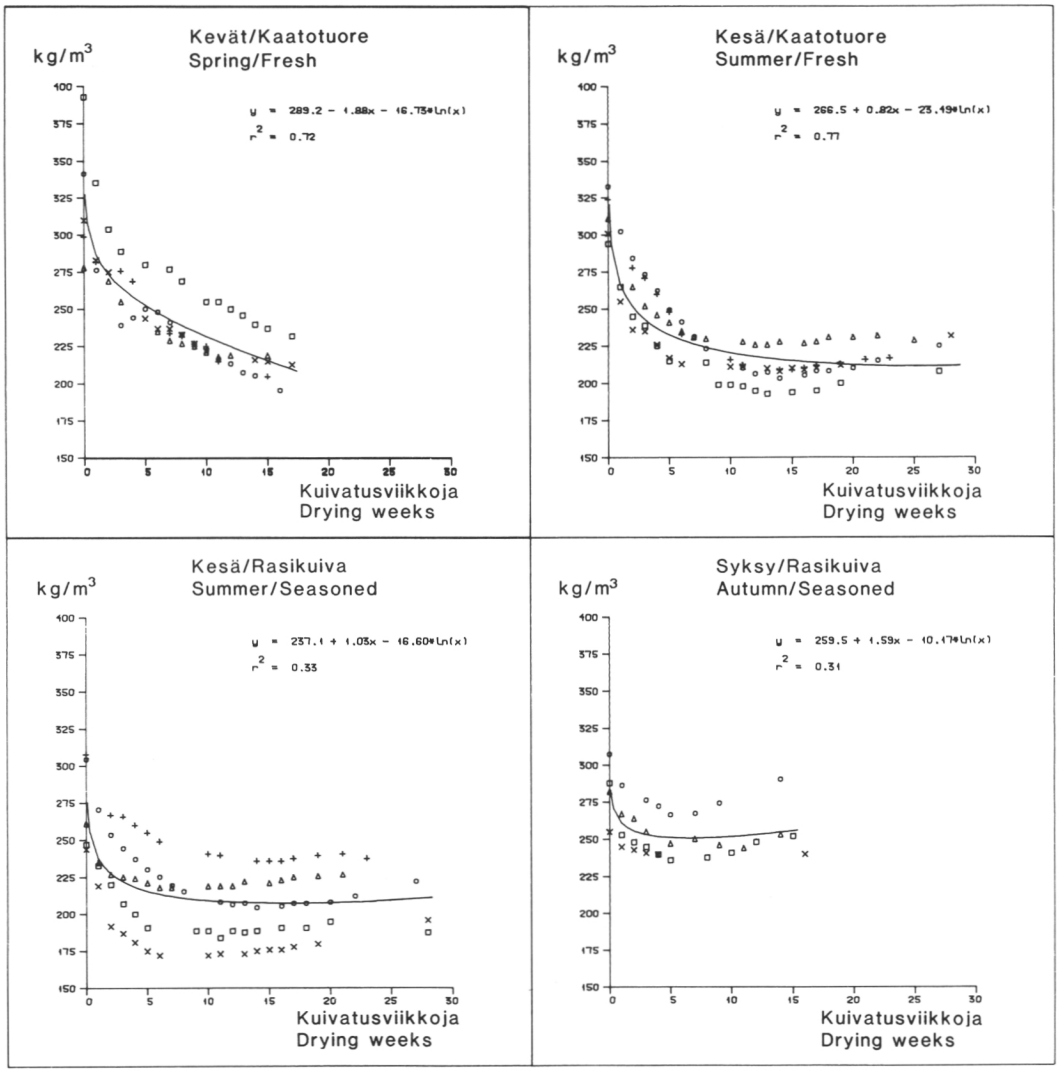




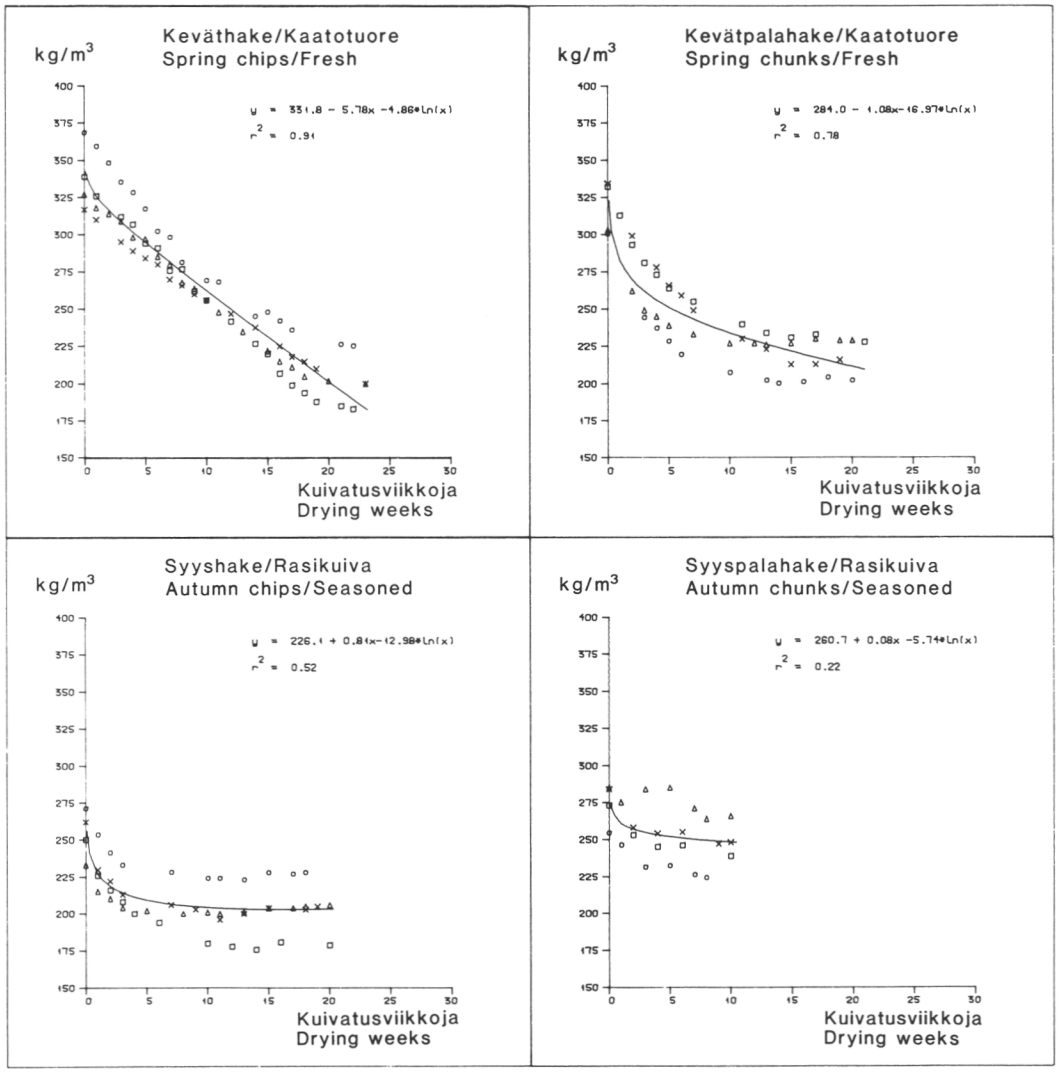




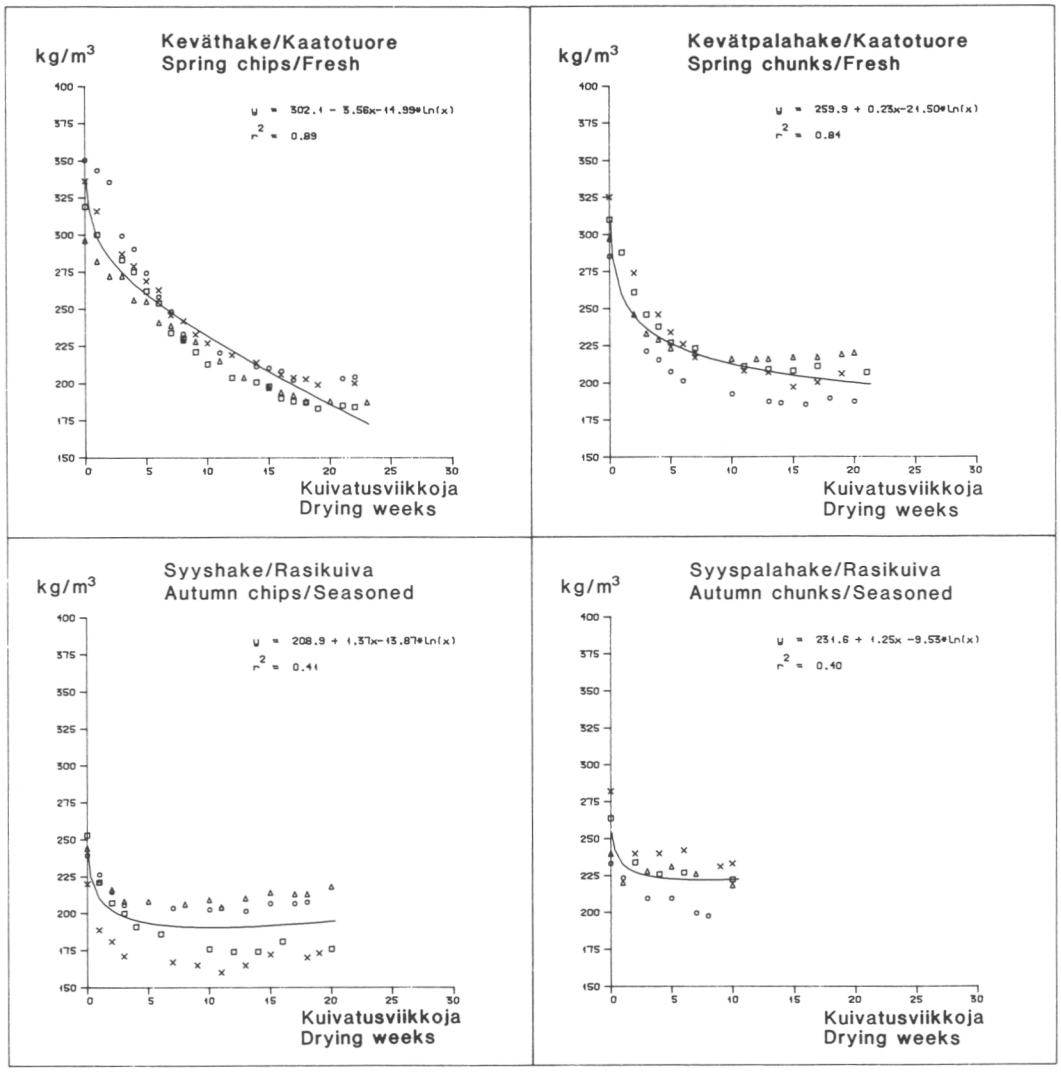
Liite 2. Ilman kyllästysvajaukset paikkakunnittain vuosina 1981 ja 1982.
Appendix 2. Vapor pressure deficit of ambient air in 1981 and 1982.



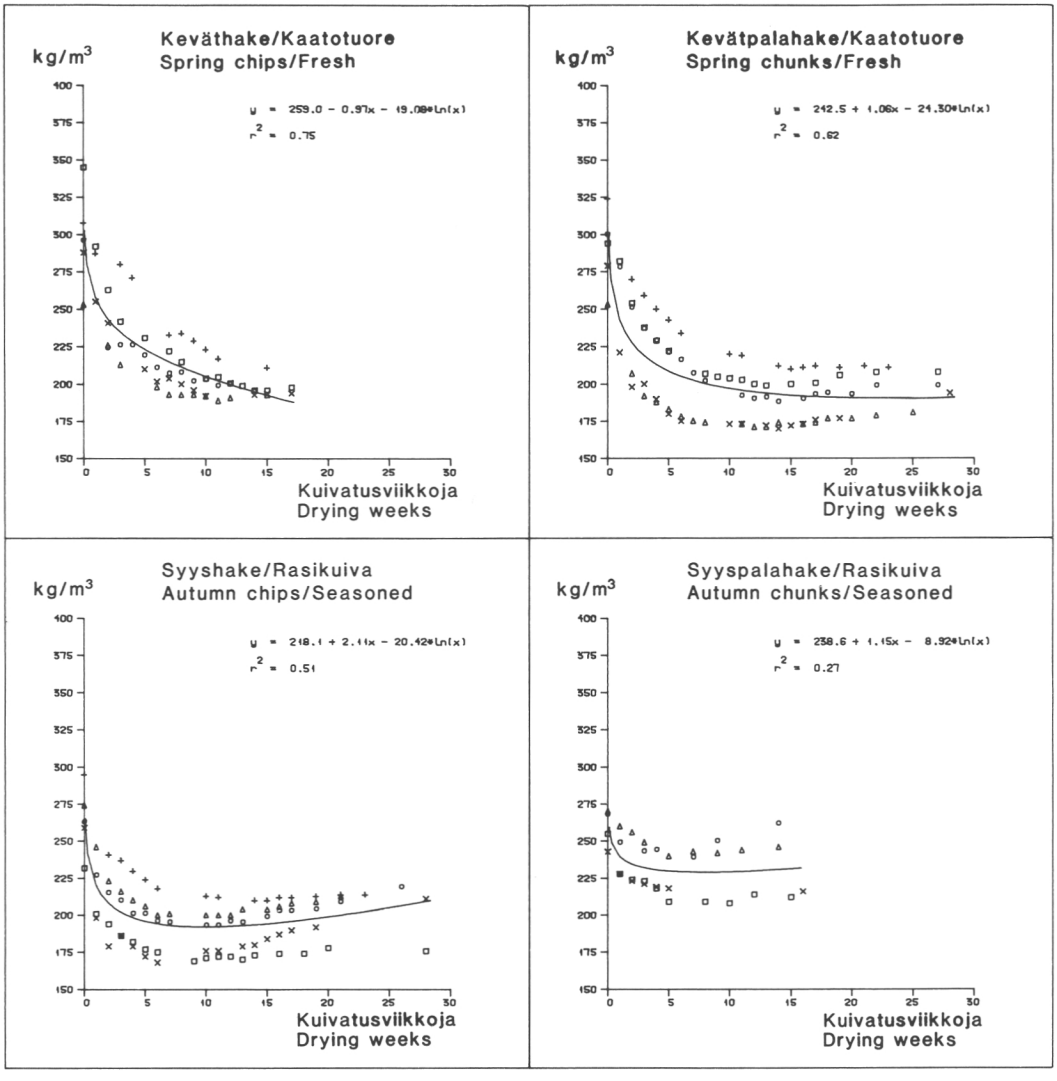
Liite 3. Hienohakkeiden painon muuttuminen vuonna 1981.
Appendix 3. Bulk densities of chips as a function of drying time in 1981.



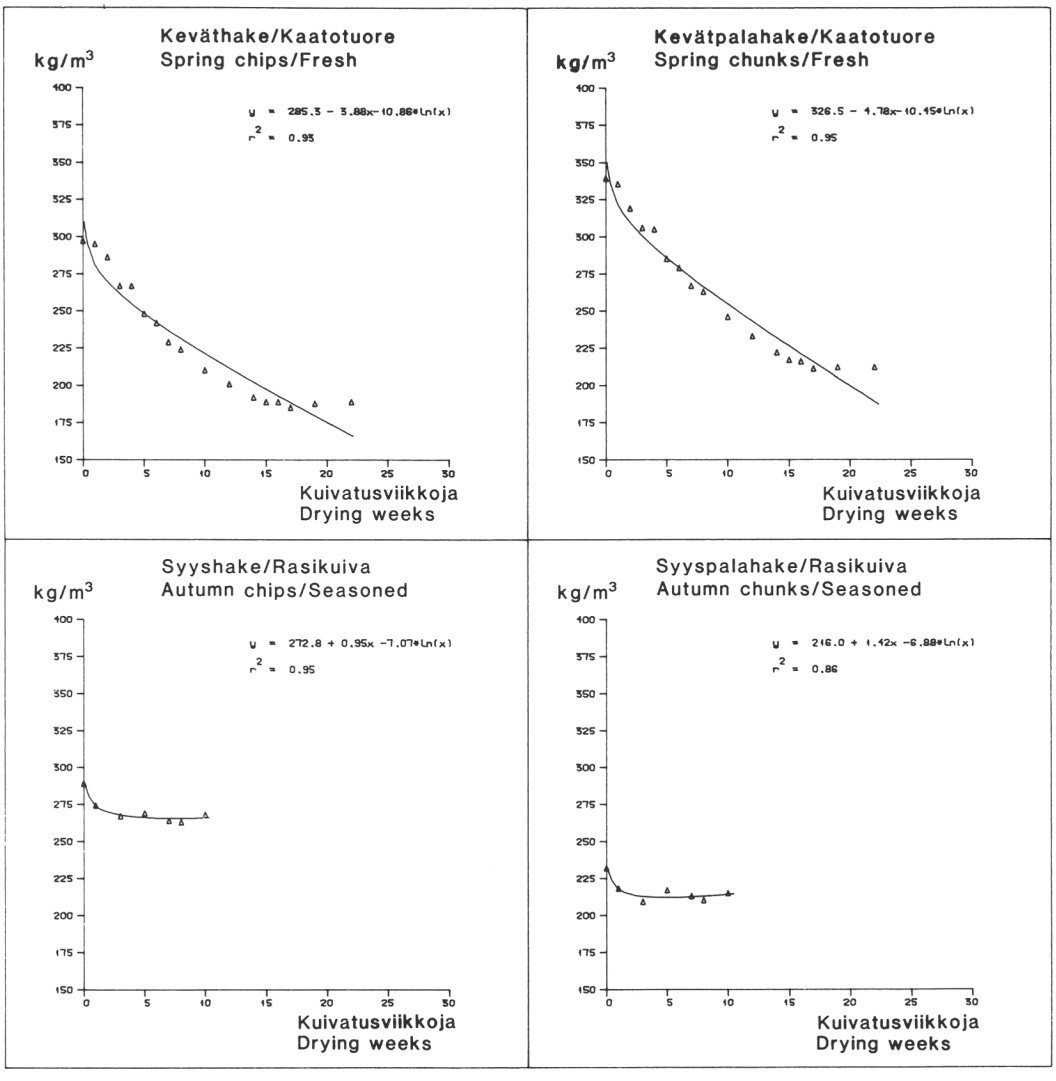
Liite 4. Hienohakkeiden painon muuttuminen vuonna 1982.
Appendix 4. Bulk densities of chips as a function of drying time in 1982.



Liite 5. Palahakkeiden painon muuttuminen vuonna 1981.
Appendix 5. Bulk densities of chunks as a function of drying time in 1981.



Liite 6. Palahakkeiden painon muuttuminen vuonna 1982.
Appendix 6. Bulk densities of chunks as a function of drying time in 1982.



Liite 7. Verkkokonteissa kuivattujen hieno- ja palahakkeiden painon muuttuminen vuonna 1982.
Appendix 7. Bulk densities of chips and chunks dried in wire mesh bins as a function of time in 1982.

V

FOLIA FORESTALIA 767

Metsäntutkimuslaitos. Institutum Forestale Fenniae. Helsinki 1990

Juha Nurmi

POLTTOHAKKEEN VARASTOINTI SUURISSA AUMOISSA

Longterm storage of fuel chips in large piles

Approved on 26.10.1990

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Nurmi, J. 1990. Polttohakkeen varastointi suurissa aumoissa. Folia Forestalia 767. 18 p.

Koivukokopuusta tehdyn polttohakkeen varastointia suurissa aumoissa tutkittiin napapiirin pohjoispuolella Sodankylässä. Tutkimuksessa selvitettiin varastoinnin pituuden, kattamisen ja pohjustamisen vaikutusta hakkeen lämpötilaan, kosteuteen, tiheyteen ja lämpöarvoon. Hake varastoitiin kahdessa 3000 i-m^3:n aumassa.

Polttohakkeen kuiva-ainetappiot kasvoivat varastointiajan pidentyessä. Aumojen kattaminen muovilla lisäsi kuiva-aine tappioita ja nosti puuaineen kosteutta estämällä puun hajoamisessa syntyvän veden haihtumisen auman pinnalta. Yli puoli vuotta kestäneen varastoinnin aikana kosteutta kerääntyi myös pohjamuovin päällä olleeseen hakkeeseen. Auman kattamista ja pohjustamista muovilla ei siis voida pitää perusteltuna puuteknologisista eikä taloudellisista syistä. Puuaineen kosteuden lisääntyminen sekä mineraalimaan sekoittuminen polttohakkeen joukkoon laskivat polttohakkeen tehollista lämpöarvoa.

Summary: Longterm storage of fuel chips in large piles.

Storing of birch wholetree chips was studied on the southwest side of Lokka reservoir, in Sodankylä at latitude 68 degrees north during 1983–85. The purpose of the study was to examine the effects of storing time, cover and underbase on pile temperature, wood moisture, dry matter losses and heat value. Two 3000 m^3-loose piles were made to carry out the study.

The dry matter losses were found to increase with time. Chips under plastic cover were found to suffer greater losses than those without cover. The use of cover also increased wood moisture content. When using plastic underbase the long storage periods seem to cause some of the moisture to collect on the bottom part of the pile. Hence it follows that the use of plastic as a cover and underbase material can not be justified. On one hand the increase in moisture content caused by the treatment and increased storage time and on the other hand the mixing of mineral soil with fuel chips had a negative effect on the heating value.

Keywords: fuel chips, fuel wood, storage.
ODC 363.7--084.4

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1. Johdanto

Puupolttoaineiden merkittävänä erona fossiilisiin polttoaineisiin verrattuna on puun ominaisuuksien, mm. kosteuden, tiheyden ja lämpöarvon vaihtelu. Puulajin ja kosteuden vaikutusta lämpöarvoon ovat tarkastelleet Heiskanen & Jokihaara (1961), Lehtonen (1977), Hakkila (1978) ja Björklund (1983). Lahovikaisuuden vaikutusta lämpöarvoon on tutkinut Salmi (1964). Yleiseltä kannalta ovat polttopuun ominaisuuksia käsitelleet Kärkkäinen (1977) ja Kofod (1983). Lisäksi Nylinder (1979) on selvitellyt lämpöarvon yhteyttä puun kosteuteen sekä puun kilpailukykyä polttoaineena öljyyn verrattuna.

Puuaineen kosteus on tärkein puun palamiseen vaikuttavista tekijöistä. Se riippuu ensisijaisesti puun kaadon jälkeisestä käsittelystä ja varastoinnista, mutta myös tuoreen puun kosteus vaihtelee. Kosteutta ja sen vähentämistä tutkittiin paljon Pienpuualan toimikunnan aikana (mm. Taipale 1960, 1962, 1963, Aittomäki 1963). Polttohaketta on kuivattu puhallusilman avulla (Gustafsson 1981, Thörnqvist 1982, Thörnqvist & Gustafsson 1983, Gislerud 1983) ja jopa savukaasuilla. Muita kuivatustapoja ovat tutkineet Alestalo (1982), Koch (1983) ja Nurmi (1987). Palakoon vaikutusta hakkeen varastointiin ja säilymiseen ovat tutkineet Sturos (1984a, b), Fredrikson & Rutegård (1985), Nurmi (1986, 1987), Arola (1988), Gjølsjø (1988), Gustafsson (1988), Hudson ym. (1988) ja Mivell (1988).

Polttohakkeen pienkuluttajien keskuudessa hakkeen kuivatus on tavanomainen toimenpide. Suurkuluttajien kannalta tämä ei kuitenkaan kannata suurten määrien sekä useiden toimittajien takia. Siksi monet teollisuustutkimuksista ovatkin liittyneet polttohakkeen varastointiin. Tätä aihetta ovat tutkineet mm. Immonen (1961), Håkansson & Numminen (1963), Annergren ym. (1964), Hajny (1966), Bergman & Nilsson (1966, 1967, 1968, 1971, 1974, 1979), Gislerud & Grønlien (1977, 1978a, b) sekä Gislerud (1978). Polttohakkeen pienkäyttäjillä ilmenneet hengitystieallergiat ovat antaneet aihetta useille tutkimuksille kymmenen viime vuoden aikana (Gislerud 1974, Strömquist ym. 1980, Thörnqvist 1980, 1983, Björklund 1982, 1983, White ym. 1983). Erityisesti fysiologisia haittoja ovat tutkineet Smith & Ofosu-Asiedu (1972), Høeg (1980, 1981), Thörnqvist & Lundström (1980), Turkkila & Knut (1982), Pesonen (1982), Pellikka (1983), Pellikka & Kotimaa (1983) ja Belin (1984).

Koska itse hakkeen kuivaaminen suurina määrinä ei kannata, puun kosteuden alentaminen ennen haketusta on mielekkäin vaihtoehto. Puun rasikuivatus sekä kokopuiden tai rankojen kuivatus kasoissa ovat edelleenkin yksinkertaisimmat ja taloudellisimmat menetelmät (Jalava 1941, Heiskanen & Hakkila 1960, Levanto 1961, Warsta 1961, Hakkila 1962, Simola & Mäkelä 1976, Liss 1979, Faeste & Johnsson 1982, Uusvaara 1984).

Tämän tutkimuksen tarkoituksena on selvittää, mitä muutoksia varastointi aiheuttaa polttohakkeen puuaineessa sekä kuinka nämä muutokset voitaisiin minimoida. Kattamisen on yleensä oletettu vaikuttavan positiivisesti puupolttoaineiden laatuun estämällä veden ja lumen pääsyn varastoitavaan materiaaliin. Tämän oletamuksen todenperäisyyden selvittämiseksi hakeaumojen osia pohjustettiin ja katettiin eri pituisiksi ajoiksi polttohakkeen varastoinnin yhteydessä. Puuaineen laadun muutoksia tutkittiin kosteuden, tiheyden, kuiva-tuoretiheyden ja auman lämpötilan kannalta.

Aloitteen tutkimuksesta teki maan suurin polttohakkeen toimittaja Vapo Oy. Yhtiö vastasi haketuksesta, hakkeen kuormauksesta ja siirrosta sekä teiden aurauksesta talviaikaan. Metsäntutkimuslaitoksen metsäteknologian osasto vastasi tutkimuksen järjestelyistä, aineiston keruusta, käsittelystä sekä raportoinnista. Tutkimus on osa Metsäntutkimuslaitoksen Pienpuun korjuu ja hyväksikäyttö -projektia.

Tutkimuksen kenttätöiden järjestelyssä avustivat Hannu Kalaja, Tapio Nevalainen, Veijo Salo ja Jaakko Kalaja Metsäntutkimuslaitoksesta sekä Martti Pyykkö Vapo Oy:n Rovaniemen konttorista. Lämpöarvonäytteiden käsittelystä vastasi Jaakko Lehtovaara Vapo Oy:n Jyväskylän laboratoriosta. Aineiston tilastollisessa käsittelyssä avustivat Arto Ketola ja Jyrki Hytönen sekä tulostuksessa Keijo Polet ja Ulla-Riitta Uusitalo. Graafiset työt tekivät Maire Ala-Pöntiö ja Leena Muronranta. Käsikirjoituksen tarkastivat Pentti Hakkila, Pertti Harstela ja Olli Uusvaara. Kiitän kaikkia avusta.

2. Aineisto ja menetelmät

Polttohake tehtiin 26.8.–5.9.1983 Sodankylässä Lokan tekoaltaan lounaisrannalla. Haketettavat hieskoivut oli kaadettu edellisenä vuonna männyn taimikon päältä ja pinottu lehdettöminä kokopuina tienvarsikasoihin. Puut haketettiin Perusyhtymän valmistamalla TT 1500 -hakkurilla suoraan ajoneuvoon, jolla hake siirrettiin varastointipaikaksi varattuun vanhaan soranottopaikkaan noin 3 km:n päähän. Hake aumattiin pyörökuormaajalla, joka tiivisti haketta aumaan epätasaisesti. Tähän ei osattu ennakolta varautua, ja tiivistyminen vaikutti joissain tapauksissa tuloksiin enemmän kuin tutkittaviksi valitut tekijät.

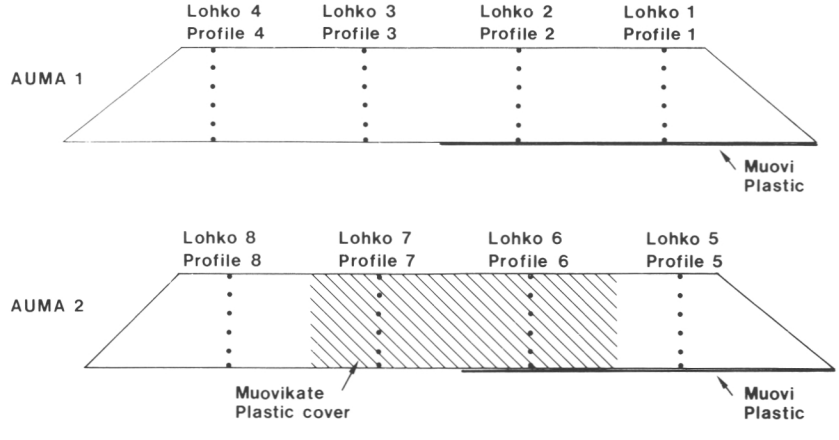
Aumoja tehtiin kaksi. Tarkoituksena oli kattaa aumojen keskiosat muovilla ja jättää päät avoimiksi. Tämän lisäksi auman toinen puoli tuli pohjustaa muovilla, jolloin kumpaankin aumaan olisi saatu neljä katteen ja pohjan yhdistelmää.

Toisen auman peittäminen ei onnistunut voimakkaitten tuulten takia, joten sen peittämisestä luovuttiin kolmen viikon kuluttua. Näin tutkimuksessa jouduttiin tarkkailemaan kahta eri tavoin käsiteltyä 3000 i-m^3:n aumaa (kuva 1). Kumpikin auma jaettiin neljään osaan, joita tässä yhteydessä kutsutaan lohkoiksi. Alla olevasta asetelmasta ilmenee kunkin lohkon kate, pohja sekä varastointiaika.

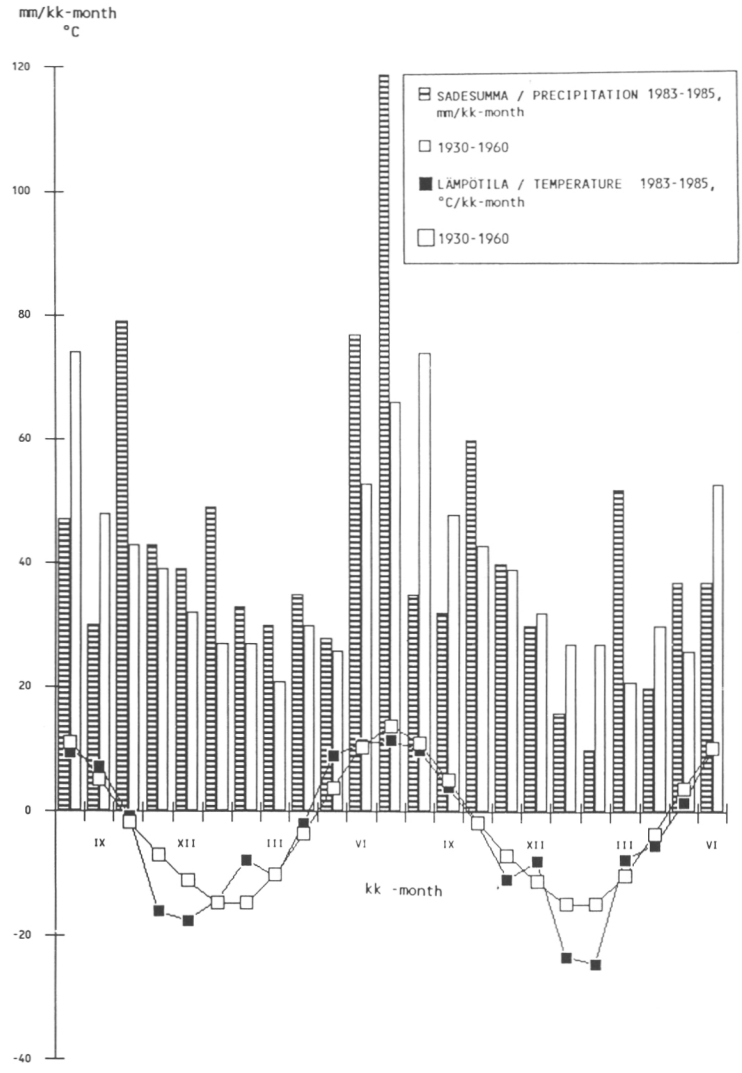
Lohko	Kate	Pohja	Varastointi-aika,kk
1	ei	on	5,5
2	ei	on	14
3	ei	ei	14
4	ei	ei	5,5
5	ei	on	18
6	on	on	18
7	on	ei	18
8	ei	ei	18

Varastoinnin aiheuttamia puuaineen muutoksia selvitettiin mittaamalla hakkeen kosteutta, tiheyttä, lämpöarvoa ja tuhkapitoisuutta näytteistä jotka, kerättiin sekä aumauksen, että auman purkamisen yhteydessä. Tätä tarkoitusta varten asetettin hakkeella täytetyt verkkopussit aumoihin kunkin lohkon keskelle pystytasoon yhden metrin ruudukkoon. Tämä helpotti näytteenottoa aumojen purkamisen yhteydessä. Lohkosta 5 auman purkamisen yhteydessä sattuneen huolimattomuuden takia ei kaikkia pusseja saatu talteen. Puuaineen kosteudet ja kuiva-tuoretiheydet määritettiin Metsäntutkimuslaitoksessa Helsingissä. Tiheys määritettiin veteenupotusmenetellä. Koska hake muodostuu lukuisista erikokoisista ja -muotoisista palasista, menetelmän käyttö on jonkin verran epätarkkaa. Hakkeen ominaisuuksien tarkkailuun rakennettiin ohuesta, perforoidusta teräksestä ylösalaisin seisova katkaistu kartio, joka läpäisi hyvin ilmaa ja vettä. Tiheyden aleneminen on ilmaistu kuiva-ainetappioina (%). Lämpöarvo ja tuhkanäytteet määritettiin Vapon Oy:n Jyväskylän laboratoriossa.

Mikrobit ja kemiallinen hajoaminen saavat hakkeessa aikaan muutoksia, joista lämpötilan kohoaminen on helpoiten havaittavissa. Näistä prosesseista vapautuvan lämmön mittaamiseksi hankittiin Vapo:n Kokkolan konepajalta turveaumojen mittaukseen tarkoitettu kaksimetrinen lämpömittari. Puuaineen kovuuden ja hakeauman tiiviyden takia mittaria oli vahvistettava ja kehitettävä. Lämpötila mitatiin lohkoittain pisteissä, jotka sijaitsivat kahden metrin välein korkeussuunnassa auman rinnettä pitkin (kuva 1). Kussakin pisteessä mittaus tehtiin 0,5, 1,0 ja 2,0 metrin syvyyksiltä. Kaikkiaan mittauspisteitä oli kahdessa aumassa 97. Lämpötiloja mitattiin keskimäärin kahden viikon välein. Aineistoa käsiteltäessä on kullekin mittauspisteelle laskettu kuukauden keskiarvo, minkä jälkeen keskiarvot on summattu lämpösummaksi. Selitet-



Kuva 1. Lohkojen sijainnit aumoissa.
Figure 1. The location of treatments in the piles.



Kuva 2. Sadesumman ja lämpötilan kuukausittaiset lukemat tutkimuksen aikana vuosina 1983–85 sekä pitkäaikaiset keskiarvot vuosilta 1930–60. Mittaukset tehty Sodankylän, Vuotson sääasemalla (Ilmatieteen laitos...).

Figure 2. The monthly precipitation and temperature during the experiment in 1983–85 and the longterm averages in 1930–60. Measurements taken at Sodankylä, Vuotso weather station.

täessä hakkeen tiheyttä lämpötilalla valittiin mittauspisteeksi aina näytteen ottokohtaa lähinnä ollut mittauspiste. Vaikkakaan aumojen lämpötilojen ja sään välistä yhteyttä ei tässä yhteydessä selvitetty, kuukauden keskilämpötilat ja sademäärät on koottu kuvaan 2.

Käsittelyjen välisiä eroja tarkasteltiin vertaamalla lohkojen puuteknisten tunnusten variansseja ja keskiarvoja. Regressioanalyysillä tutkittiin muovikatteen ja pohjan vaikutusta auman lämpötilaan ja puuaineen tiheyteen.

3. Tulokset

31. Aumojen lämpötila

Aumojen lämpötila riippui useista tekijöistä. Hakkeen kosteus, varaston koko, raaka-aineen koostumus, palakoko, auman tiivistyminen, puulaji sekä kasan tuuletus vaikuttavat niin lämpötiloihin kuin puuteknisiin ominaisuuksiin (Thornqvist 1988). Lokan aumojen kohdalla tutkittiin mittauspisteen korkeuden ja syvyyden, varastoinnin pituuden, sekä katteen ja pohjustuksen vaikutusta lämpötilaan.

Kuvat 3 ja 4 osoittavat lämpötilojen vaihdelleen ennen kaikkea vuodenajan mukaan. Lämpötilat olivat korkeimmat syksyllä pian aumauksen jälkeen, mutta laskivat monissa lohkoissa talven aikana. Seuraavana kesänä lämpötilat jälleen kohosivat. Kuvista nähdään myös lämpötilojen olleen korkeampia auman sisällä kuin pinnassa ja korkeampia yläosassa kuin pohjalla.

Mittauspisteen korkeus ja syvyys selittivät merkittävästi aumojen lämpötiloja molemmissa aumoissa ja kaikissa lohkoissa. Korkeus oli kaikissa lohkoissa hyvin merkitsevä selittäjä mutta syvyys vain osassa lohkoja (taulukko 1).

Pohjamuovi vaikutti aumojen lämpötiloihin siten, että auman 1 pohjustettu lohko 1 oli lohkoa 4 viileämpi. Toisaalta auman 2 lohkojen 5 ja 8 kohdalla tilanne oli päinvastainen. Koska pohjan käyttö oli antanut ristiriitaisen tuloksen, on selitystä haettava varsinaisten koeasetelmien ulkopuolelta. Tällainen tekijä on ollut pyöräkuormaajan tiivistävä vaikutus. Aumassa 1 ajo tapahtui lohkosta 4 lohkoon 1 päin, jolloin lohkoon 4 kohdistui eniten ja lohkoon 3 seuraavaksi eniten painetta. Vastaavasti aumassa 2 suurin tiivistyminen kohdistui lohkoon 5 ja pienin lohkoon 8. Vertailtaessa lohkoja pareittain havaittiin, että lämpötila oli johdonmukaisesti ollut aina korkeampi siinä lohkossa, jonka yli oli ajettu useimmin. Ainoan poikkeuksen tähän muodostivat katetut lohkot 6 ja 7, jotka eivät erottuneet tilastollisesti merkitsevästi (taulukko 2). Tiivistyminen näytti vaikuttaneen pohjaa enemmän auman lämpötilaan, ja siksi tiiviyttä tulisi mahdollisuuksien mukaan välttää. Myös Thörnqvist (1987) on havainnut tiivistymisen nostavan lämpötilaa. Hänen mukaansa aumapalot tapahtuvat nimenomaan pakkautuneen ja pakkautumattoman hakkeen rajapinnoissa.

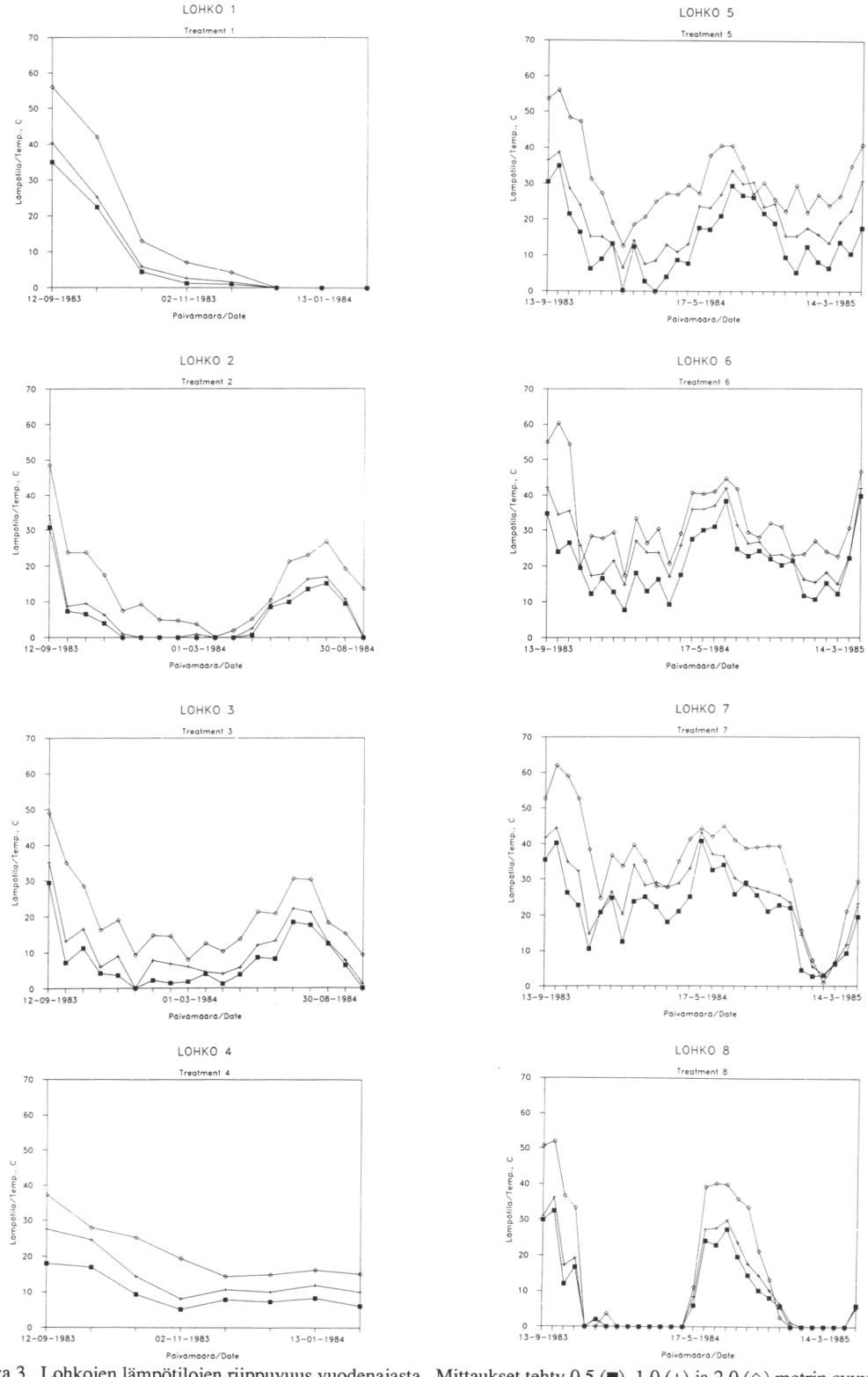
Auman kattaminen muovilla nosti lämpötiloja merkitsevästi. Lämpösummien vertailua varten auma 2 jaettiin pohjustettuihin ja pohjustamattomiin lohkoihin. Molemmissa vertailuissa kate nosti lämpötilaa. Erot olivat varsin suuret lohkojen 7 ja 8 välillä. Lohko 8 oli jäässä suurimman osan talvea, mikä johtui sen vähäisestä tiivistymisestä. Lohkojen 5 ja 6 väliset erot olivat huomattavasti pienemmät (taulukko 2).

32. Puuaineen kosteus

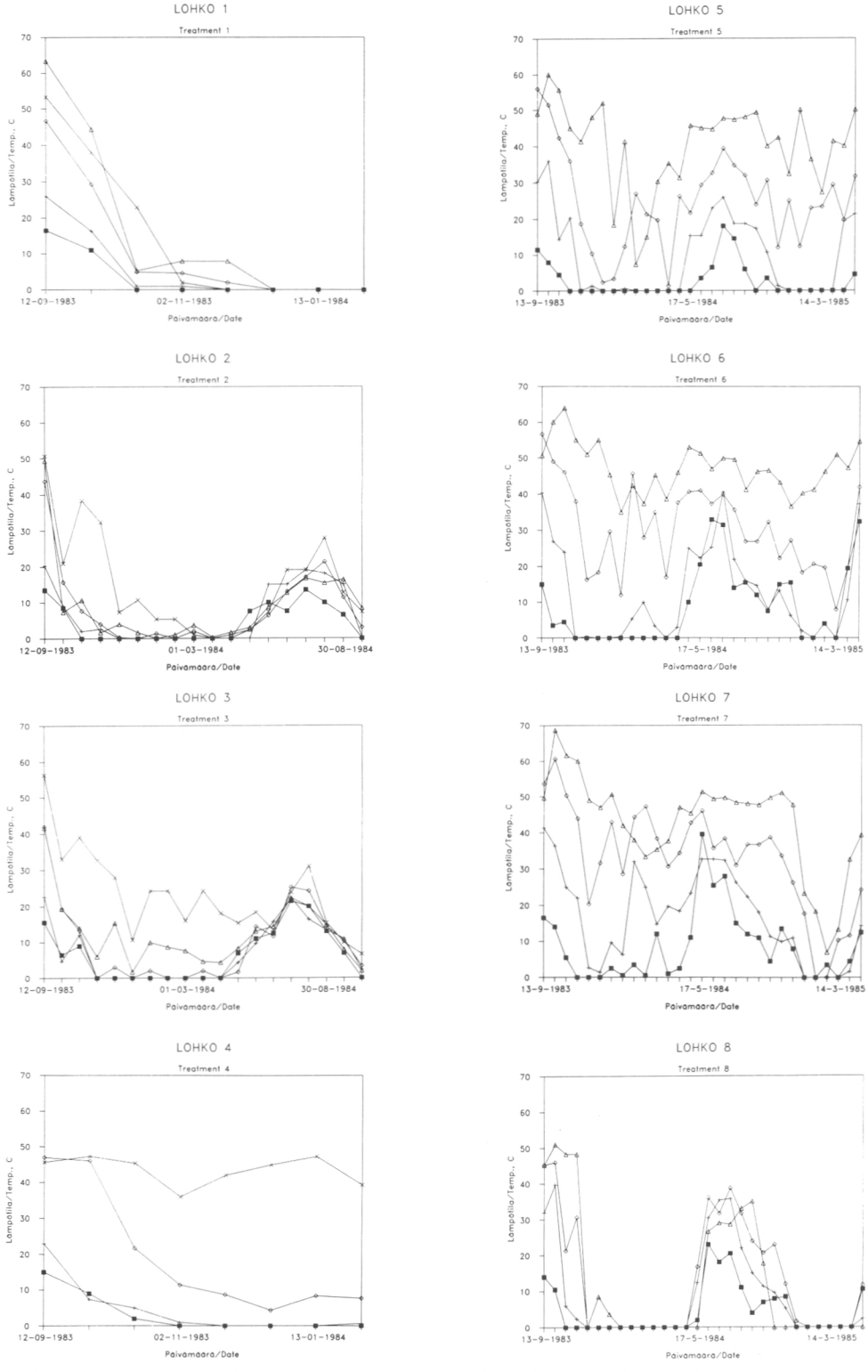
Aumojen hake tehtiin kasoissa kuivuneesta kokopuusta. Puuaineen alkukosteus oli 1. aumassa 31,1% ja 2. aumassa 30,9%. Aikaisemmissa selvityksissä ei ole todettu yhtä alhaisia kosteusarvoja kasoissa kuivuneelle kokopuulle (Hakkila 1962, 1984 ja Uusvaara 1984). Koska haketettu puutavara oli yhdenmukaista sekä kosteudeltaan että muiltakin ominaisuuksiltaan,

Taulukko 1. Aumojen lämpösumman (y) riippuvuus mittauspisteen korkeudesta (x_1) ja syvyydestä (x_2).
Table 1. The heat sum of piles (y) as a function of height (x_1) and depth (x_2) of the measurement point.

Auma *Pile*	Lohko *Treatment*	Regressiomalli *Regression model*	F-arvo *F ratio*	r^2
1		$-55,7+18,1x_1+45,1x_2$	19,8***	0,46
	1	$-9,2+6,1x_1+10,9x_2$	19,0***	0,81
	2	$-41,8+13,4x_1+65,6x_2$	27,8***	0,84
	3	$-87,1+27,4x_1+80,0x_2$	17,2***	0,76
	4	$-84,3+23,8x_1+28,1x_2$	38,0***	0,90
2		$-159,8+93,5x_1+84,1x_2$	32,1***	0,63
	5	$-284,5+121,3x1+70,3x_2$	71,4***	0,97
	6	$-222,0+126,6x_1+85,7x_2$	56,6***	0,93
	7	$-132,5+104,2x_1+98,0x_2$	64,9***	0,94
	8	$-2,3+22,5x_1+83,0x_2$	24,4***	0,86



Kuva 3. Lohkojen lämpötilojen riippuvuus vuodenajasta. Mittaukset tehty 0,5 (■), 1,0 (+) ja 2,0 (◇) metrin syvyyksiltä.
Figure 3. Pile temperatures as a function of the season. Measurements taken at depths of 0.5 (■), 1.0 (+) and 2.0 (◇) meters.



Kuva 4. Lohkojen lämpötilojen riippuvuus vuodenajasta. Mittaukset tehty 2 (■), 4 (+), 6 (◇), 8 metrin korkeuksilta (△) sekä auman päältä (×).

Figure 4. Pile temperatures as a function of the season. Measurements taken at heights of 2 (■), 4 (+), 6 (◇), 8 meters (△) and the top of the pile (×).

Taulukko 2. Lämpösummien tilastollinen merkitsevyys auman eri osissa pohjamuovia ($_x$) tai katetta (^{y}) käytettäessä.
Table 2. F ratios of analysis of variance for the heatsums of tested treatments when plastic underbase ($_x$) or cover (^{y}) are used.

Mittauspisteen sijainti *Location of the measuring point*		Vertailtavat lohkot — *Tested treatments* F-arvot — *F ratios*					
Korkeus, m *Height, m*	Syvyys, m *Depth, m*	1_xvs, 4	2_xvs, 3	5_xvs, 8	6_xvs, 7	5vs, 6^y	7^yvs, 8
2	0,5	0,23	1,77	1,92	0,80	27,91***	4,98*
	1,0	0,01	1,16	2,21	0,50	46,18***	7,12*
4	0,5	0,01	2,22	0,25	3,12	6,95*	6,34*
	1,0	0,22	0,07	0,12	1,44	2,01	4,73*
	2,0	0,27	0,13	0,05	0,74	1,85	4,28*
6	0,5	1,25	2,45	2,53	0,18	11,52**	10,92**
	1,0	5,03	0,74	18,42***	0,00	2,32	15,83***
	2,0	18,27**	0,47	5,49**	0,90	0,76	16,02***
Päältä -	0,5	31,61**	0,01	23,74***	1,35	7,43*	48,56***
From the	1,0	58,37***	5,56*	52,52***	2,28	10,13**	72,55***
top	2,0	117,28***	10,62**	60,63***	2,49	1,15	36,43***

Taulukko 3. Koivukokopuuhakkeen kosteudet (%) kokeen alussa sekä lohkoittain kokeen lopussa.
Table 3. Moisture content (%) of birch whole tree chips in the beginning of the experiment and in the end according to the treatment.

	Alussa *Starting value*	Lohko — *Treatment* 1	2	3	4
$\bar{x}$	$31,1^{ab}$	$25,3^{a}$	$39,0^{b}$	$27,8^{ab}$	$31,4^{ab}$
s	1,3	7,4	20,2	15,0	14,6
		5	6	7	8
$\bar{x}$	30,9	31,2	41,9	39,0	39,0
s	2,6	20,9	23,5	20,2	18,5

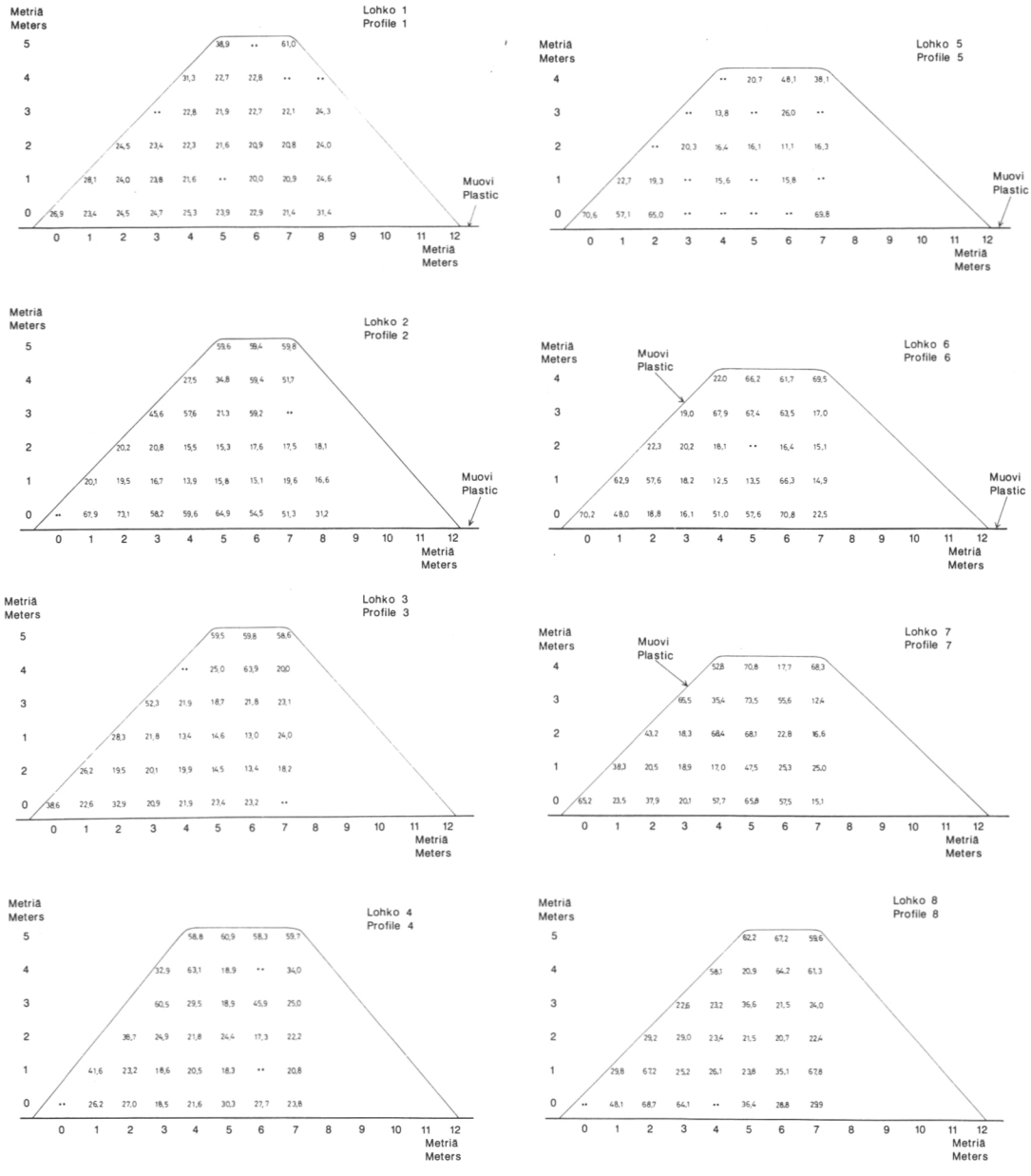
Samalla kirjaimella on merkitty ne keskiarvot, jotka yksisuuntaisen variianssianalyysin jälkeen eivät poikenneet toisistaan ($p < 0,05$).
Means indicated with the same letter do not differ from each other at 5% significance level.

voitiin olettaa varastoinnista aiheutuvien puuteknisten sekä kemiallisten muutosten olevan helposti havaittavissa.

Mikrobien aiheuttama lämpötilan nousu saa aikaan kaasujen kiertoa. Sen mukana siirtyy hakkeessa jo olevaa ja puuaineen hajoamisessa syntyvää kosteutta auman yläosaan. Siellä osa kosteudesta tiivistyy auman pinnalla olevaan hakkeeseen ja osa haihtuu ilmaan, mikäli estettä ei ole. Kuvassa 5 näkyvät purkamishetkellä vallinneet kosteudet. Puoli vuotta varastoitujen lohkojen 1 ja 4 kosteus oli siirtynyt sisemmistä osista auman pintaan. Saman ilmiön ovat aiemmin havainneet mm. Gislerud & Grønlien (1978), Thörnqvist (1983), Björklund (1982) sekä Sampson & McBeath (1989). Niin auman keskellä kuin pohjallakin hake oli hieman kuivunut. Lohkon 1 kosteus oli laskenut enemmän, mutta tilastollisesti se ei poikennut merkittävästi lohkosta 4 (taulukko 3). Lohkon 1 alhainen kosteus aiheutui ilmeisesti siitä, että kuormatraktorin pyörät eivät tiivistäneet haketta auman tässä osassa samassa määrin kuin auman 1 muissa lohkoissa. Näin ollen kaasut pääsivät kiertämään lohkossa 1 auman muita osia paremmin. Myös lohkon lämpötila oli huomattavasti alhaisempi kuin muissa lohkoissa.

Pitempään varastoidut lohkot 2 ja 3 käyttäytyivät lähes samalla tavoin kuin aiemmin puretut lohkot, eivätkä niiden kosteusarvot eronneet merkitsevästi muista lohkoista. Lohkossa 2 muovin päällä olleet hakkeet kuitenkin kastuivat. Tämä on erikoista, sillä lohkon 1 pohjahan oli kuivunut varastoinnin aikana, eikä alhaalta päin ole voinut tulla kosteutta.

Auman 2 kosteuksien keskiarvot kasvoivat kaikissa lohkoissa. Vaikkakaan lohkojen väliset erot eivät osoittautunut tilastollisesti merkitseviksi, niin lohkojen 6 ja 7 kosteus oli kuitenkin lisääntynyt 8–11 prosenttiyksikköä. Toisin kuin aumassa 1 oli aumassa 2 kosteutta kertynyt myös auman sisäosiin. Varastoinnin pitkittyessä puuaineen hajoamisesta syntyvä kosteus ei ilmeisesti ehdi poistua aumasta. Suurimmat kosteudet olivat tosin edelleenkin havaittavissa



Kuva 5. Hakkeen kosteus eri lohkoissa (puuttuva tieto = ··)
Figure 5. The moisture content of chips in different treatments (missing information = ··).

auman päällä ja pohjalla. Lohko 5 muodosti poikkeuksen, sillä sen yläosaan oli kosteutta kerääntynyt tuskin lainkaan. Toisaalta auman pohjalla olevat hakkeet olivat hyvin kosteita, mikä tukee lohkon 2 havaintoja kosteuden kertymisestä muovin päälle.

33. Puuaineen tiheys ja kuiva-ainetappiot

Niin haketta kuin muitakin organisia aineita varastoitaessa mikrobien toiminta kiihtyy ympäristön sallimissa rajoissa, mikä näkyy mm. kuiva-ainetappioina. Biomassan varastoinnissa

Taulukko 4. Koivukokopuuhakkeen tiheydet (kg/m^3) lohkoittain kokeen alussa sekä lohkoittain kokeen lopussa.

Table 4. Basic density of birch whole tree chips (kg/m^3) in the beginning of the experiment and in the end according to the treatment.

	Alussa *Starting value*	Lohko — *Treatment* 1	2	3	4
$\bar{x}$	442,25^a	459,39^c	423,03^b	433,35^{ab}	436,87^{ab}
s	11,83	14,50	40,44	32,53	20,71
		5	6	7	8
$\bar{x}$	447,91^a	410,67^b	405,81^b	401,73^b	420,97^b
s	14,67	27,47	44,07	42,12	37,01

Samalla kirjaimella on merkitty ne keskiarvot, jotka yksisuuntaisen varianssi analyysin jälkeen eivät poikenneet toisistaan ($p < 0,05$).
Means indicated with the same letter do not differ from each other at 5% significance level.

tappioiden määrään vaikuttavat eniten Thörnqvistin (1984) mukaan biomassan koostumus ja kosteus, kasan koko ja lämpötila sekä varastointiaika. Mikro-organismit pystyvät yleisesti toimimaan 20–60°C:n lämpötiloissa. Jotkut kylmää kestävät sienet tosin sietävät lähellä nollaa olevia lämpötiloja ja bakteerit jopa 75°C:n lämpöä (Thörnqvist 1988). Lisäksi kemialliset reaktiot voivat nostaa auman lämpötilan syttymispisteeseen.

Aumojen kuiva-ainetappioita on tässä tutkimuksessa tarkasteltu ennen ja jälkeen varastointia mitattujen kuivatuoretiheyksien avulla. Varastoinnin aiheuttamat kuiva-ainetappiot näkyvät oheisesta asetelmasta.

AUMA 1 (Tappiot, %)

	Lohko 1	Lohko 2	Lohko 3	Lohko 4
kuukaudessa	+0,6	–0,3	–0,1	–0,7
yhteensä	+3,9	–4,3	–2,0	–1,2

AUMA 2 (Tappiot, %)

	Lohko 5	Lohko 6	Lohko 7	Lohko 8
kuukaudessa	–0,4	–0,4	–0,5	–0,3
yhteensä	–8,3	–9,4	–10,3	–6,0

Tutkimuksen alussa mitattujen aumojen 1 ja 2 kuivatuoretiheyksien keskiarvot (442,25 ja 447,91 kg/m^3) eivät eronneet tilastollisesti merkitsevästi toisistaan. Varastoinnin aikana tapahtui kuitenkin muutoksia, joihin sisältyy myös virhetekijöitä. Lohkon 1 puuaineen tiheys oli noussut tilastollisesti merkitsevästi, ja se erosi myös kaikkien muiden lohkojen tiheyksistä. Virhe johtui ilmeisesti näytteiden väärästä käsittelystä. Lohkon 4 keskiarvo laski 437 kg:aan, mutta tiheyden muutos ei ole tilastollisesti merkitsevä (taulukko 4).

Pidemmän varastointiajan takia lohkojen 2 ja 3 puuaineen tiheys laski enemmän kuin lohkoissa 1 ja 4. Niiden keskiarvot eivät kuitenkaan eronneet toisistaan tilastollisesti merkitsevästi. Lohkon 2 tiheys oli tosin laskenut merkitsevästi lähtöarvosta. Sen puuaineen tiheyksien jakauma oli lisäksi voimakkaasti kaksihuppuinen, mikä johtui alimmassa kerroksessa muovin päällä olleista näytteistä. Niiden tiheydet olivat selvästi keskiarvoa pienemmät (365 kg/m^3). Puuaineen kosteus oli myös huomattavan suuri auman pohjalta otetuissa näytteissä, mikä lienee johtunut juuri puuaineen hajoamisesta.

Kaikkien auman 2 lohkojen puuaineen tiheydet olivat laskeneet merkitsevästi. Eniten varastoinnista oli kärsinyt katteen alla ollut hake. Lohkon 7 tappiot olivat 10,3 % ja lohkon 6 tappiot 9,4 %. Kattamattomien lohkojen 5 ja 8 tappiot olivat vastaavasti 8,3 % ja 6,0 %.

Kuiva-ainetappiot kasvoivat varastointiajan pidentyessä, mutta käsittelyt eivät eronneet paljoa toisistaan, kun varastointiaika on sama. Aikaisemmin on havaittu tappioiden keskittyneen varastoinnin ensimmäisiin kuukausiin (Thörnqvist 1983). Tässä tutkimuksessa tätä ei voitu selvästi havaita. Tosin samoin käsitellyissä, mutta eripituisia aikoja varastoiduissa lohkoissa (4, 3 ja 8) lyhyimmän ajan varastoidun lohkon 4 kuukausitappiot olivat kaikkein suurimmat. Erot lohkojen kesken olivat kylläkin pienet sen takia, että kasoissa kuivanut koivukokopuu ei sisältänyt nopeasti hajoavaa vihermassaa. Lisäksi lohkojen tiiviydet erosivat toisistaan.

Puuaineen tiheydelle laadittiin malli, jossa selittävinä muuttujina käytettiin puuaineen kosteutta, auman lämpösummaa ja lämpösumman neliötä sekä mittauspisteen sijaintia. Auman 1 puuaineen tiheys selittyi hyvin kaikilla valittujen selittäjien yhdistelmillä, mutta auman 2 puuaineen tiheys ei selittynyt pelkästään lämpösummalla eikä mittauspisteen sijainnilla. Lämpösumman ja lämpösumman neliön vaikutus oli niin pieni kummassakin aumassa, että niiden pois jättäminen ei oleellisesti huononna mallia. Käytäntöä ajatellen pelkän kosteuden käyttö on suositeltavinta, koska se on helposti mitattavissa sekä tutkituista selittäjistä merkitsevin (taulukko 5).

Taulukko 5. Puuaineen kuivatuoretiheyden (y) riippuvuus eri tekijöistä.
Table 5. Basic density of wood (y) as a function of different variables.

Auma *Pile*	Regressiomalli *Regression model*	F-arvo *F ratio*	r^2
1	$462{,}9-0{,}29x_1-0{,}98x_2+0{,}001x_3$	8,0***	0,35
2	$442{,}2-0{,}99x_1-0{,}12x_2-0{,}001x_3$	7,5***	0,38
1	$458{,}86+0{,}10x_1+0{,}17x_2$	7,2**	0,24
2	$439{,}77-0{,}99x_1+0{,}004x_2$	11,5***	0,38
1	$454{,}25-0{,}36x_1$	3,9*	0,08
2	$440{,}70-0{,}97x_1$	23,4***	0,38
1	$454{,}36-0{,}11x_2$	13,5***	0,22
2	$409{,}69-0{,}02x_2$	1,1	0,02
1	$467{,}12-2{,}43x_4-8{,}86x_5$	5,3**	0,19
2	$398{,}64-2{,}36x_4+14{,}70x_5$	1,6	0,08

x_1 = Puuaineen kosteus *Moisture content*
x_2 = Lämpösumma *Heat sum*
x_3 = Lämpösumman neliö *Square of heat sum*
x_4 = Mittauspisteen korkeus *Height of the measuring point*
x_5 = Mittauspisteen syvyys *Depth of the measuring point*

Taulukko 6. Puuaineen kuivatuoretiheyden riippuvuus eri muuttujista.
Table 6. Coefficients of determination of basic density for different independent variables.

		Muuttujat — *Independent variables*			
Auma *Pile*	Lohko *Treatment*	Lämpösumma, kosteus *Heatsum, moisture content*	Puuaineen kosteus, *Moisture content*	Lämpösumma *Heatsum*	Mittauspisteen sijainti *Location of the measuring point*
		r^2			
1	1	0,44	0,12	0,43*	0,65**
	2	0,32	0,00	0,09	0,18
	3	0,60**	0,47**	0,65***	0,27
	4	0,10	0,03	0,03	0,26
2	5	0,27	0,31	0,15	0,32
	6	0,05	0,01	0,02	0,29
	7	0,86***	0,86***	0,39*	0,41
	8	0,60*	0,40	0,29	0,23

Kun aineisto jaettiin lohkoihin, menettivät mallit merkitsevyyttään. Mallien selittävyys vaihteli 0–86%. Auman lämpösumma ja puuaineen kosteus yhdessä ja erikseen selittivät puuaineen tiheyttä merkitsevästi lohkoissa 3 ja 7. Lisäksi auman lämpösumma ja mittauspisteen sijainti selittivät merkittävästi lohkon 1 tiheyttä (taulukko 6).

34. Kokopuuhakkeen lämpöarvo

341. Kalorimetrinen lämpöarvo

Palamisessa aine yhtyy happeen, jolloin vapautuu lämpöä. Lämmön määrä voidaan mitata kokeellisesti laboratoriossa polttamalla absoluuttisen kuivaa puuta puhtaassa hapessa ns. pommikalorimetrissä. Tällöin palamisessa syntyvä vesi tiivistyy nesteeksi ja tulokseksi saadaan kalorimetrinen lämpöarvo. Normaalissa palamisessa tätä lämpöä ei kuitenkaan saada talteen, vaan se menetetään haihtuvan vesihöyryn mukana. Tätä kutsutaan teholliseksi lämpöarvoksi, joka voidaan ilmoittaa joko kuivalle tai kostealle puulle. Edellisessä vain puun palamisessa syntyvä vesi poistuu höyrynä, jälkimmäisessä taas sekä palamisessa syntyvä että puun sisältämä vesi poistuvat vesihöyrynä.

Kun puu palaa täydellisesti, kiintoaineena jää jäljelle vain tuhka. Mitä enemmän tuhkaa on, sitä alhaisempi on lämpöarvo. Suomalaisilla puulajeilla rungon puuaineessa on tuhkaa puulajin mukaan 0,39–0,45% ja rungon kuoressa 2,18–3,50% (Hakkila & Kalaja 1983). Mikäli kivennäismaata sekoittuu polttohakkeen joukkoon, tuhkapitoisuus saattaa olla huomattavasti todellisia arvoja suurempi (Thörnqvist 1983). Alla oleva asetelma osoittaa tuhkan määrän vaihdelleen suuresti tämän tutkimuksen aineistossa. Lämpöarvo on syytä laskea myös tuhkattomalle puulle, koska osaan näytteistä oli sekoittunut hyvin runsaasti kivennäismaata kuormatraktorin kuljettajan huolimattomuuden vuoksi.

Tuhkaprosentti

	Alussa	Lohko1	Lohko2	Lohko3	Lohko4
Keskiarvo	1,8	0,7	0,8	0,9	1,1
Hajonta	2,8	0,5	0,3	0,3	1,1
Maksimi	11,0	3,1	1,4	1,7	6,7
Minimi	0,4	0,3	0,5	0,4	0,5

	Alussa	Lohko5	Lohko6	Lohko7	Lohko8
Keskiarvo	1,5	2,9	6,0	5,2	3,2
Hajonta	0,9	3,1	6,5	5,1	3,5
Maksimi	3,0	10,6	28,3	19,9	14,5
Minimi	0,6	0,7	0,7	0,7	0,7

Varastoinnin pituus, kattaminen ja pohjustaminen vaikuttivat hyvin vähän ja usein eivät lainkaan polttohakkeen kalorimetriseen lämpöarvoon (taulukko 7). Aumassa 1 lohkojen 1–4 lämpöarvot ovat hieman lähtöarvoa korkeampia, mikä johtuu näytteiden lähtöarvoa alhaisemmasta tuhkapitoisuudesta. Kun lämpöarvot lasketaan tuhkattomalle puulle, eri käsittelyjen ja kokeen alussa saadut arvot ovat hyvin lähellä toisiaan. Toisessa aumassa lohko 6 erosi alussa saaduista tuloksista merkitsevästi, mutta käsittelyjen kesken ei havaittu eroja. Koska tuhkan määrä oli huomattavan suuri aumassa 2, laskettiin lämpöarvo tuhkattomalle puulle. Tällöin lohko 6 ja lähtötilanne eivät enää eroakaan merkittävästi. Käsittely ei siis vaikuttanut kalorimetriseen lämpöarvoon, vaan tässä tapauksessa kivennäismaan sekoittuminen on vaikuttanut eniten lämpöarvoon (Thörnqvist 1983).

Taulukko 7. Käsittelyn vaikutus kokopuuhakkeen lämpöarvoihin.
Table 7. The effect of treatment on the heating value of whole tree chips.

Lämpöarvo,MJ/kg *Heating value, MJ/kg*	Alussa *Starting value*	Lohko — *Treatment* 1	2	3	4	F-arvo *F value*
Kalorimetrinen *Calorimetric*	20,181	20,331	20,387	20,325	20,282	1,25
— tuhkaton puu *ash free wood*	20,552	20,471	20,560	20,505	20,514	0,50
Tehollinen *Effective*						
— kuiva puu *oven dry wood*	18,909	19,049	19,106	19,072	19,006	1,26
— tuhkaton puu *ash free wood*	19,259	19,181	19,267	19,241	19,224	0,46
— kostea puu *moist wood*	17,483^{ab}	18,166^{a}	17,065^{b}	17,909^{ab}	17,658^{ab}	3,38**
— kostea, tuhkaton puu *moist, ash free wood*	18,195^{ab}	18,297^{a}	17,225^{b}	18,079^{ab}	17,876^{ab}	3,51**

Lämpöarvo,MJ/kg *Heating value, MJ/kg*	Alussa *Starting*	Lohko — *Treatment* 5	6	7	8	F-arvo *F value*
Kalorimetrinen *Calorimetric*	20,449^{a}	20,176^{ab}	19,608^{b}	19,798^{ab}	20,131^{ab}	3,88**
— tuhkaton puu *ash free wood*	20,768	20,792	20,888	20,902	20,809	0,25
Tehollinen *Effective*						
— kuiva puu *oven dry wood*	19,179^{a}	18,938^{ab}	18,385^{b}	18,567^{ab}	18,883^{ab}	3,86**
— tuhkaton puu *ash free wood*	19,478	19,519	19,586	19,604	19,520	0,20
— kostea puu *moist wood*	18,079^{a}	17,304^{ab}	15,804^{b}	16,450^{ab}	16,816^{ab}	4,01**
— kostea, tuhkaton puu *moist and ash free wood*	18,380^{a}	17,883^{ab}	17,005^{b}	17,486^{ab}	17,452^{ab}	2,51*

342. Tehollinen lämpöarvo

Kuivan puun tehollisten lämpöarvojen erot käsittelyjen välillä olivat yhtä pienet kuin kalorimetristen lämpöarvojen erot, koska eri lohkojen puuaine on sisältänyt saman verran vetyä (5,8 %). Tällöin myös puun palamisessa syntyneen vesihöyryn sisältämä energia määrä on ollut sama.

Kostean puun tehollinen lämpöarvo voidaan ilmaista joko kuivaa tai kosteaa massaa kohti. Tässä yhteydessä on laskennan perusteena käytetty näytteen kuivaa massaa. Kostean puun tehollinen lämpöarvo saadaan vähentämällä kuivan puun tehollisesta lämpöarvosta puun sisältämän veden höyrystymislämpö:

$$W_{eff} = W_a - 2{,}45 \times \frac{u}{100 - u}$$

missä:

W_{eff} = kostean puun tehollinen lämpöarvo kuivaa puukiloa kohti (MJ/kg)
W_a = kuivan puun tehollinen lämpöarvo
2,45 = veden höyristymislämpö 20°C:n lämmössä (MJ/kg)
u = puun kosteusprosentti

Koska lohkojen 1 ja 2 kosteudet erosivat toisistaan merkitsevästi, erot heijastuivat myös kostean puun tehollisissa lämpöarvoissa. Tuhkan määrä ei vaikuttanut auman 1 eroihin. Sen sijaan aumassa 2 lohkon 6 ja alkutilanteen välinen ero muodostuu kosteuden ja tuhkan yhteisvaikutuksesta. Käsittelyn aiheuttama kosteuden lisääntyminen on myös laskenut huomattavasti lohkojen 7 ja 8 keskiarvoja. Vaikka kosteuden muutokset eivät olleetkaan tilastollisesti merkitseviä, kosteudesta johtuva energiasisällön aleneminen olisi niin huomattava, että se vaikuttaisi polttohakkeen hintaan.

Kun kosteuden, tuhkan ja kuiva-ainetappioiden yhteisvaikutus otetaan huomioon, lohkojen energiasisältö oli muuttunut seuraavasti:

AUMA 1			
Lohko 1	Lohko 2	Lohko 3	Lohko 4
+4,5	–9,4	–2,6	–2,9
AUMA 2			
Lohko 5	Lohko 6	Lohko 7	Lohko 8
–10,8	–16,2	–14,7	–10,8

Varastoinnin pituus sekä muovilla kattaminen alensivat siis oleellisesti suuressa aumassa varastoidun kokopuuhakkeen energiasisältöä.

4. Johtopäätökset

Hakkeen varastoinnin aikana korkotappioiden sekä työ- ja materiaalikustannusten lisäksi taloudellisia menetyksiä aiheuttavat kuiva-ainetappiot ja energiasisällön aleneminen. Vaikka näiltä haitoilta ei aina voidakaan välttyä, niitä voidaan kuitenkin vähentää. Varastointi on pidettävä mahdollisimman lyhyenä kuiva-ainetappioiden välttämiseksi. Myös auma tulee pitää pienenä, sillä mitä korkeampi ja laajempi auma on sen korkeampia ovat lämpötila ja kuiva-ainetappiot. Aiemmissa tutkimuksissa on todettu tappioiden olevan suurimpia varastoinnin alussa. Tällaista tulosta ei saatu tässä tutkimuksessa, koska vihermassaa ei ollut. Onkin oleellista poistaa vihermassa jo ennen haketusta. Tämä on helpointa jättämällä kaadetut puut kuivumaan rasiin, jolloin myös lehtien sisältämät ravinteet palautuvat metsämaahan.

Hakkeen peittämisen katsotaan yleisesti parantavan puun säilyvyyttä, koska se estää veden ja lumen pääsyn hakkeeseen. Tämän tutkimuksen tulokset eivät kuitenkaan vahvista tätä käsitystä. Muovin alla olleen hakkeen kosteuksien keskiarvot olivat samaa luokkaa tai suuremmat kuin peittämättömien lohkojen. Lisäksi katettujen lohkojen kuiva-ainetappiot olivat muita lohkoja suuremmat. Koska kattaminen on myös kallista, suuren auman kattaminen muovilla ei ole perusteltua.

Pohjan vaikutuksesta hakkeen ominaisuuksiin ei voida olla yhtä varmoja kuin muovipeitteen tarpeettomuudesta, koska tiivistyminen sekoitti koejärjestelyt. Ilmeisesti pitkän varastoinnin aikana kosteutta kerääntyy auman pohjalla olevan muovin päälle. Jos muovia ei käytetä, pääsee kosteus imeytymään maahan. On myös mahdollista, että muovi estää maassa olevan ilman pääsyn auman sisäisen ilmankiertoon, jolloin auman alaosissa oleva kosteus ei pääse nousemaan kaasujen mukana auman pinnalle. Vaikka muovi onkin haitallista hakkeen kosteuden kannalta, estää se kivennäismaata sekoittumasta hakkeeseen. Tämä on melkoinen etu polttolaitosten kannalta. Vaikka pohjamuovin käyt-

tö onkin helppoa, liittyy siihenkin kustannuksia, joita hakkeen käyttäjä ei epävarman edun vuoksi halunne maksaa.

Koska auman tiivistyminen on epäedullista hakkeen säilymisen kannalta, niin aumauksessa tulisi välttää kuorma- ja puskutraktorin käyttöä. Tiivistymisen estämiseksi suositeltavin vaihtoehto on hakettaa puut suoraan aumaan. Toinen vaihtoehto on aumata hake kuljettimella, mutta tämä on hidasta ja kallista.

Varastointi vaikuttaa hyvin vähän hakkeen lämpöarvoon, mikäli hake pidetään kivennäismaasta puhtaana. Tällöin hakkeen lämpösisältöön vaikuttavat enää vain puuaineen kosteus ja kuiva-aine tappiot. Näiden vaikutusta voidaan pienentää optimoimalla kokopuiden esikäsittely, varastoinnin pituus sekä välttämällä muovikatteiden käyttöä.

Kirjallisuus

Aittomäki, S. 1963. Tutkimuksia polttohakkeen ja pilkkeiden kuivatuksesta ulkoilman avulla. Pienpuualan Toimikunnan julkaisu 151. 38 s.

Alestalo, A. 1982. Kuoren ja muun biopolttoaineen kuivaus aurinkoenergialla. Tutkimusseloste. Diario 235/881/80 KTM. Enso Gutzeit Oy. Julkaisematon. 44 s.

Annergren, G., Dillen, S. & Wardheim, S. 1964. On outside storage of sprucewood chips for sulphite pulping. Svensk Papperstidning (67)4: 125–145.

Arola, R.A., Sturos, J.B. & Radcliffe, R.C. 1988. Chunkwood drying research with northern U.S. hardwoods. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6–7,1988. Vol.II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134/1988.

Belin, L. 1984. Allergic alviolitisfungal spores. Teoksessa: Gislerud, O. & Heding, N. Storing, drying and internal handling of wood fuels. Proceedings of a conference held by the International Agency (IEA) Forestry Energy Programme Group C on June 22, 1984 in Copenhagen, Denmark. Danish Institute of Forest Technology. s. 12–15.

Bergman, Ö. & Nilsson, T. 1966. Studier över utomhuslagring av tallvedsflis vid Lövholmens Pappersbruk. Summary: On outside storage of pine chips at lövholmen's Paper Mill. Institutionen för virkeslära, Skogshögskolan. Rapporter 53. 83 s.

— & Nilsson, T. 1967. Studier över utomhuslagring av aspvedsflis vid Hörnefors Sulfitfabrik. Institutionen för virkeslärä, Skogshögskolan. Rapporter 55. 105 s.

— & Nilsson, T. 1968. Studier över utomhuslagring av björkvedsflis vid Mörrums Bruk. Summary: On outside storage of birch chips at Mörrum's Sulphate Mill. Institutionen för virkeslära, Skogshögskolan. Rapporter 60. 104 s.

— & Nilsson, T. 1971. Studies on outside storage of sawmill chips. Sammanfattning: Studier över utomhuslagring av sågverksflis. Institutionen för virkeslära, Skogshögskolan. Uppsatser R71. 102 s.

— & Nilsson, T. 1974. Studies on wood deterioration in outside storage of a commercial pine chip pile. Sammanfattning: Studier över vednedbrytning vid utomhuslagring av en tallflisstack. Institutionen för virkeslära, Skogshögskolan. Rapporter R93. 75 s.

— & Nilsson, T. 1979. An experiment on outdoor storage of whole-tree chips. Sveriges Lantbruksuniversitet, Institutionen för virkeslärä. Rapport R109. 21 s.

Björklund, L. 1982. Lagring av bränsleflis i fraktionen 25–30 mm. Summary: Storage of fuelwood chips in fraction 25–30 mm. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Uppsatser 115. 26 s.

— 1983. Lagring av helträdsflis av olika trädslag samt i olika fraktioner. Summary: Storage of whole-tree chips of different species and in different fractions. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 143. 50 s.

Faeste, I. & Johansson, K.J. 1982. Tørkeforløp i syrefelte traer under forskjellige lagringsforhold. Zusammenfassung: Trocknungsverlauf bei ungeasteten Bäumen Unter verschiedenen Lagerungsverhältnissen. Norsk Institutt for Skogforskning. Rapport 2. 32 s.

Fredrikson, H. & Rutegård, G. 1985. Lagring av småved och bränsleflis i binge. Summary: Storage of chunkwood and fuel chips in bins. Uppsats. Inst. Virkeslära. Sveriges Lantbruksuniv. 151. 23 s.

Gislerud, O. 1974. Heltreutnyttelse V. Lagring av heltreflis. Summary: Whole tree utilization V. Storing of whole tree chips. Norsk Institutt for Skogforskning. Rapport 5. 29 s.

— 1978. Lagring av lauvtreflis. Et lagringsforsøk med Sande Paper Mill A/S. Norsk Institutt for Skogforskning. Rapport 9. 37 s.

— 1983. Experimental drying and storing of fuel chips. NISK. IUFRO — moniste. 5 s.

— & Grønlien, H. 1977. Lagring av heltreflis. Et lagringsforsøk med flis fra tynningsvirke ved Norsk Wallboard A/S, Gjøvik. Summary: Storage of whole-tree chips. A storage experiment with chips from thinnings at Norsk Wallboard A/S, Gjøvik. Norsk Institutt for Skogforskning. Rapport 1. 34 s.

— & Grønlien, H. 1978a. Lagring av or. Et lagringsforsøk ved Meraker Smelteverk A/S. Summary: Storage of whole-tree chips of gray alder. A storage experiment at Meraker Smelteverk A/S. Norsk Institutt for Skogforskning. Rapport 1. 36 s.

— & Grønlien, H. 1978b. Lagring av lauvtreflis. Norsk Institutt for Skogforskning. Rapport 9. 77 s.

Gjølsjø, S. 1988. Comparative studies on storage and drying of chips and chunks in Norway. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6–7, 1988. Vol. II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134/1988.

Gustafsson, G. 1981. Grundläggande studier av torkning

och lagring av bränsleflis — Etappraport 2. Nämnden för Energiproduktions forskning. NE/Bio-81-18.
— 1988. Forced air drying of chips and chunkwood. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/ Activity 6 and 7 held in Uppsala, Sweden December 6–7, 1988. Vol. II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134/1988.
Hajny, G. 1966. Outside storage of pulpwood chips. Tappi (49) 10, 97–105.
Hakkila, P. 1962. Polttohakepuun kuivuminen metsässä. Summary: Forest seasoning of wood intended for fuel chips. Communicationes Instituti Forestalis Fenniae 54(4). 82 s.
— 1978. Pienpuun korjuu polttoaineeksi. Summary: Harvesting small-sized wood for fuel. Folia Forestalia 342. 32 s.
— 1984. Metsähakkeen hankinta lämpölaitosten polttoaineeksi. SITRA. Tutkimusraportti 33. 121 s.
— & Kalaja, H. 1981. KOPO palahakejärjestelmä. Summary: KOPO block chip system. Folia Forestalia 467. 24 s.
Heiskanen, V. & Hakkila, P. 1960. Polttohakepuun kuivuminen rasissa. Pienpuualan Toimikunnan tiedotus 17. 6 s.
— & Jokihaara, L. 1961. Puupolttoaineiden lämpöarvosta. Pienpuualan Toimikunnan tiedotus 33. 5 s.
Hudson, B., Mitchell, P.C. & Gardner D. 1988. A comparative study on storage and drying of chips and chunks in the UK. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6–7, 1988. Vol. II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134/1988.
Høeg, H. 1980. Forekomst av soppsporer i forbindelse med flisfyringsanlegg og lagring av flis. Norsk Institutt for Luftforskning. Oppdragsrapport 29. 36 s.
— 1981. Forekomst av soppsporer med flisfyringsanlegg og lagring av flis. II. Norsk Institutt for Luftforskning. Oppdragsrapport 26. 16 s.
Håkanson, K. & Numminen, J. 1963. Tutkimus hakkeen polttoarvon muutoksista sitä varastoitaessa. Imatran Voima Oy. Julkaisematon raportti. 41 s.
Ilmatieteen laitos. Kuukausikatsaus Suomen ilmastoon. Vuosikerrat 1977–1979.
Immonen, V. 1961. Hakkeen varastointia ja halkojen laatua koskevia tutkimuksia Turengin Sokeritehtaalla v. 1958 ja 1959. Summary: Studies of the storage chips and quality of split fuelwood at Turenki sugar mill in 1958 and 1959. Pienpuualan Toimikunnan julkaisu 96. 30 s.
Jalava, M. 1941. Rasiin kaadettujen puiden kuivumisesta. Metsätaloudellinen Aikakauskirja 58(6): 173–176.
Koch, P. 1983. Moisture changes in oak and hickory fuel chips on roofed and unroofed Louisiana airdrying grounds as affected by pile depth and turning of chips. Forest Products Journal 33(6): 59–61.
Kofod, E.O. 1983. Biologiske og kemiske processer i braendsels flislagre. Torstoftab, udtorring og sundhedsrisici. Skovteknisk Institut. The Danish Institute of Forest Technology. 19 s.
Kärkkäinen, M. 1977. Puu — sen rakenne ja ominaisuudet. Helsinki. 442 s.
Lehtonen, I. 1977. Puu polttoaineena. Kirjallisuuteen perustuva tarkastelu. Abstract: Wood as a fuel. A study based on literature. Folia Forestalia 293. 16 s.
Levanto, S. 1961. Tutkimuksia 2-metrisen koivupolttopuun hakkuusta kesällä sekä rasiinkaatoa käytettäessä. Summary: Studies on summer felling and preparation of 2-metre birch fuelwood. Pienpuualan Toimikunnan julkaisu 130. 54 s.
Liss, J-E. 1979. Syrfällning. Institutionen för Skogsteknik, Skogshögskolan. Garpenberg. Stencil 73. 20 s.
Mivell, T. 1988. Comparisons of storages of chunkwood and fuel chips in Sweden. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6–7, 1988. Vol. II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultat 134/1988.
Nurmi, J. 1986. Chunking and chipping with conescrew chipper. Summary: Palahakkeen ja hakkeen valmistus kartioruuvihakkurilla. Folia Forestalia 659. 23 s.
— 1987. Polttohakkeen kuivatus traktorikonteissa. Summary: Drying of fuel chips and chunks in wooden bins. Folia Forestalia 687. 40 s.
Nylinder, M. 1979. Relationstal träbränslen — olja. Summary: Conversion factors fuelwood — oil. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 110. 51 s.
Pellikka, M. 1983. Homepölyaltistus polttohakkeen käsittelyn yhteydessä. Metsäntutkimuslaitoksen tiedonantoja 81. 76 s.
— & Kotimaa, M. 1983. Polttohakkeen käsittelystä aiheutuva ilman homepölypitoisuus sekä siihen vaikuttavat tekijät. Summary: The mould dust concentration caused by the handling of fuel chips and its modifying factors. Folia Forestalia 563. 18 s.
Pesonen, M. 1982. Homepölyaltistus maatiloilla hakkeen käytön yhteydessä. Emissio 1/82. s. 19–21.
Salmi, J. 1964. Lahovikaisuuden vaikutus koivupuun lämpöarvoon. Summary: The influence of decay on the heat value of birch wood. Pienpuualan Toimikunnan julkaisu 168. 27 s.
Smith, R.S. & Ofosu-Asiedu, A. 1972. Distribution of thermophilic and thermotolerant fungi in a sprucepine chip pile. Canadian Journal of Forest Research 2: 16–26.
Simola, P. & Mäkelä, M. 1976. Rasiinkaato kokopuiden korjuussa. Summary: Leaf-seasoning method in whole-tree logging. Folia Forestalia 273. 18 s.
Strömquist, L-H., Blomqvist, G., Karlsson, E., Vincent, A., Lundgren, R. & Eliasson, L. 1980. Bränsleflishantering — ett hälsoproblem? Umeå Universitet, Umeå.
Sturos, J.B. 1984a. Characterization and air drying of chunkwood and chips. USDA. For. Serv. Res. Note NC-308.
— 1984b. Ambient air drying trials — chunkwood versus chips. Biomass Fuel Drying Conference Proceedings 1984-08-08. Office of Special Programs, 405 Coffey Hall, Univ. of MN., St. Paul, MN 55108.
Taipale, A. 1960. Tutkimuksia polttohakkeen varastoinnista. Summary: Studies of the storage of fuel chips. Pienpuualan Toimikunnan julkaisu 100. 47 s.
— 1962. Sahanhakkeen kuivuminen avokeossa ja katetussa varastossa. Summary: Seasoning of chips made of sawmill waste in uncovered stack and covered store. Pienpuualan Toimikunnan julkaisu 141. 27 s.
— 1963. Sahanhakkeen kuivumisesta varastossa. Teho 3.
Thörnqvist, T. 1980. Lagring av bränsleflis i perforerade plastsäckar. Summary: Storing of fuel chips in perfo-

rated plastic bags. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 115. 50 s.
— 1982. Torkning av bränsleflis med solfångaruppvärmd luft. Summary: Drying of fuel chips with solar panel warmed air. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 126. 56 s.
— 1983. Bränsleflis förändring under ett års lagring. Summary: Fuel chips change during one year of storage. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 148. 65 s.
— 1984. Hyggesrester som råvara för energiproduktion — torkning, lagring, hantering och kvalitet. Institutionen för virkeslära. Sveriges lantbruksuniversitet, Uppsala. Rapport 152.
— 1987. Bränder i stackar med sönderdelat trädbränsle. Summary: Spontaneous combustion in piles with comminuted wood fuel. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Uppsats 163.
— 1988. Wood storage in large piles. Mechanism and risk of self-ignition. Teoksessa: Production, storage and utilization of wood fuels. Proceedings of IEA/BE Conference TASK III/Activity 6 and 7 held in Uppsala, Sweden December 6–7, 1988. Vol. II. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Uppsatser och resultater 134/1988.
— & Lundström, H. 1980. Svampförekomst vid bränsleflis hantering i mindre anläggningar. Summary: Factors affecting the occurrence of fungi in fuel ships for domestic consumption. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 117. 38 s.
— & Gustafsson, G. 1983. Kalluftstorkningens betydelse för bränsleflisens lagringsbarhet. Summary: The importance of air drying for the storing property of fuel chips. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 142. 75 s.
Turkkila, K. & Knut, S. 1982. Homeiden määrä ja laatu maatilojen hakkeessa. Summary: The amount and species of the moulds in the chips of farms. Työtehoseuran metsätiedotus 344. 4 s.
Uusvaara, O. 1984. Hakepuun kosteuden alentaminen ennen haketusta korjuuseen ja varastointiin liittyvin toimenpitein. SITRA. Tutkimusraportti 35. 30 s.
Warsta, O. 1961. Rasiin kaadetun koivun ja lepän kuivumisesta. Pienpuualan Toimikunnan tiedotus 43. 8 s.
White, M.S., Curtis, M.L., Sarles, R.L. & Green, D.W. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part 1. Moisture content and temperature. Forest Products Journal 33(6): 31–38.

Total of 72 references

Summary

Longterm storage of fuel chips in large piles

In addition to labor and material costs as well as interest losses, the long term storage of fuel chips in large quantities will cause significant dry matter losses and reductions in net energy content. Still, it is necessary to use buffer storages in climates where snow and cold will prevent contractors from supplying heating facilities in the most severe winter conditions. The purpose of this study was to find ways to reduce these disadvantages as much as possible.

The study location was chosen on the southwest side of Lokka reservoir in Sodankylä at latitude 68 degrees north. Here the material for the study happened to be already available. It is also one of the coldest areas of the country providing a great need for heating. The town itself has a 20 MW heating plant which operates on fuel chips.

Two 3000 m^3-loose piles of wholetree chips of small-sized birch (*Betula pubescens*) were constructed. The whole trees had been stock-piled for a year before chipping which took place in early September about a month before the arrival of permanent snow. A large truck mounted disc chipper was used to comminute the wood. The chips were directly blown into a van and transported to the storage site some 3 km from the chipping site. Here they were piled into two 50 meter long and 6–8 meter high piles with the help of a wheeled tractor loader.

It is commonly thought that fuel chip piles should be covered to prevent rain and snow from getting into the pile. It is also thought that dry matter losses will increase with time, the majority taking place during the early stages of storage.

To test these arguments the piles were divided into treatments in the following way. Plastic was laid down on the ground to act as an underbase for the other half of each pile. The center of the piles was covered with the same plastic giving a total of four combinations of cover and underbase and a total of eight treatments in two piles. After couple of weeks it was found out that it was impossible to hold the cover over pile 1 because of the high winds. It was decided not to cover the pile at all but to store the treatments 1 and 4 for about six months and treatments 2 and 3 for a year. The whole pile 2 — treatments 5 through 8 — was stored for a year and a half.

The effects of storage on wood were determined on the bases of moisture content, dry matter losses and heating value. Reference samples were collected when constructing the pile. Net bags filled with chips were also placed in the pile in one meter grid. This was to help the sampling procedure when destructing the piles. Pile temperatures were also monitored in each treatment.

The moisture content of chips at the end of the experiment was 31.1% (s = 1.3) for pile 1 and 30.9% (s = 2.6) for pile 2 on wet bases. This indicated a very significant reduction in moisture content prior to chipping. Also the uniformity of the moisture did give good bases for the

study. The same could be said about the wood density.

When the treatments 1 and 4, and later 2 and 3 where distructed the moisture was found to have collected on the outer and upper parts of the pile. The interior and the bottom layers had lost moisture. An exception to this is treatment 2 where the chips overlaying the plastic had gained moisture. Similar observations were made with the uncovered treatments of pile 2. The covered treatments 6 and 7, however, had some fairly high moisture concentrations even in the interior of the pile. The moisture originating from decay had no escape because of the cover and started to accumulate over time in all parts of the pile. Of all the treatments only 1 and 2 were statistically different. However, in spite of the lack of statistical evidence the chips had gained moisture over time and would definitely influence the pricing of chips.

When chips, like any organic material, are stored, the microbial fauna will be activated according to the environmental restrictions. The most important factors affecting the dry matter losses are composition of biomass, moisture, temperature, size of pile and duration of storage.

The dry matter losses for each treatment are given below. Reductions were significant in all treatments. Dry matter losses did increase with time. The greatest losses were found in covered treatments. The losses were not found to be any greater in the beginning. This may be contributed to the fact that the chips did not contain any green matter or living parenchyma cells. The figures for treatment 1 are positive due to an error in the experiment.

Treatment	Cover	Under base	Storage time, months	Dry matter losses,% /month	total	Change in energy content,%
1	no	yes	5.5	+0.6	+3.9	+4.5
2	no	yes	14	–0.3	–4.3	–9.4
3	no	no	14	–0.1	–2.0	–2.6
4	no	no	5.5	–0.7	–1.2	–2.9
5	no	yes	18	–0.4	–8.3	–10.8
6	yes	yes	18	–0.4	–9.4	–16.2
7	yes	no	18	–0.5	–10.3	–14.7
8	no	no	18	–0.3	–6.0	–10.8

Calorimetric or higher heating value is the amount of heat given by burning an oven dry sample of wood when the moisture created during combustion is condensed. When the moisture is let to evaporate we are left with effective or lower heating value of dry wood. The effective heating value of wet wood requires also the evaporation of moisture contained by wood.

When wood is completely burned only ash is left behind. The greater the amount of ash the lower the heating value. Depending on the tree species the ash content of stem wood is 0.4–0.5% and 2.2–3.5% of stem bark. It is common that mineral soil gets mixed with whole trees during harvesting and with chips during storage and increases the ash content. To avoid this mishandling of fuel the results of this study are expressed for ash free wood.

From Table 7 it is seen that the treatments were found not to be different on calorimetric or on effective heating value bases for oven dry wood. In treatments 5–8 however, they have slightly increased. This indicates an attack by brown rot which digests cellulose and leaves lignin with higher heating value. The highest increases were found with those covered treatments which also had the highest dry matter losses.

The effective heating value is greatly dependent on moisture content. One remembers that the treatments had somewhat different moisture contents. When they are taken into consideration more pronounced differences are found between the treatments. The greatest ones are found in pile 2 which indicates the negative effect of prolonged storage. When the dry matter losses are taken into consideration the total losses in energy content (%) are as indicated below.

Based on these results, it can be concluded that to avoid dry matter losses, increased moisture content and losses in the net heating value the storage time should be kept to minimum and that the piles should not be covered with plastic when it is used in direct contact with the pile.

VI

PERGAMON

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The storage of logging residue for fuel

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Abstract

The effect of storage on the fuelwood properties of Norway spruce logging residue were studied. The characteristics under study included moisture and needle content, and elemental composition. Storages included uncomminuted residue piles on the clear-cut left by single grip harvester, uncomminuted residue in large windrows at road side landing and as a third alternative a comminuted, compacted and non-compacted residue piles at a terminal. The initial moisture content of fresh residue was 56% on green weight basis. After one-year storage the residue at the clear-cut had reached an average moisture content of 28.5 and 42.2% at the landing. The moisture content of comminuted material had risen to 65.3% during nine-month storage. The original needle content of fresh logging residue was 27.7% and one year later it had decreased to 6.9% on the clear-cut and to 18.9% on the landing. The carbon content of the comminuted material had increased significantly from 50.0% to 51.1–51.3%. Simultaneously hydrogen content had decreased from 6.6 to 5.7%. Compaction had no significant effect on the carbon-hydrogen ratio. However, compaction did decrease pile temperature indicating lower dry matter losses in the compacted pile. The release of nutrients from the needles is slow. From the soil nutrition point of view, the shedding of needles is a more important factor than release of nutrients from the needles intact. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Logging residue; Norway spruce; Moisture content; Nutrients; Dry matter loss; Comminution; Storage

1. Introduction

It has been estimated that at the present removal of 62 million m^3 of stem wood per annum some 28 million m^3 of logging residue is left in the forests in Finland [1].This is one of the largest under-utilized biomass reserves in our country. However, when planning utilization of this reserve one has to take the technical, economical and environmental aspects into consideration. It has been estimated that the soil fertility factors, bearing capacity, rockiness and the small size of clear-cut areas will limit the quantity of the harvestable residue to some 8.9 million m^3 of foliage free material [1]. Residue harvesting should be limited to final cuttings as in thinning stands it is considered of vital importance to leave the needle mass in the stand to allow the nutrients to return to the cycle.

One of the more difficult tasks in biomass harvesting is how to manage the storage of the material. It is known from previous studies that

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long-term storage of comminuted biomass will amount to significant dry matter losses, reductions in net energy content and cause health risks among the users [2–6]. Nevertheless, it is necessary to use buffer storages at latitudes where winter will prevent contractors from supplying heating facilities during the most severe winter conditions. The problem is to find the right procurement schedules for different types of forest biomass.

The primary aim of this study was to find out how storage site and time factors affect the fuel quality of the residual Norway spruce (*Picea abies*) biomass. The secondary aim was to find out when and where the nutrient rich needles end up in different storage schedules, and whether the element concentrations of the needle mass would change over time.

2. Material and methods

The material was composed of Norway spruce residue from a clear-cut operation. The stand had had an average stocking of 233 m^3/ha. The stand yielded on average 108 dry tonnes of residual material per hectare.

The first storage was composed of some 60 tonnes of logging residue which was freshly forwarded to a landing and stored in an uncovered, 4.5 m high windrow for one year from September 1994 until September 1995. The second storage trial was a 1.76 hectare clearcut containing 125 dry tonnes of logging residue stored in piles formed by a single grip harvester during timber harvest. The study material was kept on the clear-cut from September 1994 until June 1995 and then forwarded to the landing. It was kept there until September 1995. The third storage trial was made up of 175 fresh tonnes of logging residue hammermilled with a Morbark 1200 tubgrinder. The material was stored in a single pile ($20 \times 10 \times 3.5$ m) at a terminal from September 1994 until June 1995. Half of the pile was compacted with a crawler tractor whereas the other half was not.

Moisture content on green weight basis was determined in the beginning ($n = 449$) and at the end of each stage of each treatment ($n = 136$) by drying the samples at 102°C to a constant weight. Percentage of needle mass of the uncomminuted material was also determined before ($n = 157$) and after the storage ($n = 95$). This was done by first drying the residue samples at 70°C then separating the needles from the branches by plugging followed by drying the separated samples at 102°C. The dry matter losses of the needle mass were determined as a loss of relative mass. This was done by measuring the oven dry weight of the lots of 100 needles at each stage of the storage trials and expressing the weight in relation to the weight of the fresh needles collected in the beginning of the trial.

To find out whether or not the nutrients leach from the needles during the storage, element concentrations (N, P, K, Ca, Mg, Mn, Fe, Zn, Cu, B) were determined from the foliage intact on the branches. The analyses were carried out with a standard method described by Halonen et al. [7]. The samples were first dried at 70°C to separate needless from the twigs. The nitrogen and phosphorus content of needless were determined by Kjeldahl method. For the determination of other elements (K, Ca, Mg, Mn, Fe, Zn, Cu, B) the needless were burned to ashes by raising the temperature to 550°C over 8 h followed by 8 h at constant 550°C. In the case of P, K, Ca, Mg, Mn, Fe, Zn and Cu the ash sample were extracted in HCl solution and the elements analyzed in a AAS spectrophotometer. Boron (B) was extracted in H_3PO_4-H_2SO_4 solution and the sample analyzed in a spectrophotometer. The analysis of carbon and hydrogen content were done with a Leco CHN-analyzer from samples with a known moisture content.

The temperature of the hammermilled material was monitored with a digital thermometer. This was done by placing heat sensors at 0.5, 1.0, 1.5 and 2.0 m depths of both compacted and non-compacted parts of the pile and recording the temperatures once a day.

Table 1
The average moisture content of the residual biomass in different storages at different times

Storage		Date				$F(p)$
		September '94	March '95	June '95	Sept '95	
Clearcut		56.0[c]	61.4[c]	46.7[b]	28.5[a]	0.000
	$n=$	447	12	40	33	
	$s=$	6.6	13.0	12.0	8.7	
Landing		56.0[b]	–	–	42.2[a]	0.000
	$n=$	447			22	
	$s=$	6.6			15.4	
Mill yard		58.9[a]	–	65.3[b]	–	0.000
	$n=$	54		29		
	$s=$	1.5		4.4		

[a,b,c] Values indicated with the same letter in horizontal direction are not significantly different (Tukey's test) from each other at 5% level.

3. Results and discussion

3.1. Moisture content

The moisture content of fresh residue was 56.0% during the harvesting operation in September 1994. On the clearcut the residue moisture content increased to 61.4% by midwinter in the heaps created by the single grip harvester. This was mostly caused by the snow cover as some of it had gone through metamorphosis and turned to ice and covered the needles and twigs. Although this was external moisture it would still be harvested with the residual biomass had it been collected in wintertime. By June 1995 the moisture content had dropped to 46.7% being slightly higher than the result reported by Thörnqvist [8]. This difference in results is most likely caused by differences in the storage site including geographic location. The reduction in moisture content since the beginning of the study in September 1994 was statistically significant. After the material had been forwarded to the landing, another three months of storage took place. By September 1995 the moisture content had dropped to 28.5%. This value was significantly lower than any time earlier (Table 1).

At the same time and site a windrow of logging residue had been stored uncovered at the landing for a year. The reduction in moisture content from the start (56.0%) to the finish (42.2%) was significant but the final moisture content was not nearly as low as that of the material that had been seasoned on the clear-cut. In a Swedish study by Nylinder and Thörnqvist [9] fresh residue had been stored on a landing from November to August of the following year and recorded a final moisture content of 35%. Although the starting moisture content (47%) was lower than in this study the reduction during one drying season was of the same magnitude (14 and 12%-units). Furthermore Lehtikangas and Jirjis [10] report an increase in moisture content from 55.9 to 60.2% for a period from October until the following August. The reason behind the different results was the variation in storage conditions. Often the storage site can not be chosen, but if possible an open, well-ventilated place should be chosen for good results.

Table 2
The oven dry needle content (%) of forwarded residue at different times of storage

Storage		Date		
		September '94	June '95	September '95
Clearcut		27.7	20.4	6.9
	$n=$	157	40	33
	$s=$	18.4	14.1	18.4
Landing		27.7		18.9
	$n=$	157	–	22
	$s=$	18.4		17.4

The final moisture content of the hammer-milled material stored at the terminal was 65.3%. This was significantly higher than in the beginning of the storage period ($p < 0.001$). There was no significant difference between the non-compacted (65.9%) and the compacted (64.6%) part of the pile. Fuel with this much moisture has a low effective heating value and would be unsuitable for many small combustion units. The additional moisture was brought by metabolic activity of microbes and living cells as well as by precipitation during the storage period.

Table 3
Nutrient composition of needle mass on the clearcut at different times of the storage. [a,b]Values indicated with the same letter in horizontal direction are not significantly different (Tukey's test) from each other at 5% level

Variable	Unit	Date				$F(p)$
		September 1994 Live trees	September 1994 Fresh residue	March 1995 Residue	June 1995 Residue	
Ash	%	5.32	5.36	5.18	5.63	0.340
N	mg/g	9.83[a]	9.74[a]	10.56[a]	11.65[b]	0.000
P	mg/g	1.25[a]	1.07[b]	1.01[b]	1.21[a]	0.001
K	mg/g	4.09[b]	3.99[a]	4.09[ab]	4.38[a,b]	0.082
Ca	mg/g	1.10	1.00	1.14	1.08	0.062
Mg	mg/g	80.04	84.28	81.92	88.340	0.285
Mn	mg/kg	1.39	1.11	1.26	1.05	0.072
Zn	mg/kg	52.30	50.95	48.68	54.11	0.693
Cu	mg/kg	2.75[b]	1.87[a]	2.65[a,b]	1.98[a]	0.002
B	mg/kg	12.86	11.60	10.13	11.33	0.129
Sample size, n		16	157	12	40	

3.2. Needle mass of logging residue

In the beginning of the study the average needle content of the residue was 27.7% on dry weight basis (Table 2). By the time the material was forwarded to the landing in June 1995 the needle content had dropped to 20.4% which is about the same as the result reported by Flinkman et al. [11] for the same time period. By the time of comminution in September 1995 most of the remaining needles had fallen on the landing. Only 6.9% of residue was needles. The second trial was of the material which had been stored on the landing. This had a final needle percentage of 18.9% at the time of comminution in September 1995.

Defoliation is not the only cause of dry matter loss. On the contrary needles also loose dry matter through decomposition. The losses were over a one year storage 20% on the clear cut area and 7% in the windrow on the road side landing. One has to assume that the conditions for bacteria and fungi infestation have to be more favourable on the clear-cut where the residue is more exposed. Granhall and Slapokas [12] have observed similar dry matter losses on broad-leaved species. They did, however, demonstrate a greater degree of dry matter loss than for spruce in this study. Hardwood species such as birch and alder lost as much as 45% of their foliage mass.

3.3. Elemental composition of needle mass

The elemental composition of spruce needles showed only minor changes in concentration over time. Although some of the changes were statistically significant a much more significant return of nutrients takes place through dropping of the needles than through leaching as discussed above. The concentration of most nutrients first decreased followed by a slow increase. This same phenomena has earlier been observed on silver birch (*B. pendula*) and some willow (*Salix*) foliage by Granhall and Slapokas [12]. They explain that the initial loss is caused by the leaching of water soluble components. In this case this would explain the difference between fresh material from the live trees and the freshly (1–2 weeks after felling) forwarded material (Table 3).

3.4. Pile temperatures of the hammermilled material

It is well known from previous studies that when wet biomass is stored the microbial activity will most likely take over. The first sign of this activity is heat generation [2–5]. This was caused by increased metabolic activity of the living cells.

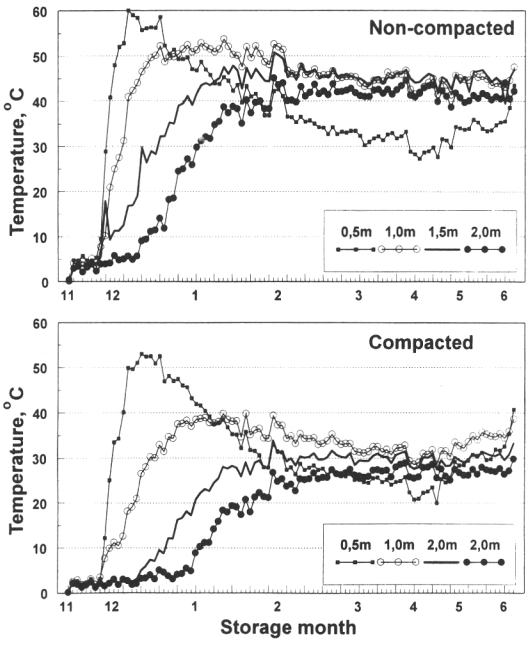


Fig. 1. The pile temperatures of compacted and non-compacted hammermilled logging residue pile at 0.5, 1.0 1,5 and 2.0 m depths measured from the top of the pile.

In this study the temperature rose very rapidly in the outer layers of the pile after the initial period of approximately one week. With time the temperature development stabilized being highest in the centre of the pile (Fig. 1).

The compaction of the pile caused the average profile temperatures to be about 15°C lower in the compacted than in the non-compacted pile section (Fig. 2). This result is contrary to earlier information on the effects of compaction [4, 5]. Thörnqvist states that wood chip piles are most likely to ignite when the pile has been compacted [4]. Although the residual material used in this study is different in composition from the two referenced studies, this is unlikely to explain the opposite results completely. The most likely reasons for the difference in results are firstly that the purposeful compaction carried out with the crawler tractor was quite thorough leaving less air for the metabolic activities. Secondly the pile in this study was not as high as in the one carried out by Thörnqvist.

3.5. Carbon and hydrogen content of hammermilled material

The elemental composition of woody biomass varies to some degree from one tree part to another [13, 14]. The carbon content of wood is about 50% of the dry weight but can be as high as 60–70% in the birch outer bark. Hydrogen content of wood is from 5–6%. Percentages as high as 8–9 are found in birch outer bark. As hammermilled logging residue is composed of wood, bark and needles its chemical composition is a product of these components.

In the beginning of the study in late September the carbon content averaged 50.0%. At the end of the trial in following June both treatments of comminuted material showed a significant increase in the carbon content (Table 4).

Table 4
The carbon and hydrogen content on dry weight basis of hammermmilled logging residue at the beginning and at the end of the trial

Element		Beginning September '94	Non-compacted June '95	Compacted June '95
C		50.03	51.14[a]	51.33[a]
	n	54	11	18
	s	1.09	0.90	0.72
H		6.64	5.73[a]	5.77[a]
	n	54	11	18
	s	0.38	0.15	0.13

[a] Values indicated with the same letter in horizontal direction are not significantly different (Tukey's test) from each other at 5% level.

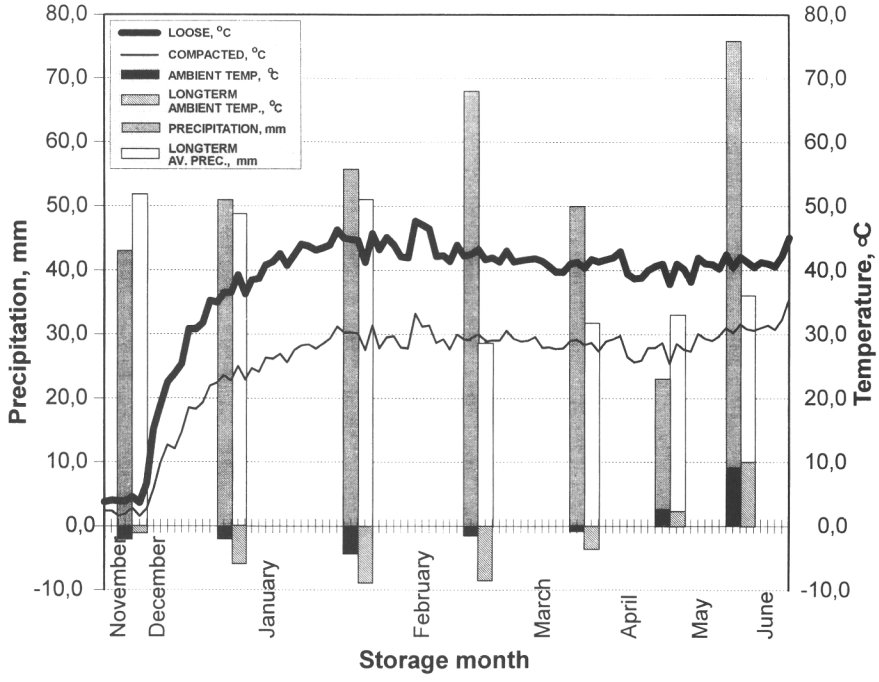


Fig. 2. The effect of compaction on the average pile temperatures. The average monthly and long term temperatures (°C) and precipatation (mm) are included.

However, it should be noted that the compaction was not a significant factor.

Hydrogen content was 6.6% at the start and was slightly higher figure than reported in earlier literature [13, 14]. After nine months of storage the hydrogen content had dropped to about 5.7%. This significant change in hydrogen content was most likely caused by the loss of volatile matter. As with carbon, the compaction was not a significant factor.

4. Conclusions

The residual biomass from spruce stands is plentiful and easy to harvest. But the drying and storage of logging residue is as complex as that of any other biomass. This study finds that clear-cut is a better drying site than landing. As a result it is recommended to dry the residue first on the clearcut in heaps left by the single grip harvester and then forwarding the material to a windrow on a landing. This will ensure lower moisture content and better storage characteristics. It should also be noted that forwarding or terrain chipping should not be carried out in wintertime due to high moisture content caused by snow and ice unless the combustion units are equipped with economizers.

Storage on the clear-cut resulted in a greater loss of needles through defoliation than on the landing. Furthermore defoliation proved to be a more important factor in nutrient cycle than leaching. This means that more nutrients remain on the site when residue material is let to dry properly before being forwarded to the landing. As an alternative, the forwarding and comminution of fresh logging residue guarantees the maximum yield of dry matter. On the negative side however, a fresh logging residue contains a lot of

moisture. Transportation of water will increase transportation costs and more importantly limit the users of logging residue to the larger and more sophisticated heating plants. Comminuted material should be combusted as soon as possible to avoid significant dry matter losses.

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References

[1] Hakkila P, Fredriksson T. Metsämme bioenergian lähteenä [Forest as a source of bioenergy]. Metsäntutkimuslaitoksen tiedonantoja 1996;613:92.

[2] Bergman Ö, Nilson T. Studier över utomhuslagring av aspvedsflis vid Hörnefors Sulfitfabrik (Outdoor storage of aspen chips at Hörnefors pulpmill). Institutionen for Virkeslära, Skogshögskolan. Rapporter 1967;55:105.

[3] Gislerud O. Heltreutnyttelse. Lagring av heltreflis. Summary: Whole tree utilization. Storing of whole tree chips. Norsk Institutt for Skogforskning. Raport 1974;5:29.

[4] Thörnqvist T. Bränder i stackar med sönderdelat trädbränsle. Summary: Spontaneous combustion in piles with comminuted wood fuel. Sveriges lantbruksuniversitet, Institutionen för Vikseslära. Uppsatser 1987;163:17.

[5] Nurmi J. Polttohakkeen varastointi suurissa aumoissa [Summary: Longterm storage of fuel chips in large piles]. Folia Forestalia 1990;767:18.

[6] Thörnqvist T, Jirjis R. Bränsleflisens förändring över tiden—vid lagring i stora stackar. Summary: Changes in fuel chips during storage in large piles. Sveriges lantbruksuniversitet, Institutionen för Virkeslära. Rapport 1990;219:49.

[7] Halonen O, Tulkki H, Derome J. Nutrient analysis methods. Metsäntutkimuslaitoksen tiedonantoja 1983;121:28.

[8] Thörnqvist T. Hyggesresternas förändring på hygget under två vegetationsperioder. Summary: The change of logging residues during storing at the clearcutting area in two growing seasons. Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden. Report 1984;150:69.

[9] Nylinder M, Thörnqvist T. Lagring av grenar och toppar i olika fraktioner. Summary: Storing of branches and tops of different fractions. Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden. Report 1980;113:45.

[10] Lehtikangas P, Jirjis R. Vältlagring av avverkningsrester från barrträd under varierande omständigheter. Summary: Storage of logging residues (softwood) in windrows under variable conditions. Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden. Report 1993;235:45.

[11] Flinkman M, Fredrikson H, Thörnqvist T. Barravfall hos hyggesrester som funktion av sommarexponeringens effekt. Summary: Needle litter in heaps of logging residues during a growing period. Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden.Report 1986;174:24.

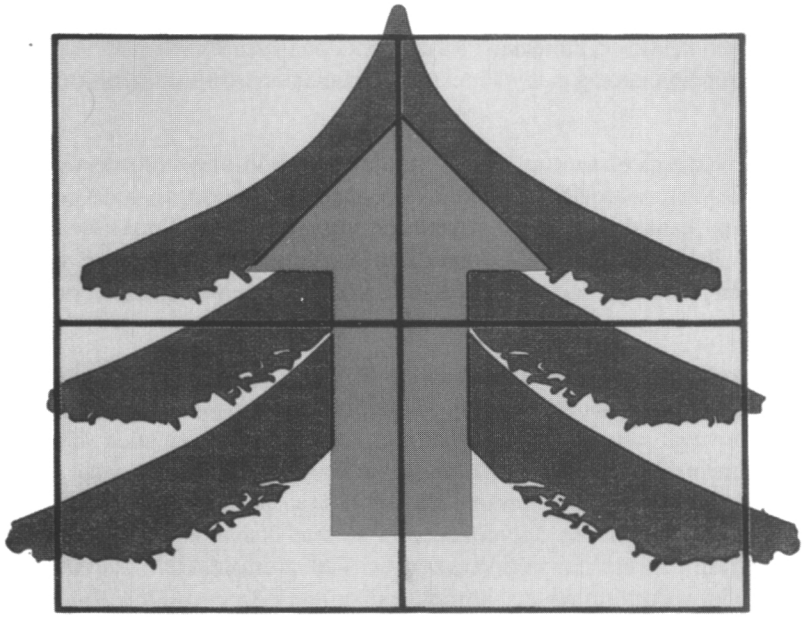
[12] Granhall U, Slapokas T. Leaf litter decomposition in energy forestry. First year nutrient release and weight loss in relation to the chemical composition of different litter types. In: Perttu K, editor. Ecology and management of forest biomass production systems. Department Ecology & Environmental Research, Swedish University of Agricultural Sciences. Report 1984;15:131–153.

[13] Thörnqvist T. Trädbränslekvalitet—vad är det? Summary: wood fuel quality—what is it? Sveriges lantbruksuniversitet SIMS Uppsatser 1985;14:18.

[14] Nurmi J. Heating values of the above ground biomass of small-sized trees. Acta Forestalia Fennica 1993;236:30.

VII

Bioenergian tutkimusohjelma



Hakkuutähteen ominaisuuksista

Juha Nurmi

Metsäntutkimuslaitoksen tiedonantoja 722, 1999

Kannuksen tutkimusasema
1999

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Biomassan pitkittyneen varastoinnin on havaittu aiheuttavan huomattavia kuiva-ainetappioita, energiasisällön alenemista sekä terveysriskejä käyttäjien keskuudessa. Ankarasta ilmastosta johtuen välivarastojen käyttö on kuitenkin välttämätöntä polttoaineen jatkuvan saatavuuden turvaamiseksi. Vaikeutena on kuitenkin löytää oikeat hakkuutähteen korjuun ja käsittelyn vaihtoehdot.

Tutkimuksen tavoitteena oli tuottaa tietoa hakkuutähteen polttoaineominaisuuksiin vaikuttavista tekijöistä sekä käsittelyvaihtoehtojen vaikutuksesta hakkuutähteestä saatavan polttopuun laatuun ja puuston kasvun kannalta tärkeiden ravinteiden vapautumisesta. Tämä toteutettiin tutkimalla kuusen tuoreen hakkuutähteen varastointia tienvarsikasoissa, joista puolet oli peitetty, sekä tutkimalla kuusen ja männyn varastointia palstalla hakkuukoneen tekemissä kasoissa.

Tuoreen hakkuutähteen kosteus vaihtelee välillä 50-55 %. Kun oksat on karsittu, pyrkii niiden kosteus asettumaan tasapainotilaan ilman suhteellisen kosteuden kanssa. Palstalla kasoissa olevat tähteet kuivuvat suuremman pinta-alansa ja kasojen harvuuden takia välivarastossa olevia tähteitä nopeammin. Molemmissa tutkituissa varastoissa hakettamattoman tähteen kosteus vaihteli vuodenajan mukaan ja oli korkein kaadon jälkeen sekä talviaikaan. Kosteus on alhaisin kesällä. Parhaan lopputuloksen saavuttamiseksi tähteen kuivatus tulisi tapahtua palstalla ja kuivuneen tähteen varastointi välivarastossa. Välivarastokasojen kattamisella ei tässä tutkimuksessa ollut vaikutusta tähteen kosteuteen.

Ravinteiden vapautuminen hakkuutähteestä on hidasta. Metsän ravinnetalouden kannalta neulasten variseminen tähteestä on paljon tärkeämpi tekijä kuin ravinteiden välitön vapautuminen hakkuutähteestä. Variseminen alentaa myös tulistimille haitallisiksi katsottujen kloorin, natriumin ja rikin määriä. Mikäli tähteet on kuitenkin logistisista syistä otettava talteen neulasineen, voidaan tähteen sisältämät ravintet palauttaa palstalle puutuhkan muodossa. Hakkuutähteen raskasmetallipitoisuudet ovat hyvin alhaiset.

Avainsanat: biomassa, hakkuutähde, neulaset, ravinteet, raskasmetallit, alkalimetallit, kuiva-ainetappiot

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1. JOHDANTO

Maailman energian kulutuksesta 5,4 % on peräisin polttopuusta. Kehittyneitten maiden energian kulutuksesta polttopuun osuus on vain 0,7 %, mutta Afrikassa vastaavasti 58 %. Edelleen puolet maapallon väestöstä on päivittäin riippuvaisia polttopuun tai puuhiilen saannista (Report of...1981). Suomessa puun osuus primäärienergian tuotannosta oli vuonna 1997 peräti 19 %. Puun osuudesta 80 % on metsäteollisuuden prosessijätettä, jonka teollisuus itse käyttää energian tuotantoonsa. Loput 20 % jää varsinaisen polttopuun osuudeksi ja muodostuu lähes kokonaan pientalojen, ensisijaisesti maatalouden käyttämästä polttopuusta. Tämä 1,1 milj. toe:n energiamäärä vastaa noin 5-6 miljoonaa kiintokuutiometriä puuta. Vaikka polttopuun käyttö lämmön tuotantoon kotitalouksissa onkin laskenut huimasti sotien jälkeen, on sillä edelleenkin vankka asema suomalaisessa lämmöntuotannossa. Tämä asema johtuu polttopuun riittävyydestä, pitkistä talvista ja puunkäytön perinteistä. Huomattakoon kuitenkin, että lämpölaitosten käyttämän metsähakkeen osuus oli vuonna 1995 vain 258 000 m^3 (Hakkila ja Fredriksson 1996). Vielä vuonna 1997 hakkuutähteen korjuumäärät olivat Suomessa reilusti alle 200 000 m^3. Kuluvan vuoden (1998) korjuumäärän arvioidaan kaksinkertaistuvan 340 000 m^3:iin. Vaikka lisäys onkin huomattava, ovat Suomen käyttömäärät erittäin pienet Ruotsiin verrattuna.

Suomen metsien koko maanpäällisen puubiomassan vuotuinen kasvu on noin 110 milj. m^3/a. Tästä määrästä teollisuuden ainespuun osuus on 56 milj. m^3. Ainespuun korjuun yhteydessä syntyy 29 milj. m^3 hakkuutähdettä, joka muodostuu latvusmassasta ja hukkarunkopuusta (Hakkila ja Fredriksson 1996). Lisäksi hakkuusäästöä kertyy 25 milj. m^3/a. Tähän määrään kuuluvat mm. taimikoitten ja vajaatuottoisten metsien pienpuustot sekä ensiharvennusrästit.

Uudistusalojen hakkuutähteen etuna pieniläpimittaisiin puihin nähden on sen talteenoton koneellisuus. Tähteet eivät edellytä yksinpuin käsittelyä, vaan ne voidaan ottaa talteen massaluontoisena polttopuuna. Hakkuutähteen erikoispiirteenä muihin puuperäisiin polttoaineisiin verrattuna on sen suuri neulasosuus. Uudistuskypsissä kuusikoissa neulasten osuus latvusmassasta on 36,1 % ja männiköissä 23,4 % (Hakkila 1991). Hakkuutähteen korjuukertymä on suurin, kun tähteet kerätään tuoreina, jolloin myös neulaset saadaan talteen. Neulaset kuitenkin sisältävät huomattavan osan puuhun sitoutuneista ravinteista.

Hakkuutähteen talteenotto rajoittuu lähinnä kuusen ja toissijaisesti männyn uudistusaloihin, sillä niillä tähteen kertymä hehtaaria kohti on suurin. Näin talteenoton kustannukset saadaan mahdollisimman alhaisiksi. Muita hakkuutähteen talteenottoa rajoittavia tekijöitä ovat mm. uudistushakkuiden pieni koko. Hakkila ja Fredriksson (1996) ovatkin arvioineet, että kuusikkovaltaisilla palstoilla ainespuun minimikertymä tulee olla 200 m^3 ja männiköissä vastaavasti 400 m^3, jotta tähteiden talteenotto olisi perusteltua. Lisäksi metsämaiden karuus tai ekologinen herkkyys rajoittavat käytettävissä olevien uudistusalojen määrää. On myös otettava huomioon, että metsätraktori kykenee ottamaan talteen noin 70 % hakkuutähteen massasta. Nämä rajoitukset huomioon ottaen korjuukelpoiseksi hakkuutähdereserviksi on laskettu 8,6 milj. m^3/a neulasineen. Vastaava luku ilman neulasia on 5,6 milj. m^3/a.

Hakkuutähteen talteenoton yksi vaikeimmin hallittavista vaiheista on sen kuivatus ja varastointi. Lukuisten esimerkkien johdosta tiedetään, että biomassan, varsinkin haketetun biomassan pitkäaikainen varastointi voi johtaa huomattaviin kuiva-aineen menetyksiin ja jopa terveyshaittoihin hakkeen käsittelijöiden keskuudessa.

Puupolttoaineiden merkittävänä erona fossiilisiin polttoaineisiin verrattuna on puun ominaisuuksien, mm. kosteuden, tiheyden ja tehollisen lämpöarvon vaihtelu. Puuaineen kosteus on tärkein puun palamiseen vaikuttavista tekijöistä. Sen suhdetta lämpöarvoon ovat tarkastelleet mm. Heiskanen ja Jokihaara (1961), Lehtonen (1977), Hakkila (1978), Björklund (1983) ja Nurmi (1993, 1997). Polttopuun kosteus riippuu ensisijaisesti puun kaadon jälkeisestä käsittelystä ja varastoinnista. Polttohakkeen pienkuluttajien keskuudessa hakkeen kuivatus on tavanomaista. Suurkuluttajien keskuudessa tämä ei kuitenkaan ole kannattavaa suurten määrien sekä useiden toimittajien takia. Siksi monet teollisuuden tutkimuksista ovatkin liittyneet polttohakkeen varastointiin (Bergman ja Nilsson 1966, 1967, Gislerud 1978). Polttopuun laatututkimuksiin ovat oleellisesti myös liittyneet ympäristöhygieniset kysymykset. Erityisesti pienkäyttäjien keskuudessa ilmenneet hengitystieallergiat ovat antaneet aihetta useille tutkimuksille kymmenen viime vuoden aikana (Smith ja Ofosu-Asiedu 1972, Turkkila ja Knut 1982, Thörnqvist 1983, Björklund 1983, White ym. 1983, Pellikka 1983, Pellikka ja Kotimaa 1983, Castren, M. & Lukkala, K. 1986, Jirjis ja Lehtikangas 1991).

Koska hakkeen kuivaaminen suurina määrinä on vaikeaa, puun kosteuden alentaminen ennen haketusta on mielekkäin vaihtoehto. Puun rasikuivatus sekä kokopuiden tai rankojen kuivatus kasoissa ovat edelleenkin yksinkertaisimmat, tehokkaimmat ja taloudellisimmat menetelmät (Hakkila 1962, Simola ja Mäkelä 1976, Liss 1979, Uusvaara 1984, Nurmi 1987).

Pitkästä lämmityskaudesta johtuen sekä polttopuu- että polttohakepuskurivarastojen ylläpito on välttämätöntä polttohakevirran katkeamattomuuden takaamiseksi. Ongelmana onkin oikeiden korjuu/varastointi-yhdistelmien löytäminen. Hakkuutähteestä saatavan puupolttoaineen laatuun voidaankin vaikuttaa oikea-aikaisella kuivatuksella ja varastoinnilla. Yleisimmät hakkuutähteen varastopaikat ovat palsta, välivarasto palstatien varressa sekä haketetun tähteen varastointi kasassa lämpölaitoksen pihassa. Siihen, mikä tai mitkä paikat ovat otollisimmat kullakin työmaalla ja tähteen käyttöpaikalla, ovat tapauskohtaisia. Niihin vaikuttavat mm. ainespuun korjuun ja hakkuutähteen talteenoton logistiikka, metsän uudistaminen, metsämaan ravinteikkuus ja lämpölaitoksen valmius polttaa joko kuivaa tai märkää tähdettä.

Kasvit tarvitsevat monia alkuaineita kasvaakseen ja pitääkseen yllä elämää. Hiili, vety ja happi ovat peräisin ilmasta eikä niitä lueta ravinteisiin kuuluviksi. Ne muodostavat kuitenkin 99 % puun kuiva massasta. Typen osuus on noin 0,3 %. Loppu 0,7 % koostuu pää- ja hivenravinteet sisältävästä mineraaliaineksesta. Pääravinteisiin kuuluvat fosfori, kalium, kalsium, magnesium ja mangaani. Hivenravinteisiin luetaan boori, rikki, kupari,sinkki, molybdeeni, kloori, natrium, pii ja koboltti. Ravinteita tarvitaan mm. alkoholiryhmien esteröintiin, energiansiirtoreaktioihin, entsymitoimintaan sekä ionitasapainon ylläpitoon. Hivenravinteisiin kuuluvat raskasmetallit edesauttavat mm. elektronien vaihtoa (Mengel ja Kirkby, 1982).

Pieni osa metsän ravinteista varastoituu puustoon. Osa siitä on kuitenkin jatkuvassa kiertokulussa ja palaa mm. neulasten mukana karikekerrokseen. Karikkeen hajoamisen ja ravinteiden vapautumisen nopeudestä kuitenkin riippuu, kuinka pian ravinteet ovat taas kasvillisuuden käytettävinä. Tätä säätelevät muun muassa ympäristön kosteus, happamuus ja lämpötila.

Tutkimuksen tavoitteena oli tuottaa tietoa hakkuutähteen polttoaineominaisuuksiin vaikuttavista tekijöistä sekä käsittelyvaihtoehtojen vaikutuksesta hakkuutähteestä saatavan polttopuun laatuun ja puuston kasvun kannalta tärkeiden ravinteiden vapautumisesta. Tavoitteeseen pyrittiin

selvittämällä, kuinka varastoaika, varaston paikka sekä välivarastokasojen suojaaminen paperikatteella vaikuttavat hakkuutähteestä saatavan polttohakkeen laatuun, so. kuinka kosteus, tuhkapitoisuus, neulasten määrä sekä polton kannalta mahdollisesti haitallisten kloorin ja natriumin määrä vaihtelee eri käsittelyiden seurauksena. Lisäksi tutkittiin puuston kasvulle tärkeiden pää- ja hivenravinteiden vapautumista hakkuutähteestä palsta- ja välivarastoinnin aikana.

2. AINEISTO JA MENETELMÄT

2.1. Aineisto

Hakkuutähteestä saatavaa puupolttoainetta voidaan varastoida palstalla hakkuukoneen jättämissä kasoissa, välivarastokasoissa ja käyttöpaikalla hakekasoissa. Tässä tutkimuksessa keskityttiin kahteen ensimmäiseen vaihtoehtoon. Tutkimuksen ensimmäisessä osassa (välivarastotutkimus) tutkittiin hakkuutähteen polttoaineominaisuuksia ja ravinteiden vapautumista välivarastolla ja toisessa (palstavarastotutkimus) vastaavasti hakkuutähteen ominaisuuksia palstalla hakkuukoneen tekemissä kasoissa.

Välivarastotutkimuksessa työmaat ja varastoalueet valittiin Mikkelin kaupungin hakkuutähteen korjuutyömailta. Tutkimusaineiston muodosti avohakkuualoilta kerätty kuusen hakkuutähde. Tähteet kasattiin palstan laitaan ainespuun ajon jälkeen 12.7. - 30.9.1995 välisenä aikana. Kasojen korkeus vaihteli välillä 3-5 metriä. Kasat sijaitsivat Mikkelin pohjoispuolella Hiirolan kylässä valtatie 72 varressa (4 kpl) ja valtatien 13 ja Korpijärven välisellä alueella (8 kpl). Kasoista joka toinen peitettiin piellä ja lasikuitukudoksella vahvistetullą voimapaperilla. Paperin leveys on 316 cm ja sitä valmistaa Pietarsaaressa UPM-Kymmene Walki Wisa.

Kasauksen yhteydessä tähteestä otettiin puu-, kuori- ja neulasnäytteet lähtötilanteen selvittämiseksi. Määrityksiä tehtiin seuraavasti: kosteus (297 kpl), tuhkaprosentti (53 kpl), pitoisuudet 19 alkuaineesta (1100 kpl), neulasprosentti (128 kpl), lämpöarvo (58 kpl) ja sadan neulasen paino (128 kpl).

Tehdyt 12 kasaa purettiin kolmessa vaiheessa siten, että kaksi peitettyä ja kaksi peittämätöntä kasaa haketettiin kerrallaan. Haketusajankohdat olivat 23.-24.1.1996, 6.-7.6.1996 ja 14.-15.1.1997. Haketuksen yhteydessä otettiin näytteet samoja määrityksiä varten kuin tutkimuksen alussakin. Koekasojen purkamisen yhteydessä otetuista näytteistä tehtiin seuraavat analyysit: kosteus (163 kpl), tuhkaprosentti (144 kpl), pitoisuudet 19 alkuaineesta (3120 kpl), neulasprosentti (127 kpl), lämpöarvo (162 kpl) ja sadan neulasen paino (64 kpl).

Palstavarastointia tutkittiin kahdella uudistushakkuualalla Laukaan ympäristössä. Toisen palstan pääpuulaji oli kuusi ja toisen mänty. Männyn päätehakkuu tehtiin 19.-23.9.1996 ja näytteiden otto tuoreesta massasta samalla 22.8.1996. Kuusikko hakattiin 2.-6.9.1996 ja näytteet otettiin samalla viikolla 6.9.1996. Hakkuutähteistä otetuista näytteistä tehtiin seuraavat analyysit: kosteus (40 kpl), tuhkaprosentti (84 kpl), pitoisuudet 17 alkuaineesta (1440 kpl), neulasprosentti (64 kpl), lämpöarvo (60 kpl) ja sadan neulasen paino (64 kpl).

Palstavarastoinnin aikana (6.2. ja 11.6. 1996) otetuista näytteitä tehtiin seuraavat analyysit: kosteus (100 kpl), tuhkaprosentti (156 kpl), pitoisuudet 17 alkuaineesta (3056 kpl), neulasprosentti (129 kpl), lämpöarvo (148 kpl) ja sadan neulasen paino (61 kpl).

2.2. Analyysit

Näytteiden kosteus (% tuorepainosta) määritettiin kuivaamalla näytteitä kaksi vuorokautta 102°C. Hiilen, vedyn ja typen määrä näytteissä määritettiin Leco CHN-analysaattorilla. Muiden alkuaineiden pitoisuudet (P, S, K, Na, Ca, Mg, Mn, Fe, B, Al, Cu, Zn, Mo, Cd, Pb, Cr, Ni,) määritettiin ICP mittauksilla, joita edelsi näytteen hajoittaminen HNO_3 + H_2O_2 liuoksessa CEM MDS-2000 mikroaaltohajoittimella. Kloridi (Cl^-) määritettiin uuttamalla näyte H_2SO_4 lioksella ja määrittämmällä potentiometrisesti saostustitrauksella. Titraattina käytettiin hopeanitraattia ($AgNO_3$). Tuhkapitoisuuden määrittämiseksi näytteet tuhkistettiin 550°C.

Hakkuutähteen lämpöarvon määritystä varten näytteet (n. 500 g) jauhettiin. Kalorimetristä polttoa varten jauheesta puristettiin näytetabletit. Kalorimetrisen lämpöarvon määritys tapahtui Leco AC-300 analysaattorilla. Kustakin näytteestä tehtiin kolme rinnakkaista määritystä. Kolmen näytteen hajonta ei saanut ylittää 0,5 %.

Neulasprosentti saatiin erittelemällä neulaset muusta näytteestä ja määrittämällä niiden osuus hakkuutähteen kuivamassasta. Sadan neulasen massa saatiin jokaisesta näytteestä erittelemällä sata kappaletta neulasia, jotka kuivattiin 102°C. Neulaset jäähdytettiin eksikaattorissa, jonka jälkeen ne punnittiin.

2.3. Tilastolliset menetelmät

Välivarastokasojen tilastollisissa tarkasteluissa käytettiin toistettujen mittausten varianssianalyysiä, jossa ryhmittelytekijöinä käytettiin aikaa ja katetta. Toistettuina mittauksina olivat kasan alkutilanne ja kasan purkamisen aikainen tilanne. Lisäksi säilytysaikojen välisiä eroja testattiin kovarianssianalyysillä, jossa kovariaattina oli alkutilanne ja ryhmittelytekijöinä olivat aika ja kate. Palstavarastointi aineistolle tehtiin yksisuuntaiset varianssianalyysit. Näyte-erien erisuuruisista variansseista johtuen tehtiin aineistoille logaritminen, 1/x tai neliöjuuri muunnos. Parittaisissa vertailuissa käytettiin Tukeyn testiä 5 % riskitasolla.

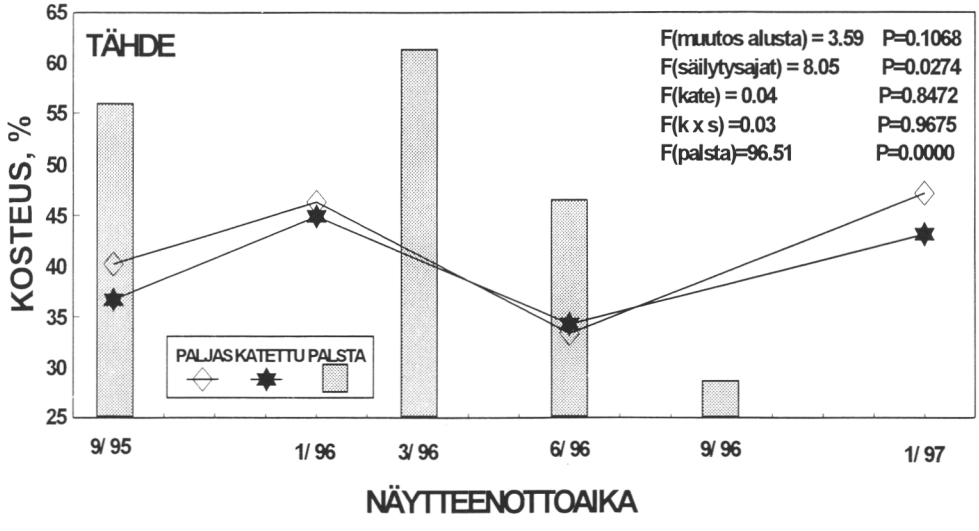
Työmaitten järjestelyssä auttoivat Pekka Auvinen Mikkelin kaupungista ja Ari Taimisto UPM-Kymmene Keski-Suomen metsäkonttorista. Hakkuutähden kattamisessa käytetyn katteen toimitti UPM-Kymmene Walki Wisa Pietarsaaresta Henrik Lassfolkin avustuksella. Metsäkoneurakoinneista vastasivat pääosin Veijo Kuukka ja Pekka Lahti. Aineiston keruun suorittivat Jaakko Miettinen ja Taisto Jaakola. Laboratorionäytteiden käsittelystä vastasivat Kaisa Jaakola, Riitta Miettinen ja Reetta Kolppanen. Seppo Vihanta vastasi laskennasta. Esa Heino ja Keijo Polet avustivat julkaisun painokuntoon saattamisessa. Kiitän kaikkia töihin osallistuneita.

3. TULOKSET

3.1. Hakkuutähteen kosteus

Välivarastoitujen vihreiden kuusen hakkuutähteiden lähtökosteus vaihteli Mikkelissä välillä 30-48 % (s=10,2 %). Koska kaatotuoreen latvusmassan kosteus vaihtelee välillä 50-55 %, on selvää, että tähteet olivat ehtineet kuivahtaa ainespuun teon ja tähteiden keruun välillä, vaikka olivatkin vihreitä. Tilanne vastanneekin täten käytäntöä melko hyvin, jolloin tähde-erien kosteus vaihtelee. Vertailun vuoksi mainittakoon, että eräässä toisessa tutkimuksessa (Nurmi 1999) kerätyssä aineistossa 90:stä hakkuutähdekuormasta otetuissa 450:ssä kosteusnäytteessä keskikosteus oli 56,0 % standardipoikkeaman ollessa 6,6 %.

Hakkuutähteen kosteus on aina korkein kaatotuoreessa massassa. Välivarastossa kosteus voi olla korkea myös talvella syksyllä siihen imeytyneestä kosteudesta eikä niinkään lumesta ja jäästä johtuen (kuva 1). Joskus talviajan kosteus saattaa ylittää kaatotuoreen kosteudenkin. Alhaisimmillaan kosteus on vastaavasti kesällä. Mikkelin välivarastokasoissa tähteen kosteus vaihteli vuoden aikana maksimissaan noin 10 kosteusprosenttiyksikköä. Tämä vastaa 2,25 MJ eroa jokaista hakkuutähdehakkeen märkäkiloa kohti. Ero on viidesosa 40 %:n kosteudessa olevan hakkeen energiasisällöstä ja niin ollen käytännön kannalta merkittävä. Tilastollisessa tarkastelussa vuodenajan vaikutus olikin merkitsevä (p=0,027). Katettujen ja kattamattomien kasojen välinen kosteusero oli sen sijaan hyvin pieni eikä ero osoittautunut tilastollisesti merkitseväksi (p=0,847).



Kuva 1. Hakkuutähteen kosteus näytteenottoajan suhteen katetuissa ja kattamattomissa kasoissa välivarastossa ja palstalla hakkuukoneen jättämissä kasoissa.

Palstalla hakkuukoneen jättämissä kasoissa varastoidun tähteen kosteus noudattaa samanlaista vuodenaikaisvaihtelua mitä välivarastossa varastoidut tähteet. Palstalla kosteus kuitenkin vaihtelee enemmän. Keskimääräinen kosteusvaihtelu kesän ja talven välillä oli yli 30 kosteusprosenttiyksikköä ja tilastollisesti merkitsevä (p=0,000). Erityisesti tulee huomata, kuinka korkeaksi tähteen kosteus voi palstalla kohota (> 60 %) varsinkin kevättalven aikana, jolloin säteilylämmön sulattama lumi jäätyy oksien ja neulasten ympärille. Tällainen jää ei juurikaan irtoa tähteistä talteenoton yhteydessä, vaan säilyy pysyvänä kosteuden lisänä. Mikäli ainespuun korjuu on tapahtunut lumettomana aikana, tulisi tähteet kerätä välivarastoon ennen lumen tuloa (kuva 1).

3.2. Hakkuutähteen neulasmassa

Neulasmassan osuus hakkuutähteestä on hyvin merkittävä. Uudistuskypsässä kuusikossa elävän latvuksen kuivamassasta neulasten osuus on noin 35 % ja hakkuutähteen kuivamassasta 30 %. Männyllä vastaavat luvut ovat 23 % ja 20 %. Neulasmassan määrittäminen hakkuutähteestä sisältää virheriskin, koska tähteen eri osissa neulasten vaihtelu oksan kärjestä rungon latvakappaleeseen on hyvin suuri. Mahdollisuus neulasten määrän painottumisesta suuntaan tai toiseen väärin painotetun otannan takia on hyvin mahdollinen, minkä takia tässä esitettyihin lukuihin tulee suhtautua pienellä varauksella.

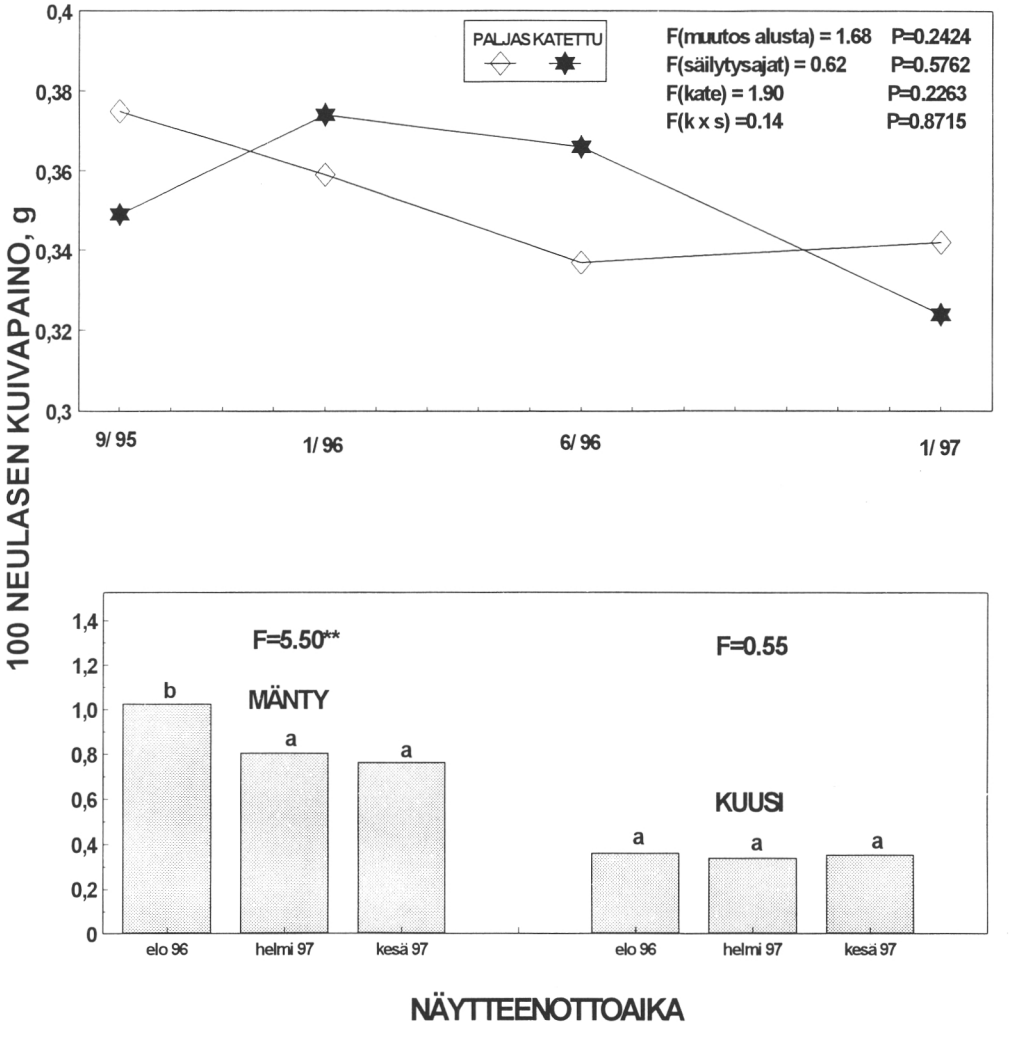
Variseminen edellyttää neulasten kuivumista. Pääosa varisemisesta tapahtuukin kesällä. Talvella neulasten kuivumista ei juurikaan tapahdu eikä neulasia myös siis irtoa tähteestä samassa määrin. Poikkeuksena on tietenkin kesänaikana kuivunnut jo ruskeaksi muuttunut tähde, josta neulaset irtoavat myös talvella. Taulukosta 1 nähdään, että palstalla parempi kuivuminen johtaa alhaisempaan neulaspitoisuuteen. Näin ollen yli 20 % tähteen sisältämästä kuivamassasta jää palstalle neulasten varisemisen seurauksena. Neulasten sisältämien ravinteiden on siten mahdollista päätyä seuraavan puusukupolven käyttöön. Toisaalta on otettava huomioon, että kertymä pienenee karisseen neulasmassan verran. Tämä puolestaan nostaa hieman talteenoton kustannuksia. Kertymä on suurin, mikäli tähteet kerätään välivarastoon tuoreena. Mikäli tuoreita tähteitä ei heti polteta, vaan varastoidaan/kuivataan, välivarastossa menetetään välivarastoinnin aikana varisevien neulasten sisältämät ravinteet ja energia.

Taulukko 1. *Hakkuutähteen neulasosuuden muutos vuoden kestäneen varastoinnin (syyskuu-syyskuu) aikana. Tähteen kosteus suluissa.*

	Neulasosuus kuivamassasta, %	
Varasto	Alussa	Lopussa
Palsta	27,7 (56,0)	6,9 (28,5)
Välivarasto	27,7 (56,0)	18,9 (42,2)

Mikkelin ympäristössä tehdyssä tutkimuksessa havaittiin välivarastoinnin pituudella olleen merkitsevä vaikutus tähteen neulaspitoisuuteen (p=0,0162). Kasojen peittämisellä sen sijaan ei ollut tilastollisesti merkitsevä (p=0,7609). Lisäksi neulasten kuivamassan hävikkiin sisältyy myös

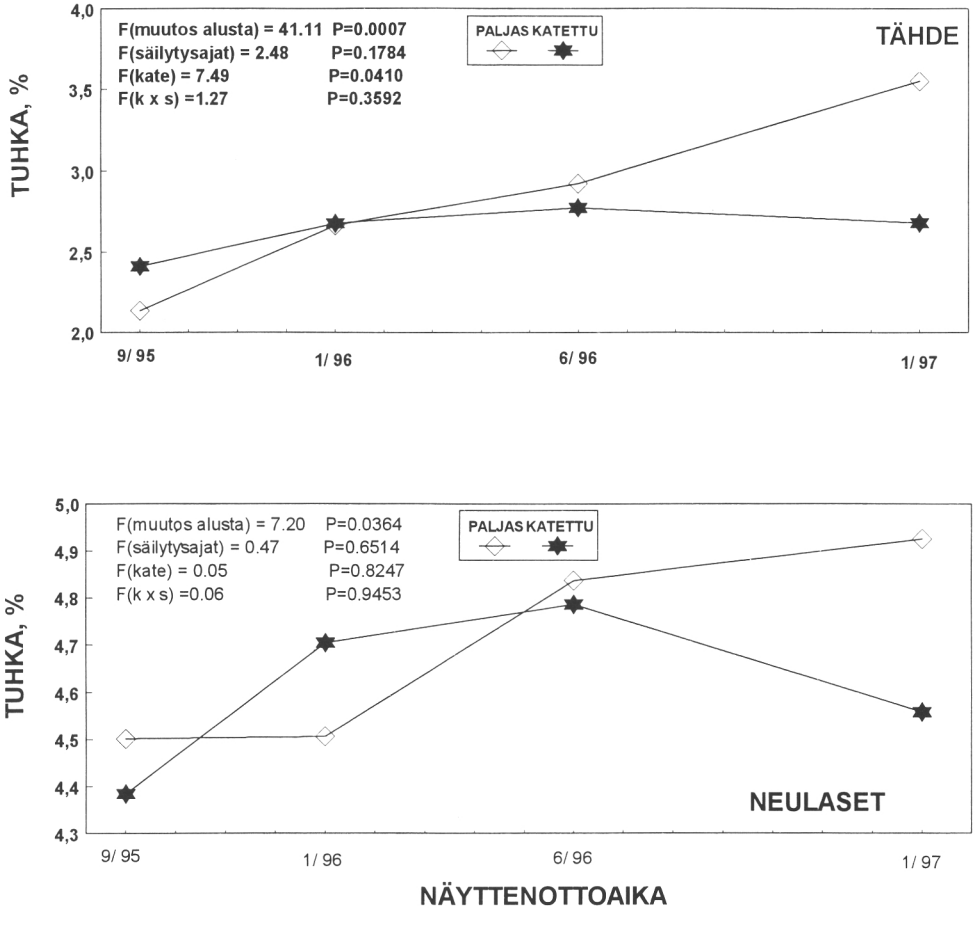
tiheyden muutos. Tämä määritettiin mittaamalla sadan kappaleen neulaserien painoja. Palstavarastoitujen männyn tähteiden neulasten paino oli alentuntunut merkitsevästi (kuva 2). Tämä massan menetys näyttää tapahtuneen jo ensimmäisen varastointivuoden syksyllä. Kuusella muutos ei ollut merkitsevä. Kuusen osalta tulos on yhteneväinen välivarastointitulosten kanssa, sillä niissäkään neulasten paino ei muuttunut varastoinnin aikana. Tulos poikkeaa aiemmin tehdystä tutkimuksesta (Nurmi 1999), jossa palstalla sadan neulasen paino aleni vuoden aikana peräti 20 %. Erona on se, että jälkimmäisessä tutkimuksessa tähteet olivat koko kesän palstalla, kun taas Laukaalla vain syksyn ja seuraavan kevään jolloin mikrobitoiminta ei ole voinnut päästä täyteen vauhtiin. Kate ei osoittautunut merkitseväksi muuttujaksi.



Kuva 2. Kuusen sadan neulasen paino näytteenottoajan suhteen välivarastossa (yllä), ja männyn ja kuusen sadan neulasen paino palstavarastossa (alla). Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.

3.3. Hakkuutähteen tuhkapitoisuus

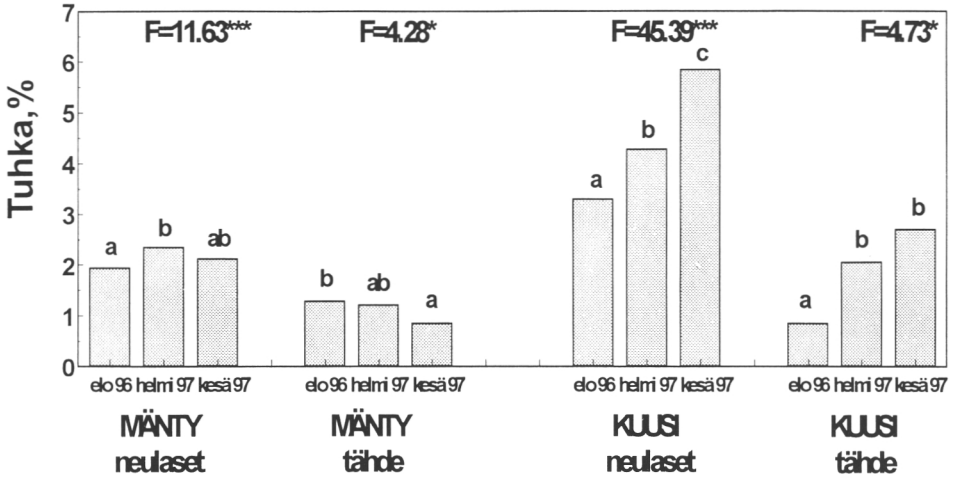
Biomassan päärakennusaineet, hiili, vety ja typpi palavat tullessaan kosketuksiin hapen ja korkean lämpötilan kanssa. Muut, palamattomat alkuaineet muodostavat tuhkan. Kuusen rungon ja oksien puuaineen tuhkapitoisuus vaihtelee välillä 0,30 – 0,63 % kuivamassasta. Kuorta sisältävän oksamassan tuhkapitoisuus on 1,9 % ja kuoren 3,0 %. Neulasten tuhkapitoisuus on tätäkin korkeampi (4,2 – 5,1 %) (Voipio ja Laakso 1992). Tässä tutkimuksessa neulasten tuhkapitoisuus vaihteli välillä 4,2 – 4,9 % ja hakkuutähteen tuhkapitoisuus 2 – 2,5 %. Välivarastoinnin pidentyessä niin neulasten kuin hakkuutähteenkin tuhkapitoisuus lisääntyi ja oli 4,5-5 % pisimpään varastoiduissa kasoissa (kuva 3). Muutos alkutilanteesta oli tilastollisesti merkitsevä ($p<0,001$). Lisäksi katetuissa kasoissa tuhkaa oli vähemmän kuin kattamattomissa. Seikkaa voidaan pitää viittauksena siitä, että katetuissa kasoissa kuiva-ainetappiot voisivat mahdollisesti olla peittämättömia alhaisemmat ($p=0,041$).



Kuva 3. Kuusen hakkuutähteen ja neulasten tuhkapitoisuus (%) välivarastossa näytteenottoajan suhteen.

Palstalla varastoidun kuusen neulasten sekä tähteen lähtötaso oli varsin alhainen, neulasilla vain reilun kolmen prosentin luokkaa ja tähteellä vain prosentin verran kuiva-aineesta. Pitoisuudet ovat varastoinnin edetessä kuitenkin kohonneet merkitsevästi. Puunkorjuuta seuranneeseen kesäkuuhun mennessä neulasten tuhkaprosentti oli jo kuusi ja tähteenkin kolme. Neulasten on jonkin verran korkeampi palstalla kuin välivarastossa. Tämä saattaa johtua siitä, että palstalla tähteet ovat levittäytyneet suuremmalle alalle ja lämpötila sekä kosteusolot ovat saattaneet olla suotuisemmat.

Myös männyn kohdalla muutokset ovat merkitseviä, mutta muutos neulasten tuhkapitoisuudessa (2-2,3 %) on varsin pieni vaikkakin merkitsevä. Luvut ovat samaa tasoa mitä Voipio ja Laakso (1992) ovat esittäneet männyn tuoreille neulasille. Männyn tähteen tuhkapitoisuus on sen sijaan alentunut eikä lisääntynyt kuten saattaisi olettaa. Tämä voi johtua neulasmassan pienestä osuudesta tuhkanäytteissä, mutta ei luultavaa (n=58). Lisäksi huomattakoon, että kuusen neulasten ja tähteen tuhkapitoisuudet ovat männyn vastaavia osia huomattavasti suuremmat ja ero näyttää vain kasvaneen varastoinnin aikana (kuva 4).



Kuva 4. Männyn ja kuusen neulasten ja hakkuutähteen tuhkapitoisuus (%) palstavarastossa näytteenottoajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.

3.4. Varastoinnin vaikutus hakkuutähteen alkuainekoostumukseen

3.4.1. Pää-ja hivenravinteet

3.4.1.1. Välivarastointi

Suurissa kasoissa välivarastoidun hakkuutähteen pääravinnepitoisuudet muuttuvat erittäin hitaasti (liitteet 1-6). Tähteessä tilastollisesti merkitseviä muutoksia havaittiin vain kaliumin kohdalla varastointiaikojen välillä. Varsinaista tilastollisesti merkitsevää muutosta alkutilanteesta, missä on otettu huomioon lähtötaso, ei tapahtunut millään pääravinteella. Myöskään kattaminen ei vaikuttanut näiden alkuaineitten pitoisuuksiin.

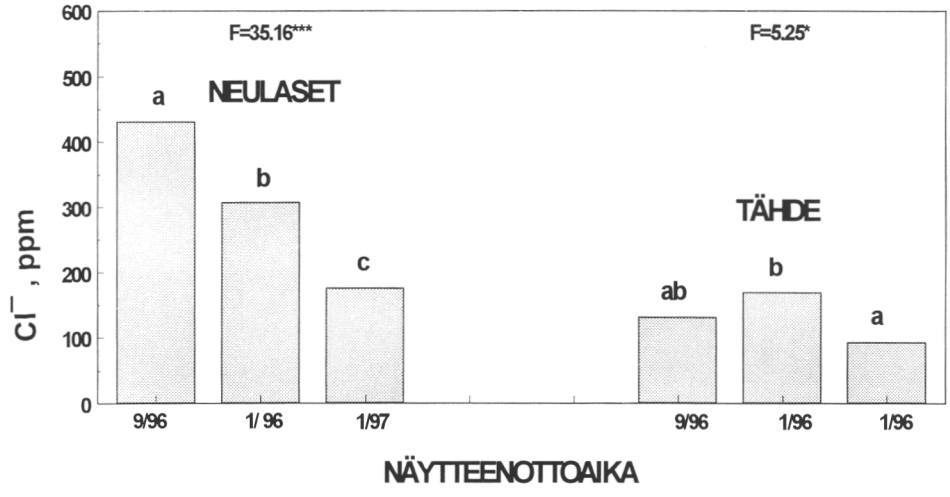
Aineiston perusteella on kuitenkin nähtävissä, että neulasista alkaa hitaasti vapautua ravinteita varastoinnin aloitusta seuranneena kesänä. Näin on erityisesti kaliumin, kalsiumin, mangaanin ja fosforin laita. Näiden muita ravinteita nopeampi vapautuminen johtuu lähinnä siitä, että ne eivät ole niinkään neulasten rakenneosia, vaan osallistuvat solujen entsyymi-, ja energianvaihtotoimintaan ja ovat täten helpommin vapautuvia kuin sellaiset rakennusaineet kuten hiili ja vety.

Tähteessä hivenravinteista vain rikin todettiin konsentroituvan jonkin verran varastoinnin aikana ($p=0,0249$). Raskaammista metalleista alumiinin, kuparin, raudan ja sinkin pitoisuudet eivät konsentroitunet alkutilanteesta. Raudan ja sinkin pitoisuudet vaihtelivat tosin merkitsevästi vuodenajasta toiseen ($p=0,0071$ ja $0,0069$). Tämä selittyy kasojen välisillä eroilla varastoinnin alussa.

Neulasissa sen sijaan raskasmetallit konsentroituvat merkitsevästi. Näyttääkin siltä, että pääravinteet vapautuvat mikrobitoiminnan seurauksena raskasmetalleja nopeammin, mikä johtaa puolestaan raskasmetallien osuuden nousuun jäljelle jäävässä neulasmassassa. Koska neulasia varisee runsaasti varastoinnin edetessä ja neulasistakin löydetyt pitoisuudet ovat pienet, ei konsentroituminen näy tähteestä otetuista näytteissä.

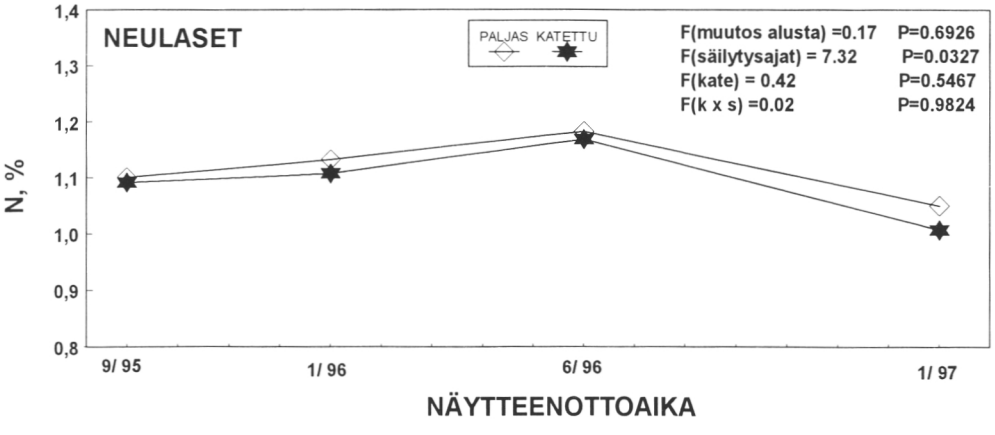
Natriumin ja kloorin oletetaan olevan osavastuussa tulistinpintojen korroosio-ongelmista. Natriumia löytyy hakkuutähteestä, mutta pitoisuudet ovat alhaiset vaihdellen välillä 21-32 ppm. Varastoinnin aikana tapahtuvat muutoksetkaan natriumin määrässä eivät olleet merkitseviä ($p=0,9639$). Kattamisella ei ollut merkitsevää vaikutusta natriumin eikä muidenkaan hivenravinteiden pitoisuuksiin.

Kloorin on kasvin kannalta välttämätön fotosynteesissä (Mengel ja Kirkby, 1982). Klooria löytyykin tuoreista kuusen neulasista noin 400 ppm, mutta puuaineessa sitä ei ole. Kloridi onkin yksi liikkuvimmista ioneista (Cl^-), joka vapautuu helposti. Varastointi laski merkitsevästi neulasten kloridipitoisuuksia (kuva 5). Muutos on ollut vähäinen, mutta tilastollisesti merkitsevä. Syynä saattaakin olla neulasosuuden vaihtelu tähdenäytteissä.



Kuva 5. Kuusen neulasten ja tähtee kloridipitoisuus (Cl^-) palstavarastossa näytteenottoajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.

Typpi on kivennäismailla usein puiden kasvua voimakkaimmin rajoittava tekijä. Karikekerroksen kuolleen orgaanisen aineen hajoamisella on tärkeä osuus typen saatavuuden kannalta. Kuusen neulasissa typpeä oli hieman yli yksi prosentti kuiva-aineesta. Typpeä ei vapautunut merkitsevässä määrin tutkituissa välivarasto-olosuhteissa. Varastointiaikojen välillä tosin oli eroja, mutta ne ovat lähtöisin alkutilanteen erisuuruisista konsentraatioista. Kate ei myöskään vaikuttanut typen vapautumiseen (kuva 6). Neulasten variseminen jää siis ainoaksi keinoksi palauttaa typpi takaisin kiertoon. Koska kuitenkin vain pieni osa typestä on kasveille käyttökelpoisessa ammonium- tai nitraattityppenä, ei neulasten varisemisella liene kovin suurta välitöntä merkitystä puuston typen saannin kannalta.



Kuva 6. Kuusen neulasten typpipitoisuus (N) välivarastossa näytteenottoajan suhteen.

3.4.1.2. Palstavarastointi

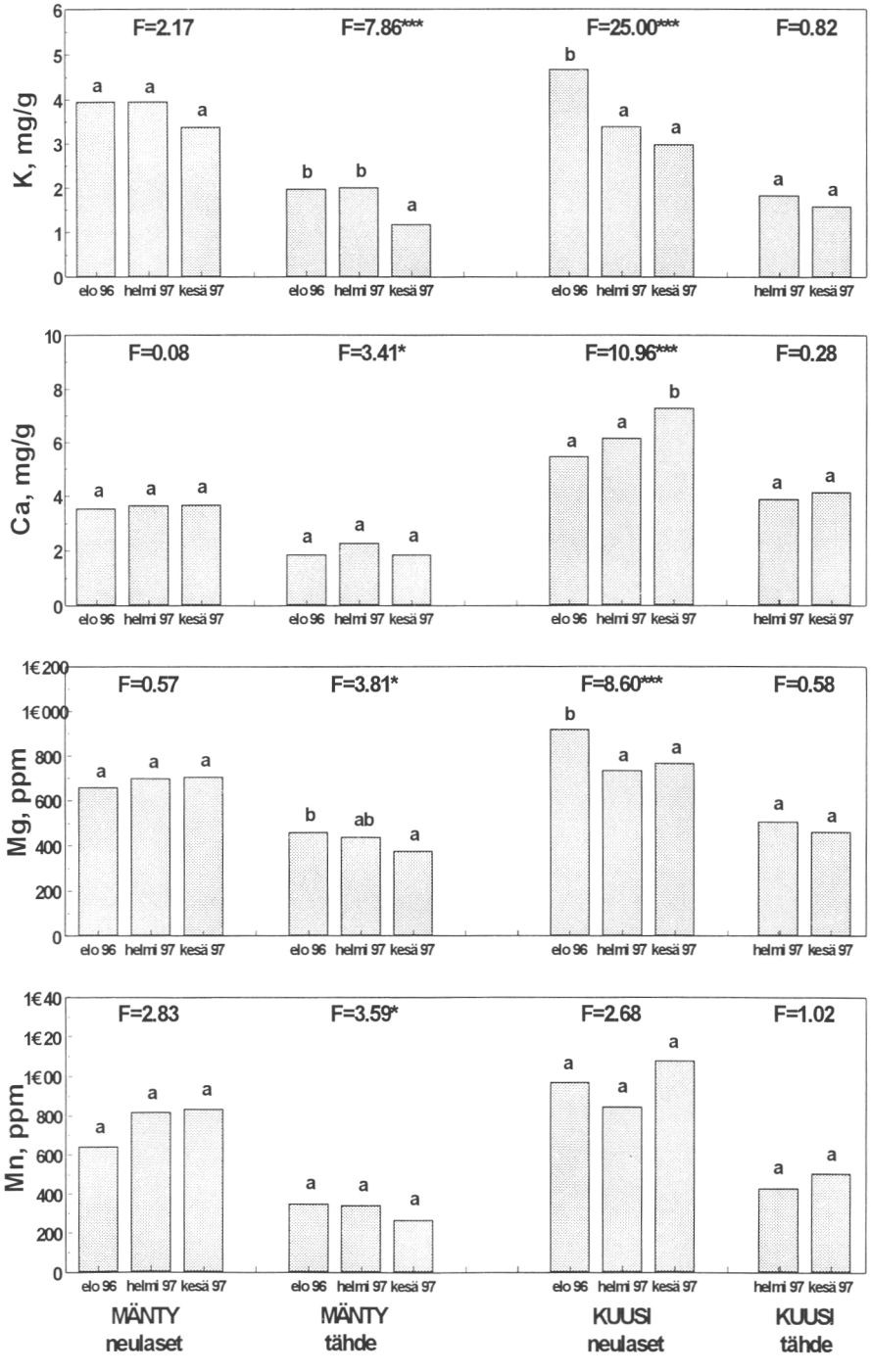
Varastoinnin vaikutuksesta pää- ja hivenravinteiden pitoisuuksiin männyn ja kuusen hakkuutähteessä havaittiin seuraavaa. Yleensä pitoisuudet laskivat tähteessä varastoinnin aikana, kuitenkin niin, että erot olivat männyllä yleisesti merkitsevät, mutta kuusella eivät. Koska ravinnepitoisuudet ovat korkeimmat neulasissa, korostuu tämän biomassakomponentin tärkeys alkuaineitten kulkeutumista tarkasteltaessa. Raudan, alumiinin, kuparin ja sinkin pitoisuudet kasvavat neulasissa varastoinnin aikana. Tämä johtuu siitä, että muut alkuaineet vapautuvat herkemmin mikrobitoiminnan tuloksena neulasista, jolloin jäljelle jäävien alkuaineitten pitoisuudet kasvavat. Koko tähdemassassa kuitenkin myös näitten pitoisuudet laskevat neulasten varisemisen myötä.

Kuusen kaliumin, mangaanin, kalsiumin ja magnesiumin pitoisuudet eivät muuttuneet tähdemassassa merkitsevästi. Myöskään fosfori-, boori-, rikki- ja natriumpitoisuudet eivät muuttuneet. Tulos on melko yhteneväinen välivarastoinnista saatujen tulosten kanssa. Kuusen neulasissa kaliumin ja magnesiumin pitoisuudet laskivat. Kalsiumin ja mangaanin pitoisuudet puolestaan kasvoivat. Kalsiumin kohdalla pitoisuuden lasku oli merkitsevästi. Selityksenä voisi olla se, että kuusen neulasista otettujen näytteiden kalsiumpitoisuuksien varianssit eivät toteuttaneet yhtäsuuruusvaatimusta. Männyn tähteen kaikki pitoisuudet ovat säännönmukaisesti laskeneet merkitsevästi. Tämä johtui ennen muuta neulasten varisemisesta. Neulasten pitoisuuksissa ei booria ja metalleja lukuunottamatta tapahtumut merkitseviä muutoksia (kuvat 7-9).

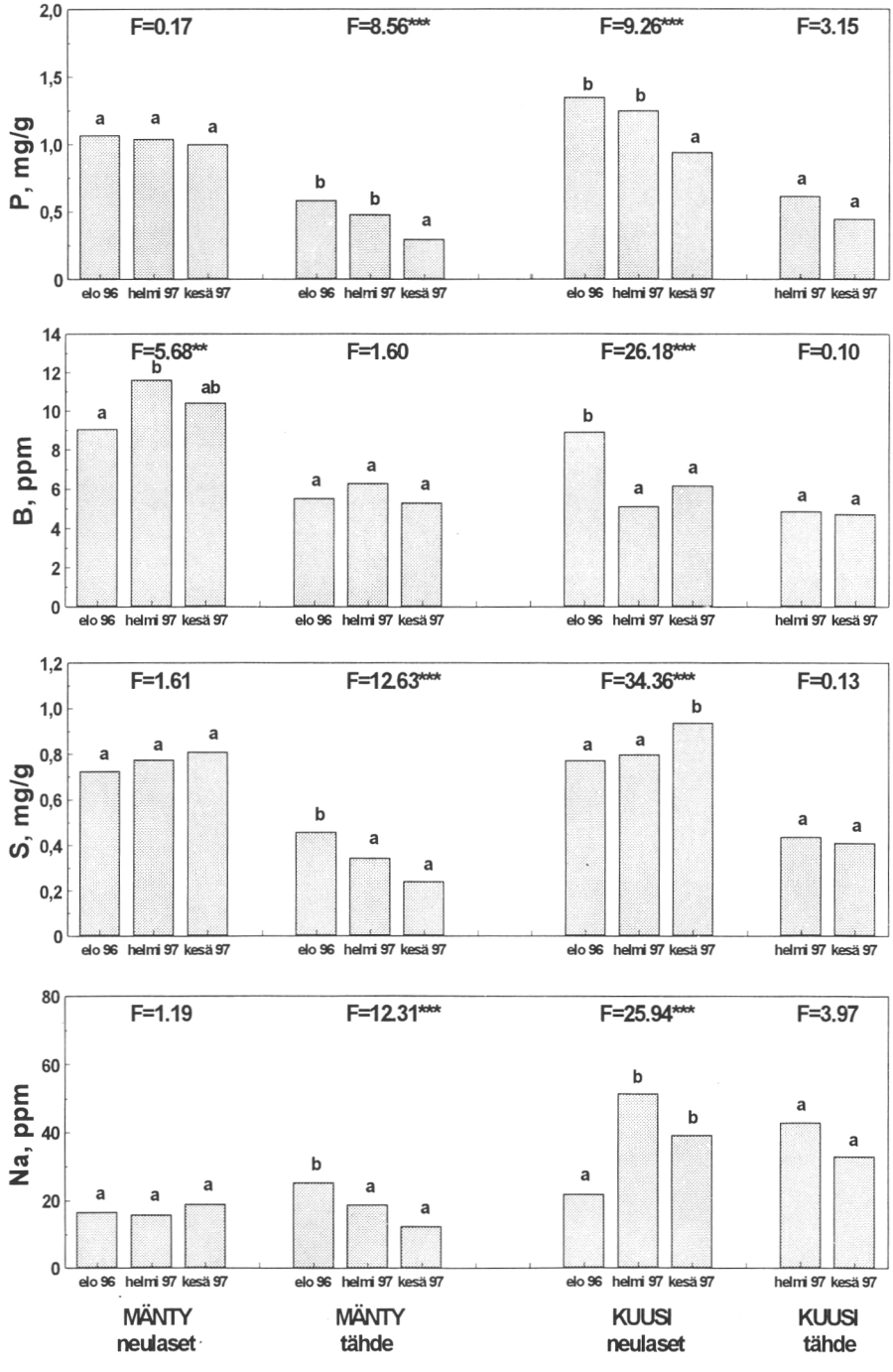
Männyn tuoreitten neulasten klooridipitoisuus on alle puolet kuusen neulasten sisältämästä kloridista (< 200 ppm). Lisäksi pitoisuuksien aleneminen ei ole yhtä nopeata kuin kuusella. Ainespuun tekoa seuranneena kesäkuussa pitoisuus oli vielä 160 ppm, mikä on suunnilleen sama kuin kuusella. Palstalla varastoidun kuusen neulasten kloridipitoisuus oli tuoreessa massassa sama kuin välivarastoidussakin tähteessä (n. 450 ppm). Lisäksi varastopaikalla ei näyttäisi olevan merkitystä kloridipitoisuuksien alenemisen kannalta, sillä varastoinnin lopuksi otetuista näytteistä määritetyt pitoisuudet olivat noin 170 ppm.

Männyn tähteessä kloridipitoisuus on alhaisempi kuin kuusen tähteessä. Tämä johtuu kuusen suuremmasta neulasmassan osuudesta sekä tuoreen tähteen kohdalla kuusen neulasten suuremmista pitoisuuksista. Koska klooria esiintyy nimenomaan tähteiden neulaskomponentissa, voidaan varastoinnilla oleellisesti vähentää sen määrää hakkuutähteestä saatavasta polttohakkeessa. Lisäksi kloridipitoisuudet alenevat nopeasti, erityisesti kuusen neulasista.

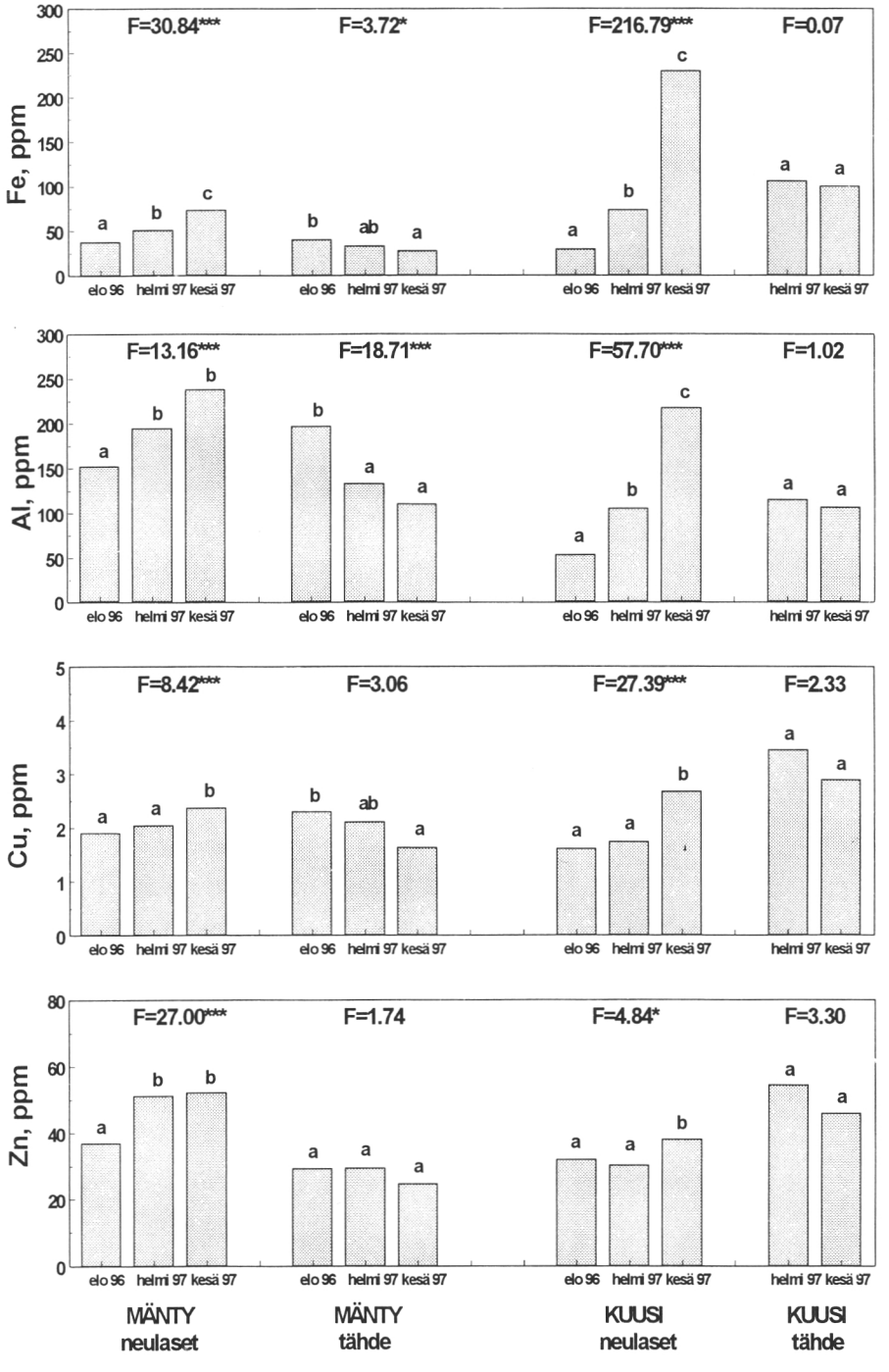
Kadmium-, kromi-, lyijy-, molybdeeni- ja nikkelipitoisuudet jäivät kuusen hakkuutähteessä alle määritysrajan. Tämä ei tarkoita sitä, että niitä ei olisi hakkuutähteessä, vaan että niiden pitoisuudet ovat niin pienet ettei niitä voitu havaita käytetyillä menetelmillä. Nämä vähäiset määrät voivat kuitenkin konsentroitua puutuhkaan.



Kuva 7. *Männyn ja kuusen tähteen kalium- (K), kalsium- (Ca), magnesium- (Mg) ja mangaani- (Mn) pitoisuus palstavarastossa näytteenottoajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.*



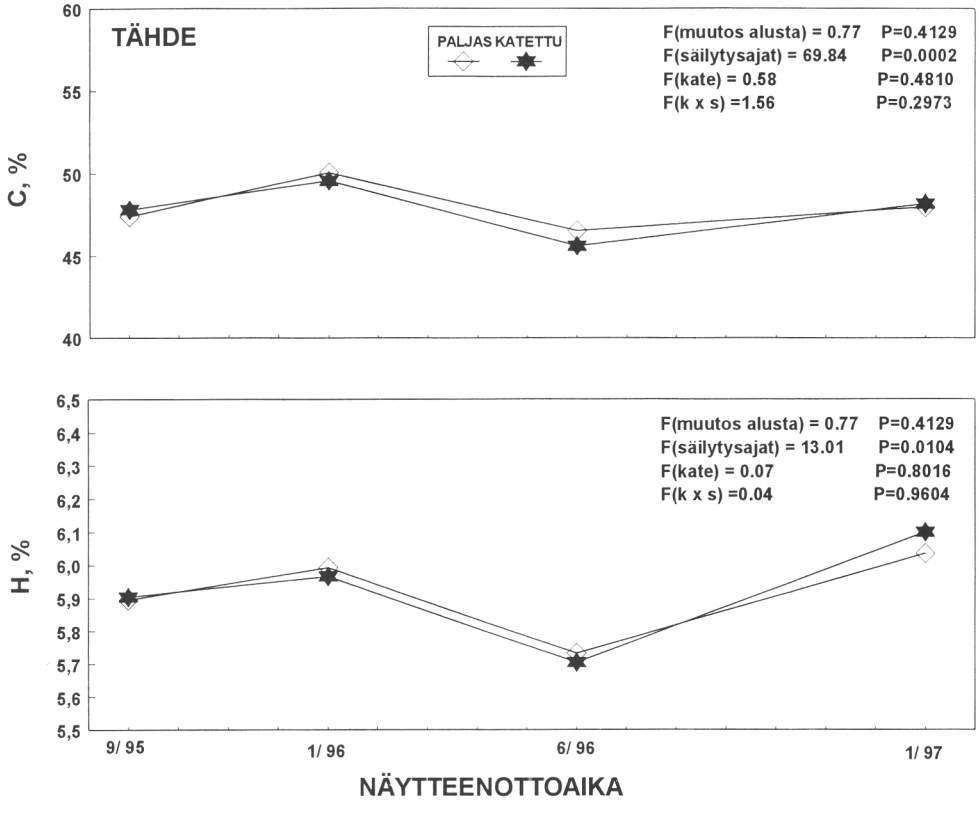
Kuva 8. *Männyn ja kuusen tähteen fosfori- (P), boori- (B), rikki- (S) ja natrium- (Na) pitoisuus palstavarastossa näytteenottoajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.*



Kuva 9. *Männyn ja kuusen tähteen rauta- (Fe), alumiini- (Al), kupari- (Cu) ja sinkki- (Zn) pitoisuus palstavarastossa näytteenottoajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.*

3.4.2. Hiili ja vety

Muutokset hiilen ja vedyn pitoisuuksissa eivät muuttuneet varastointiaikana. Näytteenottoajankohtien so. vuodenaikojen välillä oli kuitenkin eroja, jotka selittyvät eri suuruisilla lähtötasoilla. Lisäksi hiilivetyjen vapautuminen on kesän aikana vilkkainta (kuva 10). Koska hiili ja vety ovat sitoutuneet toisiinsa hiilihydraateissa ja ligniinissä, pysyvät niiden suhteet samana aineen hajotessa mikrobitoiminnan tuloksena. Täten myös massayksikköä kohti lasketun lämpöarvon tulisi pysyä muuttumattomana.



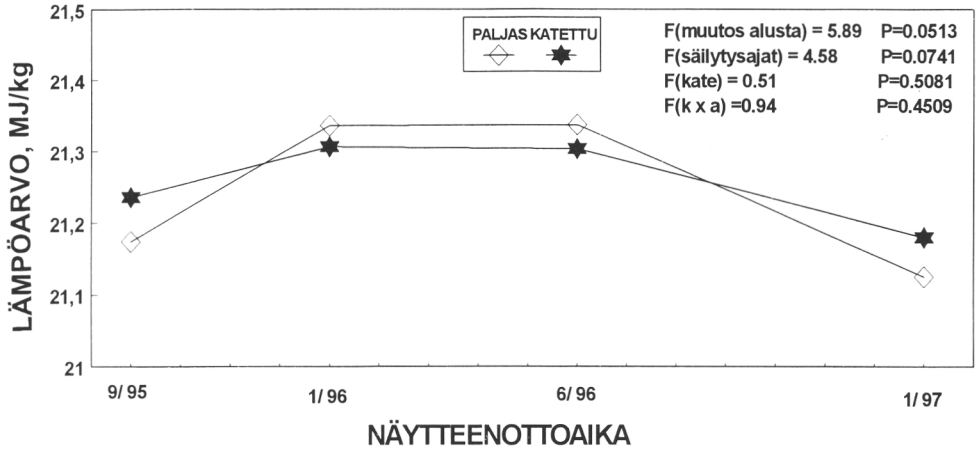
Kuva 10. Kuusen hakkuutähteen hiili- (C) ja vetypitoisuus (H) välivarastossa näytteenottoajan suhteen.

3.5. Hakkuutähteen lämpöarvo

Hakkuutähteen kalorimetrinen lämpöarvo riippuu ensisijaisesti hiilen ja vedyn suhteellisista osuuksista. Koska tämä suhde on hieman erilainen hemiselluloosassa, ligniinissä ja uuteaineissa, lämpöarvo vaihtelee siten hieman myös puu-, kuori- ja neulasmassan kesken. Lisäksi tehollinen lämpöarvo vaihtelee suuresti kosteuden mukaan. Havupuiden oksien puuaine

poikkeaa rakenteeltaan runkopuusta siinä, että oksien alapuolelle muodostuu lylyä. Lylyn yksi tunnusomainen piirre on normaalipuuta korkeampi ligniinin määrä. Ligniinin lämpöarvo on selluloosaa ja muita puun sisältämia hiilihydraatteja korkeampi. Tämän johdosta havupuiden oksissa olevan puuaineen lämpöarvo on rungon puuainetta korkeampi. Myös korkea uuteainepitoisuus nostaa oksapuun lämpöarvoa. Männyn ja kuusen oksien kuoren lämpöarvo on puolestaan oksia hieman korkeampi. Aiemmista tutkimuksista tiedetään, että männyn neulasettoman oksamassan tehollinen lämpöarvo 0 %:n kosteudessa on 20,09 ja kuusen 19,41 MJ/kg (Nurmi 1997). Vastaavasti neulasten lämpöarvot ovat 21,04 ja 19,19 MJ/kg. Männyn neulasen lämpöarvo on siis muuta latvusmassaa korkeampi, kun taas kuusella ero neulasten ja oksien välillä on pieni. Tästä seuraa, että neulasten varisemisella tulisi männyllä olla suurempi vaikutus keskimääräiseen lämpöarvoon kuin kuusella.

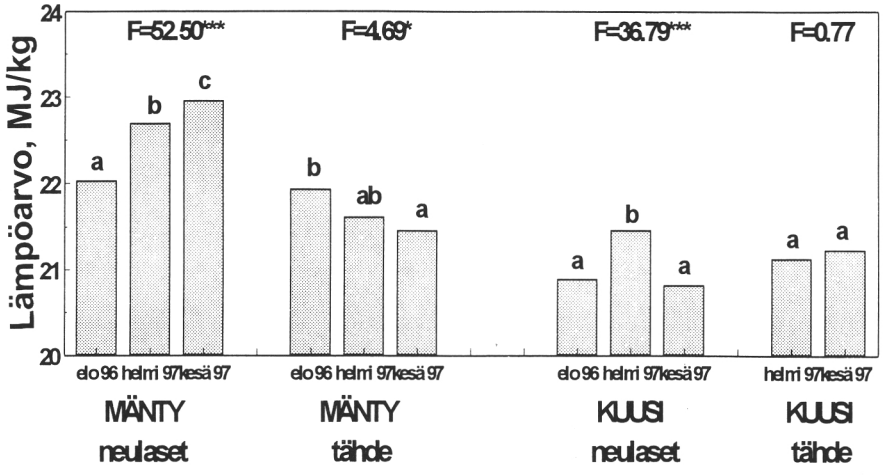
Kuusen välivarastoinnin aikana Mikkelissä keskimääräiset kuiva-aineen tehollliset lämpöarvot vaihtelivat välillä 19,8-20,1 MJ/kg (kalorimetrinen lämpöarvo = 21,2-21,4 MJ/kg). Vaihtelu oli pieni, eikä varastointiaikojen välillä ollut tilastollisesti merkitseviä eroja (kuva 11). Lieneekin niin, että vaikka tähteen nettolämpöarvo alenee neulasten varisemisen, lahoamisen ja uuteaineitten vapautumisen kautta, pysyy keskimääräinen kuiva-aineen tehollinen lämpöarvo samana hiilen ja vedyn suhteen pysyessä lähes samana varastoinnin ajan. Näin ollen vain kosteus jää jäljelle merkittävänä tehollista lämpöarvoa säätelevänä tekijänä.



Kuva 11. *Kuusen hakkuutähteen kalorimetrinen lämpöarvo MJ/kg välivarastossa näytteenottoajan suhteen.*

Kuusen palstavarastointi ei myöskään aiheuta lämpöarvollisia eroja varastointiajan suhteen. Massaa tosin menetetään mm. neulasten varisemisena, mutta se ei näy lämpöarvossa. Tukeyn testin parittaiset vertailut antavat viitteen siitä, että kuusen neulasten lämpöarvo olisi talvella jopa merkitsevästi ($p < 0{,}001$) suurempi kuin kesällä (kuva 12). Tyhjentävää syytä tähän on vaikea löytää. Yksi voisi olla se, että kesäaikana haihtumisen ja mikrobitoiminnan takia hiilivetyyhdisteitä vapautuu biomassasta alentaen niiden osuutta ja samalla nostaen palamattoman tuhkan osuutta. Lisäksi näytteiden otantaan saattaa liittyä epätarkkuutta, mikä osaltaan on saattanut vaikuttaa lopputulokseen.

Palstavarastoidun männyn hakkuutähteen tehollinen lämpöarvo aleni varastoinnin edetessä tilastollisesti merkitsevästi 20,6:sta 20,2:een MJ/kg. Kuten yllä mainittiin kuusen yhteydessä, tämä muutos voi johtua aineenvaihdunnallisista syistä tai otantaan liittyneestä virheestä. Muutokset männyn hakkuutähteen lämpöarvossa johtunevat kuitenkin suurelta osin neulasmassan osuuden alenemisesta. Miksi neulasten lämpöarvo on noussut näin merkitsevästi noin 22:sta 23:een MJ/kg, ei ole tietoa.



Kuva 12. Männyn ja kuusen hakkuutähteen kalorimetrinen lämpöarvo palstalla näytteenotto-ajan suhteen. Samalla kirjaimella merkitty ne keskiarvot, jotka eivät eroa toisistaan 5 %:n merkitsevyystasolla.

4. PÄÄTELMÄT

Tuoreen hakkuutähteen kosteus vaihtelee välillä 50-55 %. Kun oksat on karsittu, pyrkii niiden kosteus asettumaan tasapainotilaan ilman suhteellisen kosteuden kanssa. Palstalla kasoilla olevat tähteet kuivuvat suuremman pinta-alansa ja kasojen harvuuden takia välivarastossa olevia tähteitä nopeammin. Mikäli hakkuut tehdään syksyllä tai talvella, tähteet eivät kuivu palstallakaan ennen seuraavaa kesää. Pikemminkin talviaikainen varastointi lisää niiden kosteutta pintajään ja lumen muodossa. Mikäli taas hakkuu on tehty keväällä tai kesällä, kuivuvat tähteet palstalle hakkuukoneen tekemissä kasoissa usein erittäin hyvin. Parhaan kosteuden saavuttamiseksi olisi tähteiden annettava kuivua palstalla kesän yli ja kerättävä syksyllä välivarastoon odottamaan talviaikaista haketusta. Näin voidaan säilyttää saavutettu hyvä laatu, koska lunta ja jäätä ei pääse kertymään tähteeseen. On kuitenkin muistettava, että mikäli talvella hakatuilla aloilla olevaa tähdettä ei voida kuivattaa hakkuuta seuraavan kesän yli, tulisi tähteet kerätä välivarastoon välittömästi ainespuun korjuun jälkeen. Näin estetään lumen ja jään mukanaan tuoma lisäkosteus.

Tähteen varastointi/kuivattaminen palstalla vaikuttaa oleellisesti hakkuutähteen kertymään. Suurin kertymä saadaan, mikäli tähteet kerätään tuoreena. Tällöin tosin joudutaan kuljettamaan

paljon vettä tähteen mukana, mistä syntyy kustannuksia. Monissa nykyaikaisissa laitoksissa kostean polttohakkeen poltto ei tuota vaikeuksia, mutta toistaiseksi valtaosa laitoksista ei ole rakennettu vastaanottamaan näin kosteata polttoainetta. Mikäli tähteiden annetaan kuivua palstalla, paranee tähteestä saatavan polttohakkeen tehollinen lämpöarvo siinä määrin, että neulasten varisemisen johdosta tapahtuva massan menetys korvautuu täysimääräisesti kosteuden alenemisella. Lisäksi metsämaan ravinteikkuuden kannalta lienee edullista antaa ravinnerikkaan neulasmassan varista kuivumisen seurauksena palstalle. Tulee myös muistaa, että pitkäaikaisen välivarastoinnin seurauksena läheskään kaikki neulaset eivät päädy polttoon, vaan ne varisevat varastolle, jolloin niistä ei ole hyötyä enempää metsämaalle kuin lämpölaitoksellekaan.

Ravinteiden vapautumisen todettiin olevan hidasta varastoinnin aikana. Välivarastoinnissakaan ei ole pelättävissä, että suuria määriä ravinteita huuhtoutuisi pintavesiin. Metsän ravinnetalouden kannalta neulasten variseminen onkin paljon tärkeämpi tekijä kuin ravinteiden välitön vapautuminen hakkuutähteestä. Näin menetellessä alenee myös tulistimille haitallisiksi katsottujen kloorin, natriumin ja rikin määrät. Mikäli tähteet on kuitenkin logistisista syistä otettava talteen neulasineen, voidaan tähteen sisältämät ravinteet palauttaa palstalle puutuhkan muodossa.

Tuhkan määrä lisääntyy tähteessä ja varsinkin neulasissa biologisen hajoamisen myötä noin 50-100 % vuoden mittaisen varastoinnin aikana. Lisäys riippuu neulasosuuden suuruudesta. Mitä vähemmän neulasia, sitä vähemmän tuhkapitoisuus lisääntyy varastoinnin pidentyessä. Varastopaikalla ei näyttäisi olevan kovin paljon vaikutusta tuhkan määrään. Koska lisäys on melko huomattava, täytynee se ottaa huomioon lämpölaitoksilla, vaikkakaan se ei tuottane käsittelyvaikeuksia. Tutkimuksen mukaan tuhkan määrä oli pienempi katetuissa välivarastokasoissa. Tämä viittaa pienempiin kuiva-ainetappioihin. Näiden tulosten perusteella on kuitenkin mahdotonta sanoa, onko katteella tässä suhteessa todellista käytännön merkitystä.

Hakkuutähteen lämpöarvon muutokset painoyksikköä kohti ovat pienet, sillä hiiltä ja vetyä vapautuu suurin piirtein samassa suhteessa. Massan nettoenergian määrään sen sijaan vaikuttaa huomattavasti enemmän neulasten ja pienten oksien variseminen joiden aiheuttama kuiva-aineen hukka voi olla jopa 30 %. Suurin vaikutus teholliseen lämpöarvoon on kuitenkin kosteudella.

Ruotsissa hakkuutähteen pitkäaikainen varastointi välivarastossa on yleinen käytäntö, jolla pyritään parantamaan hakkuutähteestä saatavan polttoaineen laatua. Olosuhteiden parantamiseksi hakkuutähdekasat peitetään kaksinkertaisella voimapaperilla, jonka kestävyyttä on parannettu piki- ja lasikuitukudoskerroksilla. Tutkimusten mukaan menettely alentaa hakkuutähteen kosteutta huomattavasti (Jirjis 1996). Tämän tutkimuksen tulokset eivät kuitenkaan tue oletusta, että kattaminen edesauttaa kasojen kuivana pysymistä ja vähentää kosteusvaihteluita kasoissa. Lisäksi katteella ei ollut vaikutusta ravinteiden vapautumisenkaan kannalta. Onkin kysyttävä, miksi kate ei toiminut kosteutta vähentävänä tekijänä? Ensinnäkin kate oli liian kapea ainakin kooltaan suurimpiin kasoihin. Tästä seuraa, että osa sadevesistä ja lumen sulavesistä on ohjautunut katteen reunojen yli kasoihin. Toisaalta osa kasoista oli sen kokoisia, että kasan ylimmät kerrokset ovat toimineet peittona, joista lumi on sitten keväällä osin sulanut kasaan, osin haihtunut, so. peittämättömät kasat ovat kattaneet itse itsensä. Erot ruotsalaisiin tutkimuksiin selittynevät sillä, että suurin osa heidän laajasta tutkimusaineistostaan on kerätty eteläisemmiltä leveysasteilta, missä suhteellisesti suurempi osa sateesta tulee vetenä. Lisäksi siellä on kokemuksesta opittu mitoittamaan kasan korkeus oikein paperin leveyteen nähden niin, että kasat ovat matalampia ja tulevat jotakuinkin paperilla katetuksi. Tämän tutkimuksen tulosten perus-

teella kattamisesta saatava hyöty/kustannus suhde on kyseenalainen vihreän hakkuutähteen peittämisessä. Mikäli peittämisessä onnistutaan ja menetelmää käytetään kuivan ruskean tähteen peittämiseen, saattaa polttohakkeen parempi laatu hyvinkin korvata kattamisesta aiheutuneet kustannukset. Tuleekin mainita, että kapeutta lukuunottamatta katteena käytetty paperi sopi erinomaisesti tähteiden peittämiseen. Paperin lujuus, valon kesto ja levitettävyys olivat ilmeisen hyvät.

KIRJALLISUUS

Bergman, Ö. & Nilsson, T. 1966. Studier över utomhuslagring av tallvedsflis vid Lövholmens Pappersbruk. Summary: On Outside Storage of Pine Chips at Lövholmen's Paper Mill. Institutionen för virkeslära, Skogshögskolan. Rapporter 53. 83 s.

Bergman, Ö. & Nilsson, T. 1967. Studier över utomhuslagring av aspvedsflis vid Hörnefors Sulfitfabrik. Institutionen för virkeslärä, Skogshögskolan. Rapporter 55. 105 s.

Björklund, L. 1983. Lagring av helträdsflis av olika trädslag samt i olika fraktioner. Summary: Storage of whole-tree chips of different species and in different fractions. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 143. 50 s.

Castren, M. & Lukkala, K. 1986. Hakelämmityksen ja työperäisten altisteiden vaikutus maanviljelijöiden hengityselinoireisiin. Summary: Effects of heating with wood chips and occupational predispositions on farmers' respiratory symptoms. Työtehoseuran Julkaisuja, No 282.

Gislerud, O. 1978. Lagring av lauvtreflis. Et lagringsforsfk med Sande Paper Mill A/S. Norsk Institutt for Skogforskning. Rapport 9. 37 s.

Hakkila, P. 1962. Polttohakepuun kuivuminen metsässä. Summary: Forest seasoning of wood intended for fuel chips. Communicationes Instituti Forestalis Fenniae 54(4). 82 s.

Hakkila, P. 1978. Pienpuun korjuu polttoaineeksi. Summary: Harvesting small-sized wood for fuel. Folia Forestalia 342. 32 s.

Hakkila, P. 1991. Hakkuupoistuman latvusmassa. Folia Forestalia 773. 24 s.

Hakkila, P. & Fredriksson, T. 1996. Metsämme bioenergian lähteenä. Metsäntutkimuslaitoksen tiedonantoja 613. 92 s.

Heiskanen, V. & Jokihaara, L. 1961. Puupolttoaineiden lämpöarvosta. Pienpuualan Toimikunnan tiedotus 33. 5 s.

Jirjis, R. & Lehtikangas, P. 1991. Storage of forest residues in covered windrows. In: Suadicani, K. (ed), Proceedings from joint meeting. IEA/BEA Activity 4 (Wood preparation, storage and drying) and 5 (Measurement and evaluation of wood fuel). Silsoe Research Institute, 12-14 June 1991. Danish Forest and Landscape Research Institute. Research Report No 10: 46-53

Jirjis, R. 1996. Handling and storage of uncomminuted forest residues. In: Hudson, J.B. & Kofman, P.D.(eds). Harvesting, storage and road transportation of logging residues. Proceedings of a workshop of IEA-BA-Task XII activity 1.2, held in October 1995 in Glasgow, Scotland - Danish Forest and Landscape Research Institute, Hørsholm, Denmark. s. 41-49. ISBN 87-89822-56-0

Lehtonen, I. 1977. Puu polttoaineena. Kirjallisuuteen perustuva tarkastelu. Abstract: Wood as a fuel. A study based on literature. Folia Forestalia 293. 16 s.

Liss, J.-E. 1979. Syrfällning. Institutionen för Skogsteknik, Skogshögskolan. Garpenberg. Stencil 73. 20 s.

Mengel, K. & Kirkby, E.A. 1982. Principles of plant nutrition. International Potash Institute, Bern. 3rd edition. 655 s.

Nurmi, J. 1987. Polttohakkeen kuivatus traktorikonteissa. Summary: Drying of fuel chips and chunks in wooden bins. Folia Forestalia 687. 40 s.

Nurmi, J. 1993. Heating values of the above ground biomass of small-sized trees. Acta Forestalia Fennica 236. 30 s.

Nurmi, J. 1997. Heating values of mature trees. Acta Forestalia Fennica 256. 28 s.

Nurmi. J. 1999. Storage of logging residues for fuel. Biomass and Bioenergy. Painossa.

Pellikka, M. 1983. Homepölyaltistus polttohakkeen käsittelyn yhteydessä. Metsäntutkimuslaitoksen tiedonantoja 81. 76 s.

Pellikka, M. & Kotimaa, M. 1983. Polttohakkeen käsittelystä aiheutuva ilman homepölypitoisuus sekä siihen vaikuttavat tekijät. Summary: The mould dust concentration caused by the handling of fuel chips and its modifying factors. Folia Forestalia 563. 18 s.

Pesonen, M. 1982. Homepölyaltistus maatiloilla hakkeen käytön yhteydessä. Emissio 1/82. s. 19-21.

Report of the technical panel on fuewood and charcoal on its second session. A/CONF. 100/PC/34, 25 February 1981.

Simola, P. & Mäkelä, M. 1976. Rasiinkaato kokopuiden korjuussa. Summary: Leaf-seasoning method in whole-tree logging. Folia Forestalia 273. 18 s.

Smith, R.S. & Ofosu-Asiedu, A. 1972. Distribution of thermophilic and thermotolerant fungi in a spruce-pine chip pile. Canadian Journal of Forest Research 2: 16-26.

Thörnqvist, T. 1983. Bränsleflis förändring under ett års lagring. Summary: Fuel chips change during one year of storage. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Rapport 148. 65 s.

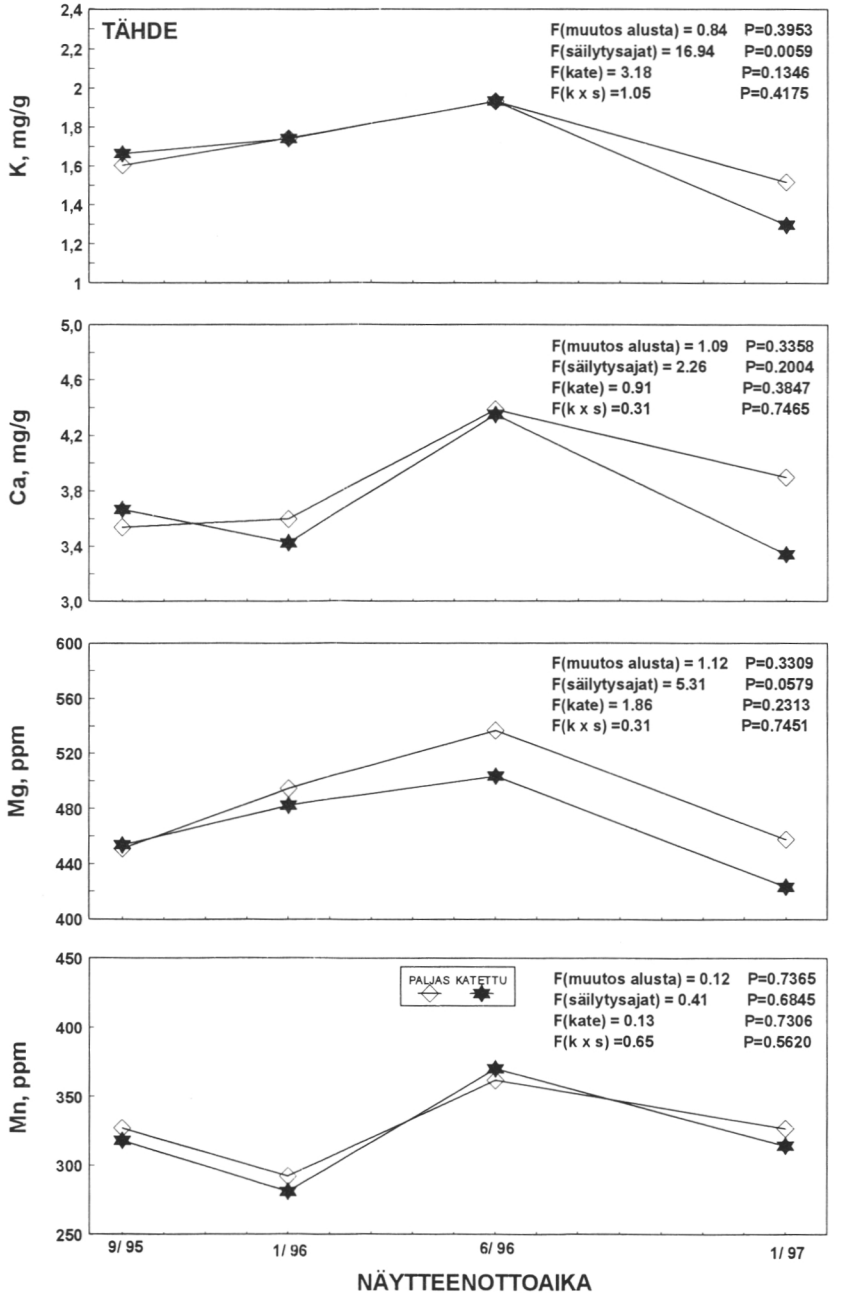
Turkkila, K. & Knut, S. 1982. Homeiden määrä ja laatu maatilojen hakkeessa. Summary: The amount and species of the moulds in the chips of farms. Työtehoseuran metsätiedotus 344. 4 s.

Uusvaara, O. 1984. Hakepuun kosteuden alentaminen ennen haketusta korjuuseen ja varastointiin liittyvin toimenpitein. Summary: Decreasing the moisture content of chipwood before chipping, harvesting and storage measures. Folia Forestalia 599. 31s.

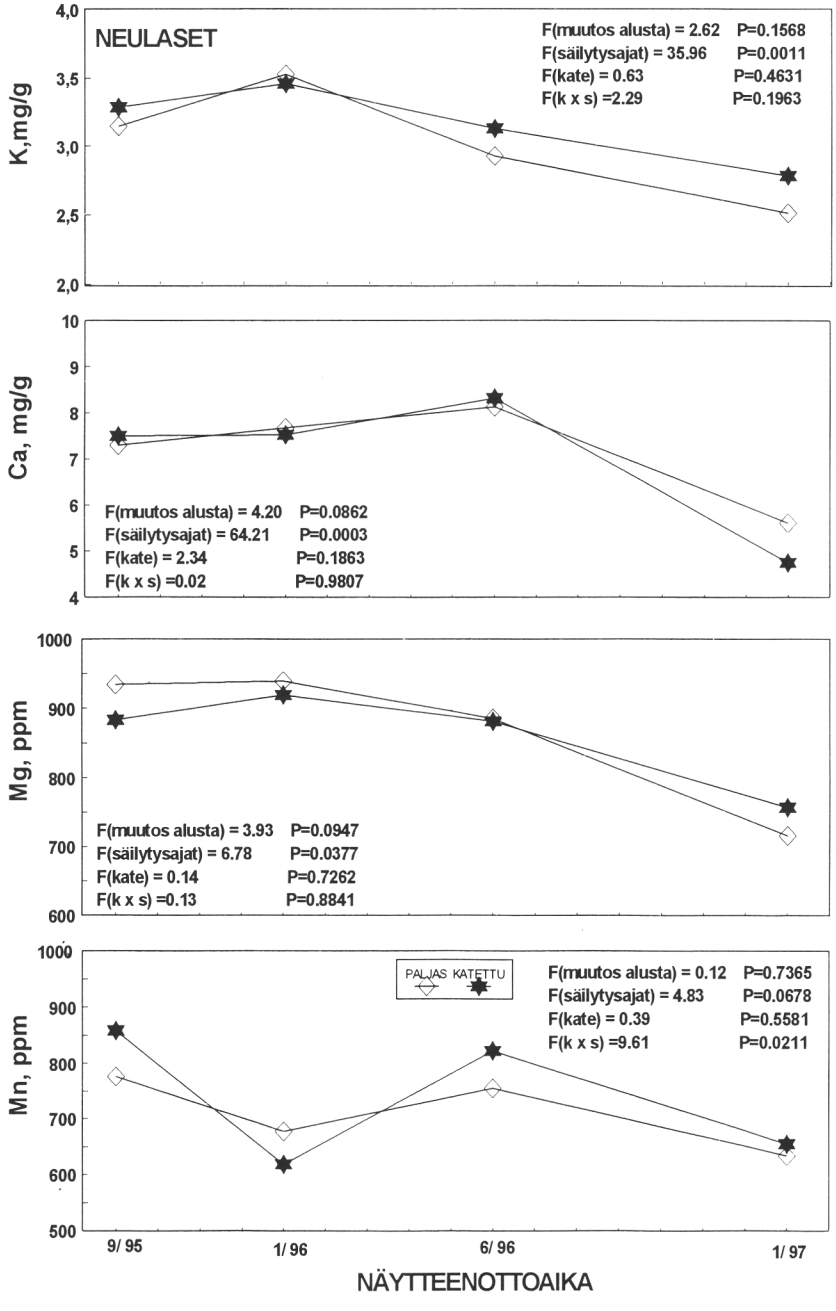
Voipio, R. & Laakso, T. 1992. Pienikokoisten puiden maanpäällisen biomassan kemiallinen koostumus. Folia Forestalia 789. 22 s.

White, M.S., Curtis, M.L., Sarles, R.L. & Green, D.W. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part 1. Moisture content and temperature. Forest Products Journal 33: 31-38.

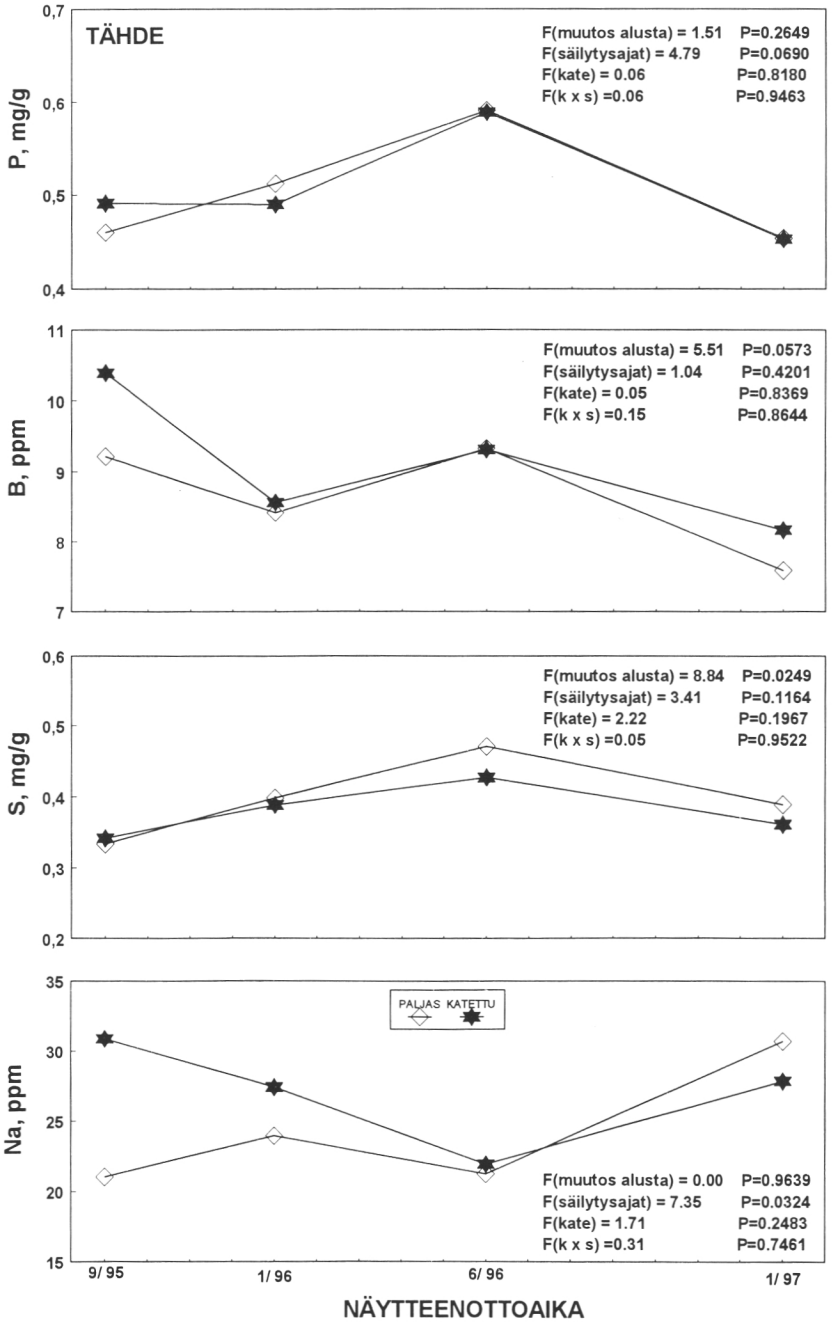
Liite 1. Kuusen tähteen kalium- (K), kalsium- (Ca), magnesium- (Mg) ja mangaani- (Mn) pitoisuus välivarastossa näytteenottoajan suhteen.



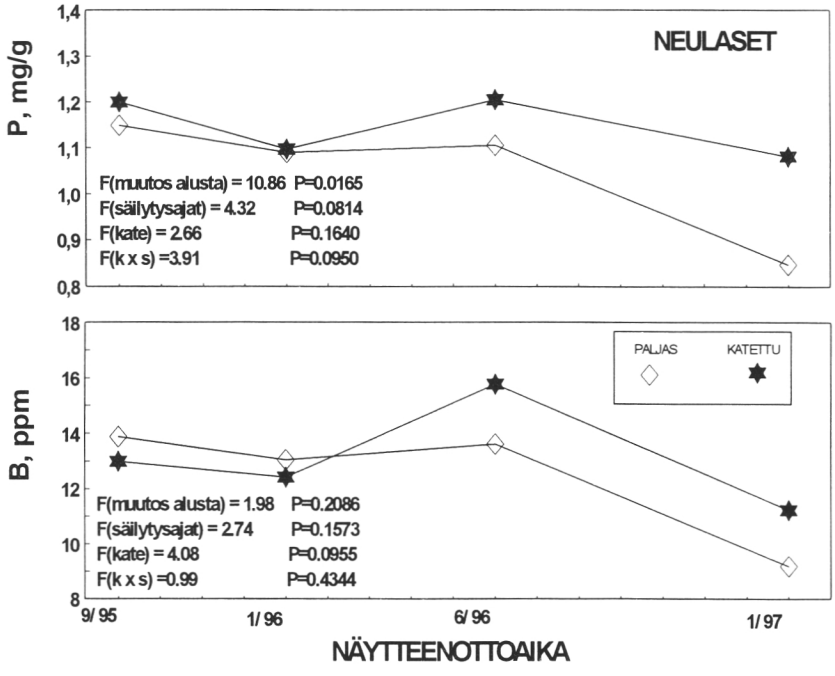
Liite 2. *Kuusen neulasten kalium- (K), kalsium- (Ca), magnesium- (Mg) ja mangaani- (Mn) pitoisuus välivarastossa näytteenottoajan suhteen.*



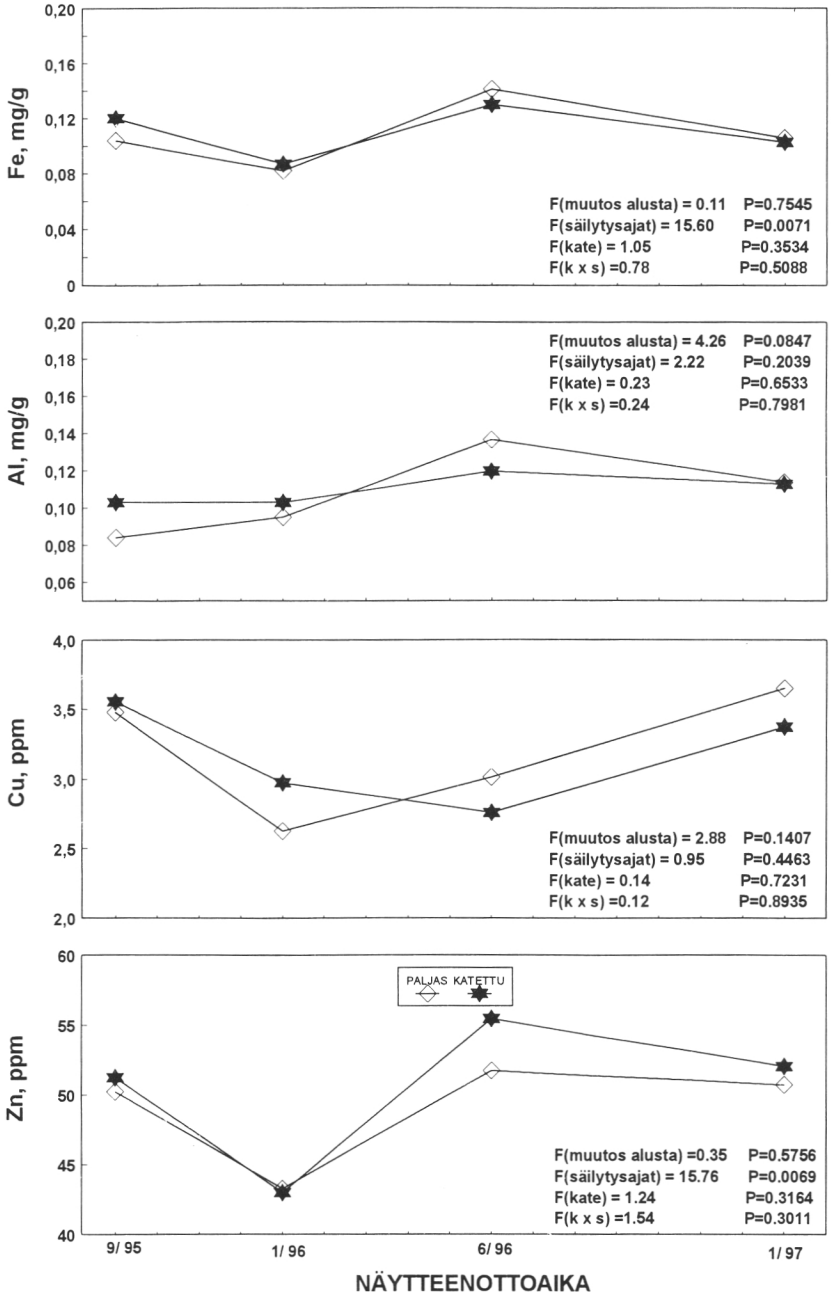
Liite 3. Kuusen tähteen fosfori- (P), boori- (B), rikki- (S) ja natrium- (Na) pitoisuus välivarastossa näytteenottoajan suhteen.



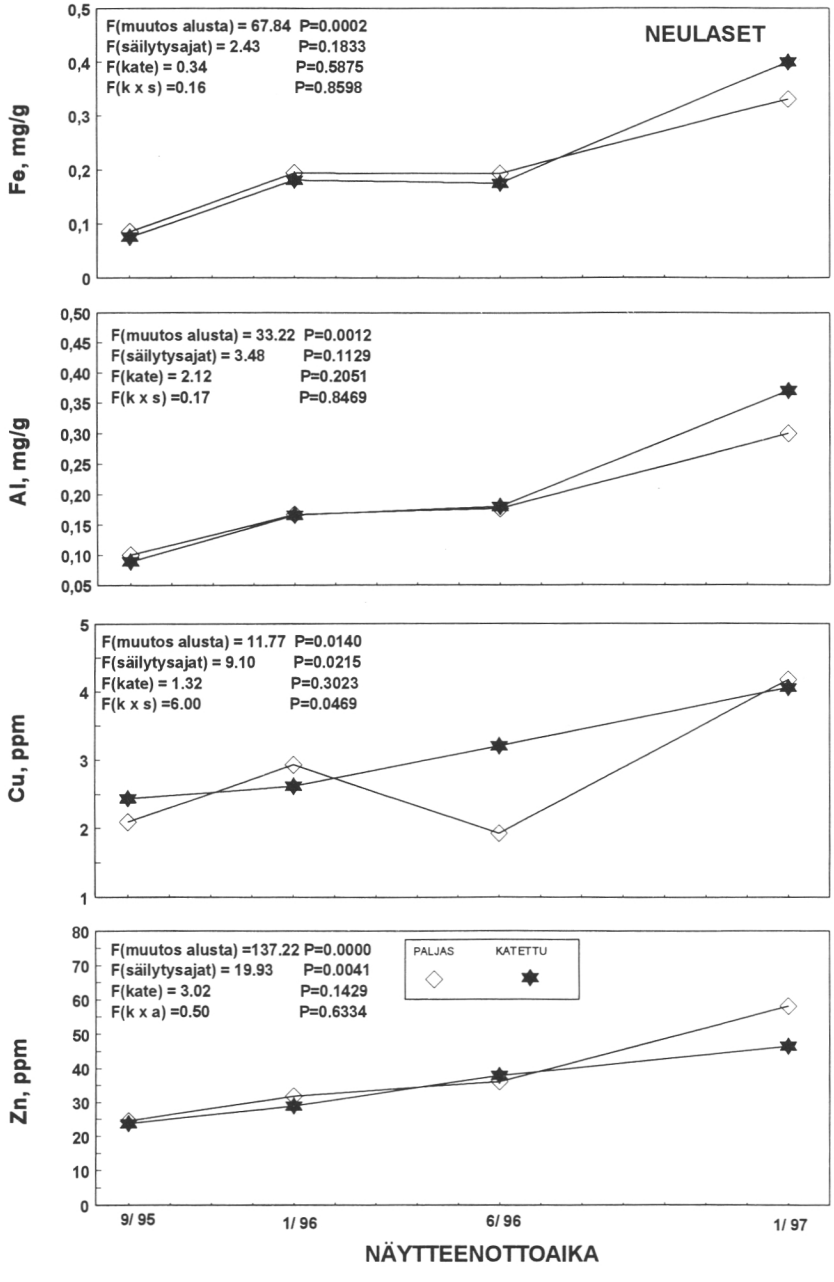
Liite 4. *Kuusen neulasten fosfori- (P) ja boori- (B) pitoisuus välivarastossa näytteenottoajan suhteen.*



Liite 5. Kuusen tähteen rauta- (Fe), alumiini- (Al), kupari- (Cu) ja sinkki- (Zn) pitoisuus välivarastossa näytteenottoajan suhteen.



Liite 6. *Kuusen neulasten rauta- (Fe), alumiini- (Al), kupari- (Cu) ja sinkki- (Zn) pitoisuus välivarastossa näytteenottoajan suhteen.*



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