Effects of Wood Properties and Chipping Length on the Operational Efficiency of a 30 kW Electric Disc Chipper

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Abstract

The development of efficient woody biomass comminuting processes and systems is of great importance for establishing bio-refineries. Using hybrid systems, which store excess energy from a diesel engine during periods of low loading for use during peak loading times, may yield higher energy efficiency compared to direct diesel-powered comminuting systems. In order to design hybrid chippers, a series of data are required on the load variations, in order to estimate the amount of energy that needs to be stored, and the peak power required. As a consequence, a detailed knowledge of the effects of wood properties on the direct power consumption during chipping is relevant. Therefore, the objectives of this work were to study the effects of wood properties (size and density) of pine, spruce and birch trees from early thinnings in the north of Sweden on the specific power and energy demand and time consumption of a 30 kW electric chipper while producing chips of two sizes. The study has generated models that replicate the processes, which can be used when designing efficient hybrid systems. The butt area had a significant effect on the power requirements when chipping and, along with chip length, had a significant effect on the energy requirements. Butt area and chip length also had a significant effect on the chipping productivity. There were small effects caused by the OD densities and by different species. These findings agree with previous studies and can be used for designing future hybrid chippers.

Keywords: chipper, energy consumption, productivity, efficiency, hybrid systems

1. Introduction

Forest biomass is increasingly utilized worldwide for different markets, such as construction, pulp and paper, chemicals and fuels. Before being used for industrial chemical and thermo-chemical processes, the wood must be comminuted. This is mainly carried out using mechanical processes such as chipping or crushing. For most processes, the quality of chips is defined by their homogeneity i.e. their particle size distribution. Thus, chipping is preferable to crushing since it produces particles with more predictable properties. For many processes, such as combustion of solids, a wide range of fuel particle sizes may significantly reduce the efficiency of the conversion process. Thus, the development of efficient woody biomass comminuting processes and systems is of great importance in order to achieve these targets.

In general, chippers operating at industrial sites are run with electric engines while machines operating at terminals, or close to forests, are run using diesel engines. Using electricity is preferred because of technical (easier to build and maintain), economic (cheaper and higher energy efficiency) and environmental (e.g. powered by electricity from renewable sources) benefits, among others. However, such systems require connection to a power grid which is only possible at industrial sites and some terminals. A third option is to use hybrid systems, which store excess energy from the diesel engine during periods of low loading for use during peak loading times, either in batteries, capacitors, flywheels or hydraulic storage devices (Sun et al. 2010). This means that the diesel engine is running under more efficient operating conditions and may also make it possible to recover some kinetic and potential energy, for instance from braking and from crane movements. Such systems may give higher energy efficiency compared to a direct diesel-powered system. For forest machines, potential savings from hybridization of 15–30% have been predicted (Swedish Forest Agency 2012). When designing a hybrid system for chipping, it is essential to understand the variations in the power required over time. Work to develop such systems is currently being undertaken in many different markets (Larsson 2012).

In order to design hybrid chippers, an understanding of the operational conditions is necessary. Data on load variations, to estimate the amount of energy that needs to be stored, and on the power that is required during peaks, are required. Direct measurements of the torque and rotation speed (Nurmi 1986, Liss 1987, Van Belle 2006, Spinelli et al. 2012) make it possible to focus on the chipping process and to eliminate the influence of other factors such as operator skill, the log loading system and engine efficiency. The exclusion of these factors was necessary in order to increase the accuracy in this study, but factors such as the loading system may increase the chipper idling time, usually accounting for approximately 10% of the productive work time (c.f. Röser et al. 2012), and could generate energy for charging an electrical accumulator.

The measurement of the operational fuel consumption as a measure of energy consumption for chipping is commonly carried out (e.g. Aman 2011, Yoshioka 2006). Magagnotti and Spinelli (2011) found that the energy used for chipping represents only about 3% of the energy return (solid fuel wood) for an industrial diesel drum chipper. However, diesel consumption makes up 36% of the operational costs for roadside chipping (Marchi et al. 2011) and the use of it significantly contributes to greenhouse gas emissions (Van Belle 2006).

There are many factors influencing the efficiency of chipping processes. The influence of chipper geometry (parameters such as knife sharpness, spouting angle, side angle and the number of knives) on disc chipping has been studied by Hartler (1986), Uhmeier (1995), Hellström (2008, 2009) and Abdallah (2011). Among the wood parameters, density, temperature (especially if the wood is frozen) and moisture content are known to influence the process (Kivimaa and Murto 1949, Papworth and Erickson 1966, Liss 1991). Kivimaa and Murto (1949) showed that an increase in chip length from 2.5 to 50 mm resulted in a reduction of energy requirement per produced energy by about 88%. The production of larger chips can decrease the required energy per tonne, per oven dry-tonne (OD t) and per cubic metre (m^3) significantly (cf. Nurmi 1986). However, Spinelli et al. (2012) showed that a novel knife design for disc chippers can significantly improve the quality of chips for small boilers, without reducing the machine energy efficiency. Wood piece size has a significant effect on productivity and energy demand, as efficiency was found to be proportional to the size of wood used (Liss 1987; 1991, Van Belle 2006, Ghaffariyan et al. 2013). Different tree species have different wood properties, e.g. depending on the growth rate of trees and species, the resultant wood has a different density/hardness, which also affects the chipping efficiency (Liss 1991).

Small diameter trees from early thinnings represent a great resource of biomass for refinery purposes in Finland and Sweden, where, respectively, 2.5 and 1.3 million m^3 of forest chips are produced annually from small trees, that is around 33% and 20% of the respective total potential resource (Routa et al. 2012). The main tree species in the region are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst) and birch (*Betula* spp.), all of which have different wood properties.

Knowledge about the influence of factors such as wood properties on direct power consumption during chipping is of relevance to the development of efficient comminuting systems.

Knowledge of the specific electricity consumption is of importance for designing hybrid systems i.e. describing the variation and peaks in workload that the electricity generator (diesel engine) must handle.

The objectives of this work were to study the effects of wood properties (size and density) of pine, spruce and birch on the specific power energy demands and time consumption of a 30 kW electric chipper when producing chips in two sizes, in order to create models which can be used when designing efficient hybrid systems based on similar chippers.

2. Material and methods

Delimbed stemwood logs from pine, spruce and birch were sampled from a thinning site in the coastal area of Västerbotten (64°06′ N, 20°37′ E and 60 m.a.s.l.), northern Sweden. The sampled stand had a density of 3200 trees/ha, an average tree size diameter of 8.1 cm at breast height (*dbh*) and an average height of 8.3 m. In total, about 30 m^3 of solid round-wood were harvested by thinning from below and transported to the experimental site (Biofuel Technology Centre in Umeå) a few days after cutting. The biomass was stored in three piles (by species) on open asphalted ground (uncovered) for 3 weeks before trials. The chipping trials were carried out over five days in October 2012. A to-

Table 1 Properties of trees per species and diameter size class (1–5) used in experiments using average and standard deviation (*Sd*) values. Diameter at butt end = D_{butt}, diameter at half length = D_{middle}, diameter at top = D_{top}, moisture content, wet basis = *MC*

Class, cm	Properties	Birch (n = 53)		Pine (n = 62)		Spruce (n = 61)	
		Average	*Sd*	Average	*Sd*	Average	*Sd*
1: ∅<9	D_{butt}, cm	7.91	0.77	7.73	1.01	8.05	0.70
	D_{middle}, cm	6.26	0.71	6.39	1.20	6.88	0.97
	D_{top}, cm	4.33	0.78	4.85	1.10	4.95	0.95
	Length, m	3.55	0.38	3.67	0.50	3.24	0.46
	Mass, fresh, kg	3.55	0.38	12.7	5.09	11.5	3.17
	MC, %	45.2	1.1	61.7	1.4	62.9	2.9
	Density, OD kg m^{-3}	499	46	407	26	383	44
2: 9≤∅<11	D_{butt}, cm	10.20	0.66	10.3	0.63	9.88	0.55
	D_{middle}, cm	7.96	0.63	8.54	0.85	8.19	0.51
	D_{top}, cm	5.94	0.99	6.57	1.05	5.97	0.51
	Length, m	3.75	0.44	3.61	0.31	3.72	0.68
	Mass, fresh, kg	16.80	2.86	20.9	4.81	19.3	4.77
	MC, %	44.1	0.1	62.0	0.2	65.0	2.9
	Density, OD kg m^{-3}	481	33	378	28	368	20
3: 11≤∅<12	D_{butt}, cm	11.60	0.27	11.5	0.27	11.5	0.29
	D_{middle}, cm	9.14	0.92	9.56	0.64	9.38	0.82
	D_{top}, cm	7.40	0.99	7.59	1.08	7.18	1.12
	Length, m	3.90	0.45	3.77	0.53	3.75	0.65
	Mass, fresh, kg	22.70	2.36	27.6	3.84	24.6	4.94
	MC, %	43.9	1.3	62.6	0.1	60.5	4.8
	Density, OD kg m^{-3}	482	24	378	25	403	40
4: 12≤∅<13	D_{butt}, cm	12.50	0.20	12.4	0.3	12.5	0.3
	D_{middle}, cm	9.90	0.90	10.3	0.5	10.3	0.6
	D_{top}, cm	7.15	1.33	7.74	1.70	8.40	1.32
	Length, m	3.88	0.49	4.04	0.44	3.74	0.42
	Mass, fresh, kg	26.10	4.38	32.7	2.81	30.3	4.45
	MC, %	43.6	0.6	62.6	1.3	62.3	0.5
	Density, OD kg m^{-3}	483	70	382	20	351	37
5: 13≤∅≤14	D_{butt}, cm	13.60	0.27	13.3	0.28	13.5	0.38
	D_{middle}, cm	11.30	0.71	10.9	1.69	11.4	1.02
	D_{top}, cm	9.50	1.03	9.54	1.04	9.63	1.52
	Length, m	3.63	0.56	3.60	0.39	3.40	0.65
	Mass, fresh, kg	34.20	5.58	35.9	4.9	34.5	5.1
	MC, %	44.1	0.3	60.9	2.5	60.8	1.5
	Density, OD kg m^{-3}	506	35	380	58	372	33

tal of 185 logs (63 pine, 61 spruce, 52 birch) were randomly sampled from the piles. Their lengths fell in the range 2.6–5.1 m, the diameters of their butt ends (d_{butt}) ranged from 5.6 to 14.4 cm and their mass (fresh weight) ranged from 3.5 to 43.5 kg. The total mass was 4189 kg. The diameter was measured for each log at the butt end (d_{butt}) at half length (d_{middle}) and at the top (d_{top}). The length and mass of each tree log were also measured. The logs were sorted by species and d_{butt} into five classes: 1) Ø < 9 cm, 2) 9 ≤ Ø < 11 cm, 3) 11 ≤ Ø < 12 cm, 4) 12 ≤ Ø < 13 cm and 5) 13 ≤ Ø ≤ 14 cm (Table 1). Each combination of species ($n = 3$) and diameter class ($n = 5$) (15 treatment combinations) was repeated three times. Each treatment combination was carried out using two different disc chipper knife settings (nominal lengths of 8 mm (»short«) and 12 mm (»long«)).

The chipper used was an Edsbyhuggen 250H (Edsbyhuggen AB, Sweden, year of manufacture 2011) with a 30 kW electric motor (Busck T1C 200L-4), which had an efficiency of 91.2–93.5% at full load (Swedish Energy Agency 2010) (Fig. 1). It had a hydraulic system (15 l) that drove a vertical pair of feed-rollers with an in-feed opening of 250×250 mm. The speed of the feed rollers was constant over the whole experiment. The chipper was equipped with a steel disc 825 mm in diameter and 38 mm thick, with 4 knives, giving a total mass of 205 kg. The disc formed an angle of 45° with the feed direction and rotated at 540 rpm. The 4 knives were adjustable to produce chips from 5 to 12 mm in target length. The chips produced were blown for 2.0 m into an expulsion tube by means of a fan and then collected in 1.5 m^3 plastic bags.

The first batch of logs was chipped to a length of 12 mm and the second to 8 mm. The electricity supply to the chipper was connected to a Fluke Power Log data logger during the experiment, giving instantaneous measurements of the electricity used by the engine. These data were logged at a sampling frequency of 2 Hz (1 observation every 0.5 seconds). The instrument was calibrated before starting the experiments. The chipping output was defined as the scaled mass of each log and its solid volume, which was calculated using the butt and top diameters with the length in the formula for the volume of a truncated cone. The dry density of each log was determined as the ratio between its dry mass and volume. Individual logs were manually fed into the chipper, butt end first.

To determine the moisture content (*MC*, wet basis), 30, five litre buckets of chips were collected (150 litres in total); the chips were collected from the output stream. Each bucket was filled by merging together sub-samples from three trees per diameter class (for each species and treatment combination). It was assumed that all trees in each diameter class had approximately the same *MC*. The *MC* was determined in accordance with CEN/TS 14774-2. The same oven-dried samples used for determining *MC* were used for the determination of particle size distribution in accordance with CEN/TS 15149-1. The sieves used were suitable for length classes 31.5 mm, 16 mm, 8 mm and 3.15 mm.

The time taken to chip each individual log (»chipping time«) was determined from the power measurements (the time was also manually recorded with a stopwatch for comparison). Chipping took place from

Fig. 1 Edsby chipper (left) and preparation of logs for experiments (right)

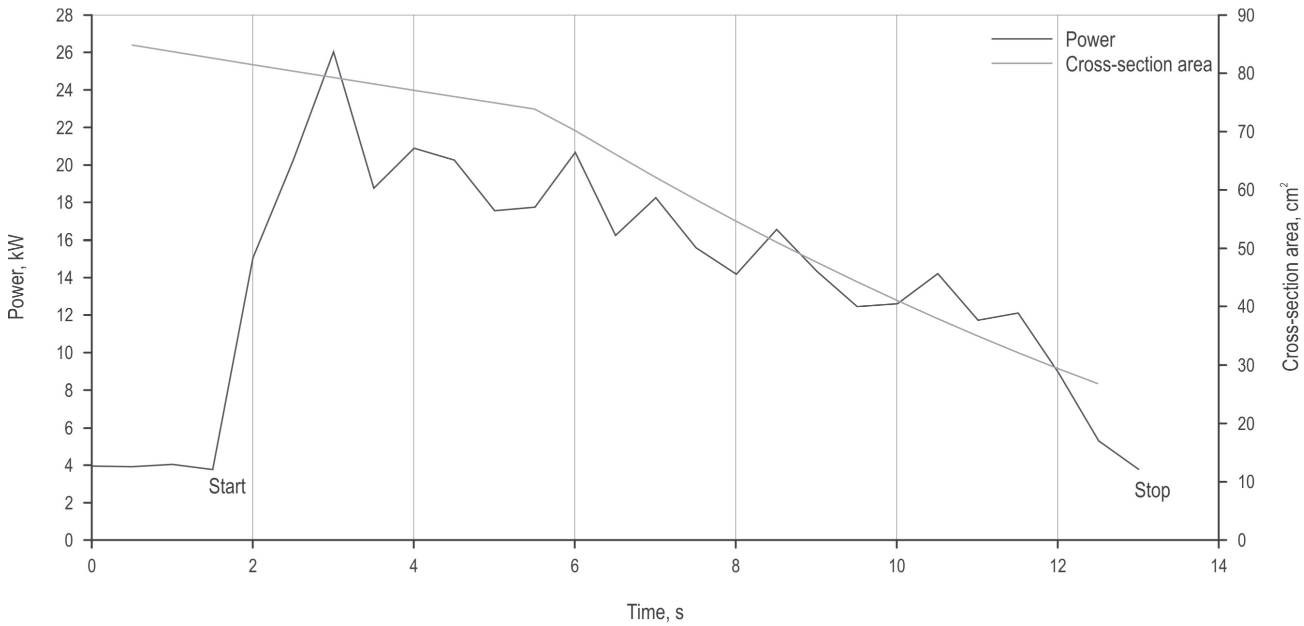

Fig. 2 Example of graph showing the chipping time and power demand for a pine stem (D_{butt}=10.4 cm, length= 3.23 m). The approximate cross-sectional area (grey curve) in contact with the knives is shown on the y-axis on the right (assumes constant feeding rate and linear variation in diameter from butt to top) and the power demand for chipping on the y-axis on the left

the moment that 1) the power had reached a threshold of at least 6.0–9.2 kW above the idle power of the chipper (in the absence of logs) and 2) the power consumption increased at a rate of 1 kW s^{-1}. The end of each repetition occurred when the power consumption had dropped below 5.5 kW at a rate of 0.6–0.7 kW s^{-1} (Fig. 2).

The absolute maximum power (kW) demand reached over the chipping time for each run represented the »maximum power demand«. The »energy

Table 2 Average results of the chipping experiments (standard deviation in parentheses). Required maximum power = *P*, energy demand = *E*, productivity = *Pr*

	Treatment					
	Chip length, 8 mm			Chip length, 12 mm		
	Birch (*n* = 26)	Pine (*n* = 31)	Spruce (*n* = 30)	Birch (*n* = 26)	Pine (*n* = 32)	Spruce (*n* = 31)
P_{max}, kW	25.0 (9.08)	24.1 (8.43)	21.7 (6.78)	22.1 (9.6)	24.9 (7.70)	25.0 (9.08)
E, kWh t^{-1}	3.91 (0.56)	3.33 (0.56)	3.27 (0.51)	3.37 (0.48)	2.77 (0.59)	3.91 (0.56)
E_{net}*, kWh t^{-1}	2.85(0.20)	2.37 (0.23)	2.32 (0.31)	2.35 (0.24)	1.97(0.14)	2.85(0.20)
E, kWh OD t^{-1}	6.98 (1.0)	8.77 (1.38)	8.45 (1.29)	6.02 (0.89)	7.27 (1.42)	6.98 (1.0)
E_{net}*, kWh OD t^{-1}	5.09 (0.37)	6.23 (0.64)	5.98 (0.81)	4.201 (0.43)	5.21 (0.38)	5.09 (0.37)
E, kWh m^{-3}	3.54 (0.64)	3.38 (0.66)	3.19 (0.43)	2.84 (0.51)	2.78 (0.63)	3.54 (0.64)
E_{net}*, kWh m^{-3}	2.57 (0.29)	2.39 (0.22)	2.26 (0.20)	1.98 (0.27)	1.99 (0.27)	2.57 (0.29)
Pr, OD t h^{-1}	2.33 (0.88)	1.86 (0.72)	1.74 (0.64)	2.28 (0.99)	2.36 (0.86)	2.33 (0.88)
Pr, m^3 h^{-1}	4.42 (1.71)	4.89 (1.94)	4.59 (1.60)	4.87 (2.09)	6.24 (2.41)	4.42 (1.71)
Feeding speed, m s^{-1}	0.19 (0.01)	0.19 (0.01)	0.19(0.01)	0.23 (0.02)	0.24 (0.02)	0.23(0.02)

*The power used when the machine was idling has been deducted from the total power

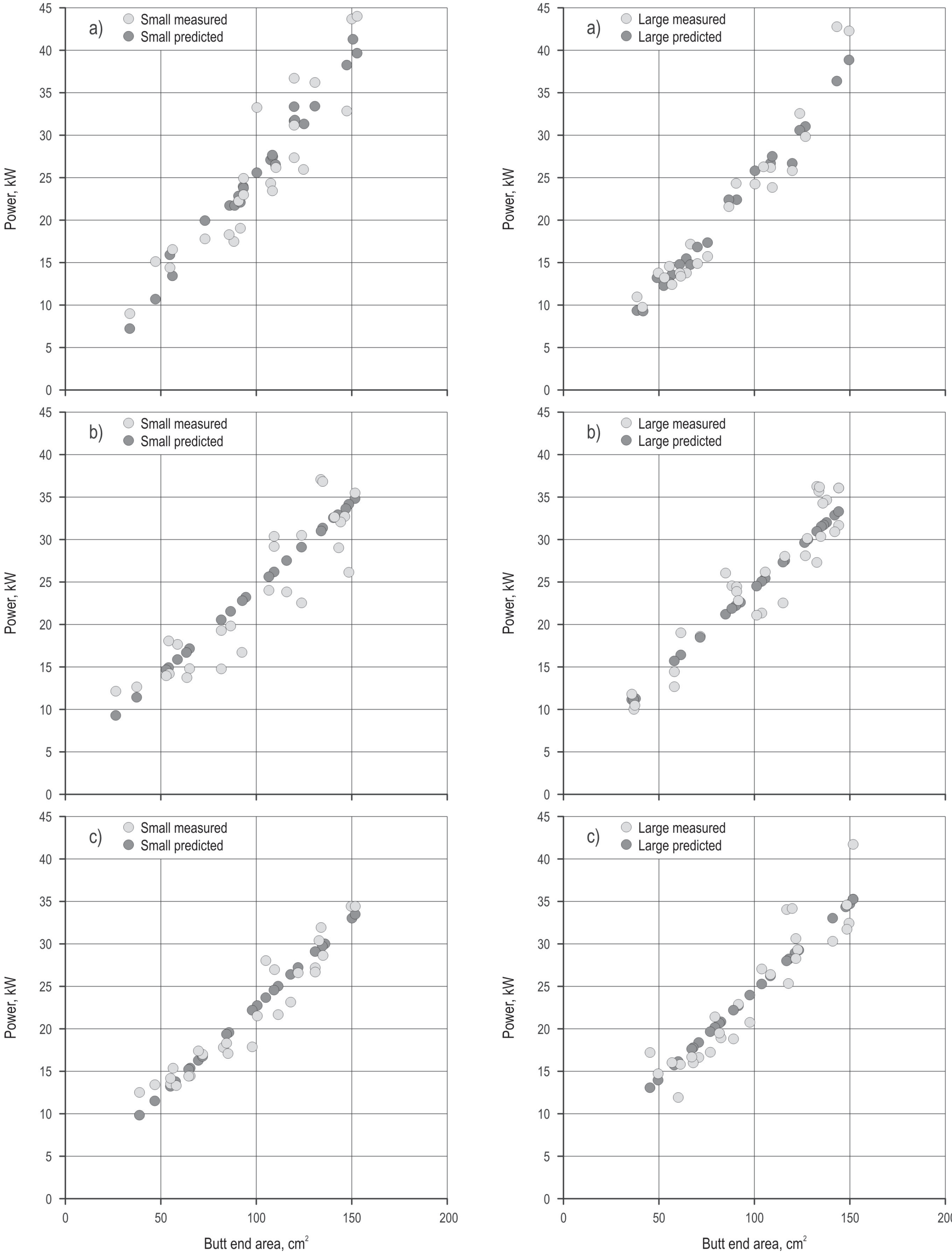

Fig. 3 Required maximum power (P_{max}) for chipping as a function of a log's butt-end area; a) birch, b) pine, c) spruce

demand« (kWh ODt^{-1}; kWh m^{-3}) was obtained by integration of the total power demand over the chipping time for each run divided by the mass/volume of each log. The mechanical energy required for the direct interaction between the knives and the wood, henceforth referred to as »net energy demand«, was calculated by integrating the difference between the total power over chipping time and the power used running the chipper in the absence of logs (estimated as the average power over at least 4 s immediately before or after the chipping). The »chipping productivity« (ODt h^{-1}; m^3 h^{-1}) was obtained as the ratio between the OD mass/solid volume of each log (output) and its chipping time.

Statistical analyses of data were carried out using the software Minitab 16 (Minitab Ltd). General Regression Models (GLM) were used to detect significant factors and differences ($p < 0.05$) between chipping treatments and to model the results in the experiment. For the analysis of required maximum power (P = kW), energy demand (E = kWh ODt^{-1}; kWh m^{-3}) and productivity (Pr = ODt h^{-1}; m^3 h^{-1}), the following hypothetic linear models were used:

$$P, E = \mu + \alpha_i^{(L)} + \beta_1(A) + \beta_2(\rho) + \varepsilon_i \quad (1)$$

$$ln(Pr) = \mu + \alpha_i^{(L)} + \beta_1(\ln(A)) + \beta_2(\ln(\rho)) + \varepsilon_i \quad (2)$$

Where μ = overall mean, α = factor fixed effect, β_1, β_2 = constants and ε = random error. »L« is the length class (»short« and »long«) of the chips, »A« is the butt area (cm^2) and »ρ« is the wood density (OD kg m^{-3}). These factors were selected based on the work of Liss (1987, 1991) and the specific experimental factors. A correlation test was used to exclude collinearity among factors. The original data were transformed to the natural logarithmic scale for the productivity models in order to obtain linear relationships. Only the significant factors ($p \leq 0.05$) were included into the final models.

The dataset contained 52, 63 and 61 observations, respectively, for birch, pine and spruce; 10% of the original observations for each of the species were randomly extracted and reserved as witness samples for model validation by using paired t-tests with a 5% significance level.

3. Results

The observed time for chipping each log varied between 11.5 and 24.9 s. There were obvious differences in required power (P) and energy demand (E) and in productivities (Pr) between the different tested chip sizes (Table 2).

The power required for chipping consisted of two parts: one part was proportional to the mass flow through the chipper (for a given chip size), with the other being constant, regardless of chip production (including friction and powering of the hydraulic pump for the feed-rolls). The maximum power required for chipping (P_{max}) was roughly proportional to the butt cross-sectional area of the stems, which explained most of the variability; it was almost independent of the chip length, which accounted for only slight variation (1%) (Fig. 3, Table 3). However, longer chips required significantly higher peak power than the shorter ones in the case of spruce (Eq. 5). In the case of birch, the maximum power absorbed was also directly correlated to the density, which accounted for a small part of the variability (2%) (Table 3, Eq. 3).

The higher mass flow through the chipper for thicker logs meant that the chipping energy per m^3 increased linearly with the reciprocal cross-sectional area (Fig. 4, Eqs. 9–11); the relationship was statistically significant in all cases (Table 3). This means that the chipping energy per m^3 decreased with increasing stem diameter. When the energy required for running the chipper whilst not chipping was subtracted (E_{net}), the dependence on stem diameter became less evident. The chip size also had a significant effect for all species (Table 3), since longer chips reduced the energy requirements (Eqs. 6–11), due to the minor refinement. The chipping energy per m^3 was about 20% less for a nominal chip size of 12 mm, compared to 8 mm. At the same time, an increase of OD density significantly increased the energy demand per m^3, while the density was inversely proportional to the energy per OD t, since density and output (OD t) are directly related. The wood density effect was generally less than the stem size and the chipping length, becoming significant only in some of the cases (Eqs. 8–9), (Table 3).

The significant relationships shown in Table 3 are described by the following equations:

$$P_{\text{max birch}} = -14.6240 + 0.2651 \cdot A + 0.0272 \cdot \rho; \text{ kW} \quad (3)$$

R^2 (adj) = 89.18%, F = 190.499, p < 0.001

$$P_{\text{max pine}} = 3.7002 + 0.2040 \cdot A; \text{ kW} \quad (4)$$

R^2 (adj) = 83.93%, F = 293.425, p < 0.001

$$P_{\text{max spruce}} = 1.6388 + 1.7673 \cdot L + 0.2089 \cdot A; \text{ kW} \quad (5)$$

R^2 (adj) = 88.47%, F = 208.157, p < 0.001

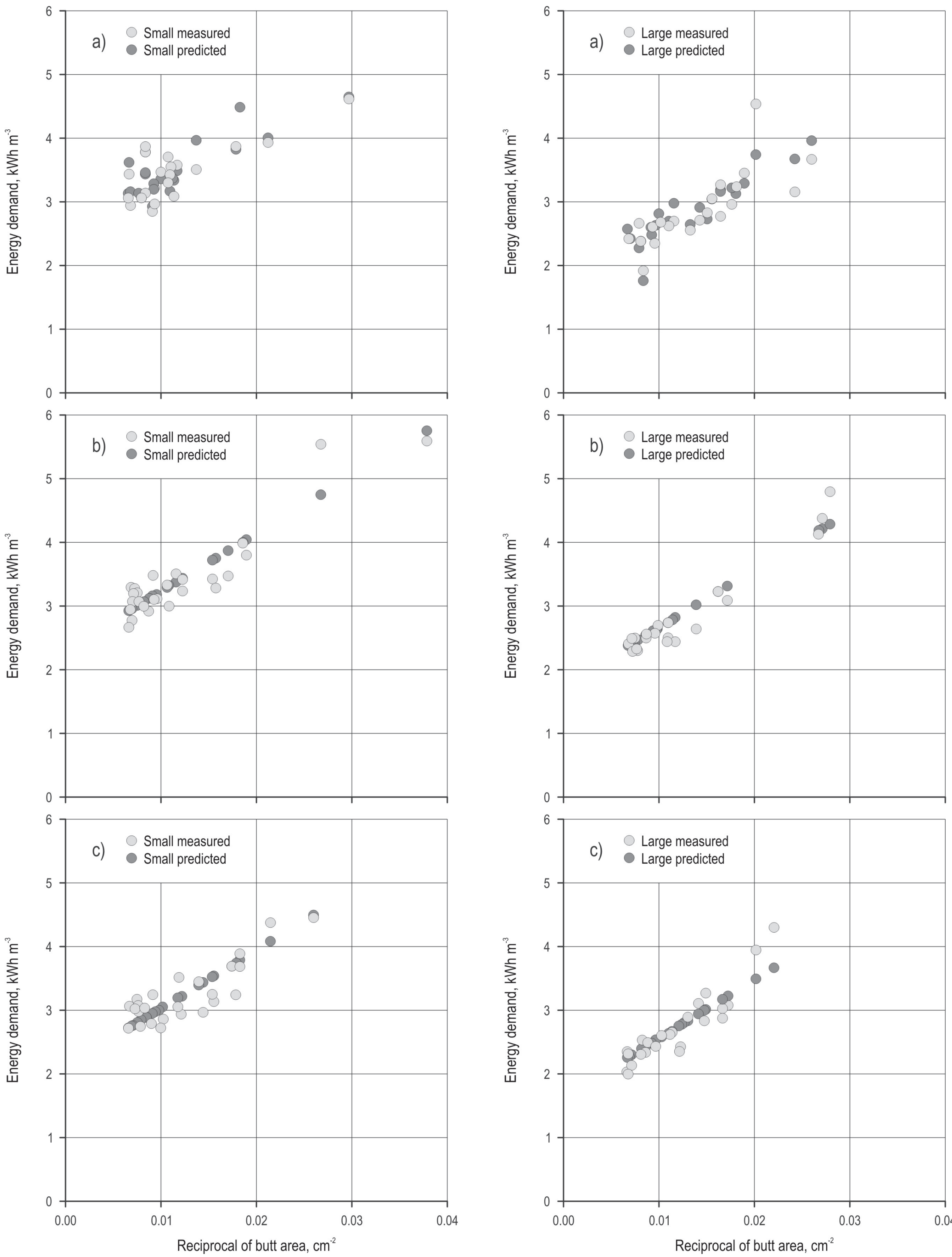

Fig. 4 Chipping energy per m^3 as a function of the reciprocal of butt area; a) birch, b) pine, c) spruce

Table 3 Analysis of variance table for maximum power (P_{max}) and energy demand (E) as a function of significant factors and variables included in the models

Birch	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
P_{max}, kW	Butt area, cm^2	1	3497.220	3497.220	366.98	<0.001
	Density, OD t m^{-3}	1	60.210	60.210	6.32	0.016
	Residual error	44	419.310	9.530		
E, kWh OD t^{-1}	Chip length, mm	1	15.408	15.408	65.52	<0.001
	Butt area, cm^2	1	29.451	29.451	125.23	<0.001
	Residual error	44	10.348	0.235		
E, kWh m^{-3}	Chip length, mm	1	3.141	3.141	47.73	<0.001
	Butt area, cm^2	1	6.984	6.984	106.12	<0.001
	Density, OD t m^{-3}	1	2.358	2.358	35.83	<0.001
	Residual error	43	2.830	0.066		
Pine	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
P_{max}, kW	Butt area, cm^2	1	3069.290	3069.290	293.43	<0.001
	Residual error	55	575.310	10.460		
E, kWh OD t^{-1}	Chip length, mm	1	30.654	30.654	50.12	<0.001
	Butt area, cm^2	1	84.703	84.703	138.49	<0.001
	Residual error	54	33.028	0.612		
E, kWh m^{-3}	Chip length, mm	1	4.596	4.596	51.54	<0.001
	Butt area, cm^2	1	19.890	19.890	223.02	<0.001
	Residual error	54	4.816	0.089		
Spruce	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
P_{max}, kW	Chip length, mm	1	42.810	42.810	6.66	0.013
	Butt area, cm^2	1	2591.600	2591.600	402.90	<0.001
	Residual error	52	334.490	6.430		
E, kWh OD t^{-1}	Chip length, mm	1	22.585	22.585	46.28	<0.001
	Butt area, cm^2	1	62.204	62.204	127.46	<0.001
	Density, OD t m^{-3}	1	30.520	30.520	62.53	<0.001
	Residual error	51	24.891	0.488		
E, kWh m^{-3}	Chip length, mm	1	3.021	3.021	51.91	<0.001
	Butt area, cm^2	1	9.695	9.695	166.57	<0.001
	Residual error	52	3.027	0.058		

$$E_{\text{tot birch}} = 5.2067 - 1.1704 \cdot L + 149.088 \cdot A^{-1};\ \text{kWh ODt}^{-1} \quad (6)$$

R^2 (adj) = 77.48%, F = 80.127, p < 0.001

$$E_{\text{tot pine}} = 6.5568 - 1.4683 \cdot L + 186.598 \cdot A^{-1};\ \text{kWh ODt}^{-1} \quad (7)$$

R^2 (adj) = 77.61%, F = 98.057, p < 0.001

$$E_{\text{tot spruce}} = 13.8361 - 1.3218 \cdot L + 236.837 \cdot A^{-1} - 0.02154 \cdot \rho;\ \text{kWh ODt}^{-1} \quad (8)$$

R^2 (adj) = 77.99%, F = 64.788, p < 0.001

$$E_{\text{tot birch}} = -0.3146 - 0.5782 \cdot L + 72.7758 \cdot A^{-1} + 0.0059 \cdot \rho;\ \text{kWh m}^{-3} \quad (9)$$

R^2 (adj) = 82.39%, F = 72.731, p < 0.001

$$E_{\text{tot pine}} = 2.3135 - 0.5697 \cdot L + 90.4222 \cdot A^{-1};\ \text{kWh m}^{-3} \quad (10)$$

R^2 (adj) = 83.45%, F = 142.135, p < 0.001

$$E_{\text{tot spruce}} = 2.1027 - 0.4704 \cdot L + 91.3848 \cdot A^{-1};\ \text{kWh m}^{-3} \quad (11)$$

R^2 (adj) = 81.18%, F = 117.475, p < 0.001

where L = 0 for the chip length »8 mm« and 1 for the chip length »12 mm«.

The productivities ($m^3\ h^{-1}$), based on effective chipping work time (excluding all waiting times), were strongly correlated to the stem diameter (Fig. 5, Table 4).The productivities were roughly proportional to the cross-sectional area of the logs fed into the chipper, while the feeding speed difference was small (0.04 m/s) almost constant with a little reduction in feeding rate seen for thicker logs (Fig. 5). As the chip length was increased from 8 to 12 mm, the productivity increased, and the difference between the two sizes was 22% at a cross-sectional area of 80 cm^2 (Fig. 5). The OD density became significant, in the case of spruce (Eq. 14), and it was directly correlated with the productivity in terms of OD t, due to the fact that the mass fed to the machine increased with log density. Based on the significant relationships found in the analyses (Table 4), the following two models were created:

$$\text{Pr}_{\text{birch}} = e^{-4.2031+0.1521 \cdot L} \cdot A^{1.0866};\ \text{ODt h}^{-1} \quad (12)$$

R^2 (adj) = 92.91%, F = 201.835, p < 0.001

$$\text{Pr}_{\text{pine}} = e^{-4.1708+0.2150 \cdot L} \cdot A^{1.0372};\ \text{ODt h}^{-1} \quad (13)$$

R^2 (adj) = 91.03%, F = 285.275, p < 0.001

$$\text{Pr}_{\text{spruce}} = e^{-11.5447+0.2011 \cdot L} \cdot A^{1.0713} \cdot \rho^{1.2157};\ \text{ODt h}^{-1} \quad (14)$$

R^2 (adj) = 92.03%, F = 208.781, p < 0.001

$$\text{Pr}_{\text{birch}} = e^{-3.5721+0.2166 \cdot L} \cdot A^{1.1030};\ \text{m}^3\ \text{h}^{-1} \quad (15)$$

R^2 (adj) = 92.68%, F = 292.080, p < 0.001

$$\text{Pr}_{\text{pine}} = e^{-3.5059+0.2170 \times L} \cdot A^{1.1032};\ \text{m}^3\ \text{h}^{-1} \quad (16)$$

R^2 (adj) = 92.26%, F = 334.658, p < 0.001

$$\text{Pr}_{\text{spruce}} = e^{-3.3025+0.1921 \cdot L} \cdot A^{1.0596};\ \text{m}^3\ \text{h}^{-1} \quad (17)$$

R^2 (adj) = 92.27%, F = 323.116, p < 0.001

where L = 0 for the chip length »8 mm« and 1 for the chip length »12 mm«.

The *t*-tests for validation showed, in all cases, *p*-values > 0.05. The smallest *p*-value was 0.124 in the case of Eq. 12 for birch productivity ($m^3\ h^{-1}$).

When the 12 mm chipper knife setting was used (long), birch logs with smaller diameters tended to result in finer chips than those with larger diameters (Fig. 6), with a similar trend for spruce but not for pine. When the 8 mm chipper knife setting was used (short) on pine and spruce, there was an opposite trend with smaller diameter stems resulting in coarser chips than the larger diameters. There were very few particles (< 0.5%) that did not pass through the 31.5 mm sieve, which means that the chip quality should be adequate for combustion in small-scale generators, even with the chipper set for 12 mm.

In general, if chipper settings (i.e. short and long) are considered together, a significantly higher mass fraction of the birch chips was in the size interval l8–16 mm, compared to spruce (p = 0.037). As a consequence, compared to the two softwoods, significantly (p = 0.015) fewer birch chips fell into the size interval 3.15–8 mm. Thus, birch chips tend to be slightly larger than softwoods in general; however the combination of species and chipping length masked those differences to a certain extent (Table 5).

4. Discussion

The results from this study mostly agree with findings in the literature on wood chipping processes. The

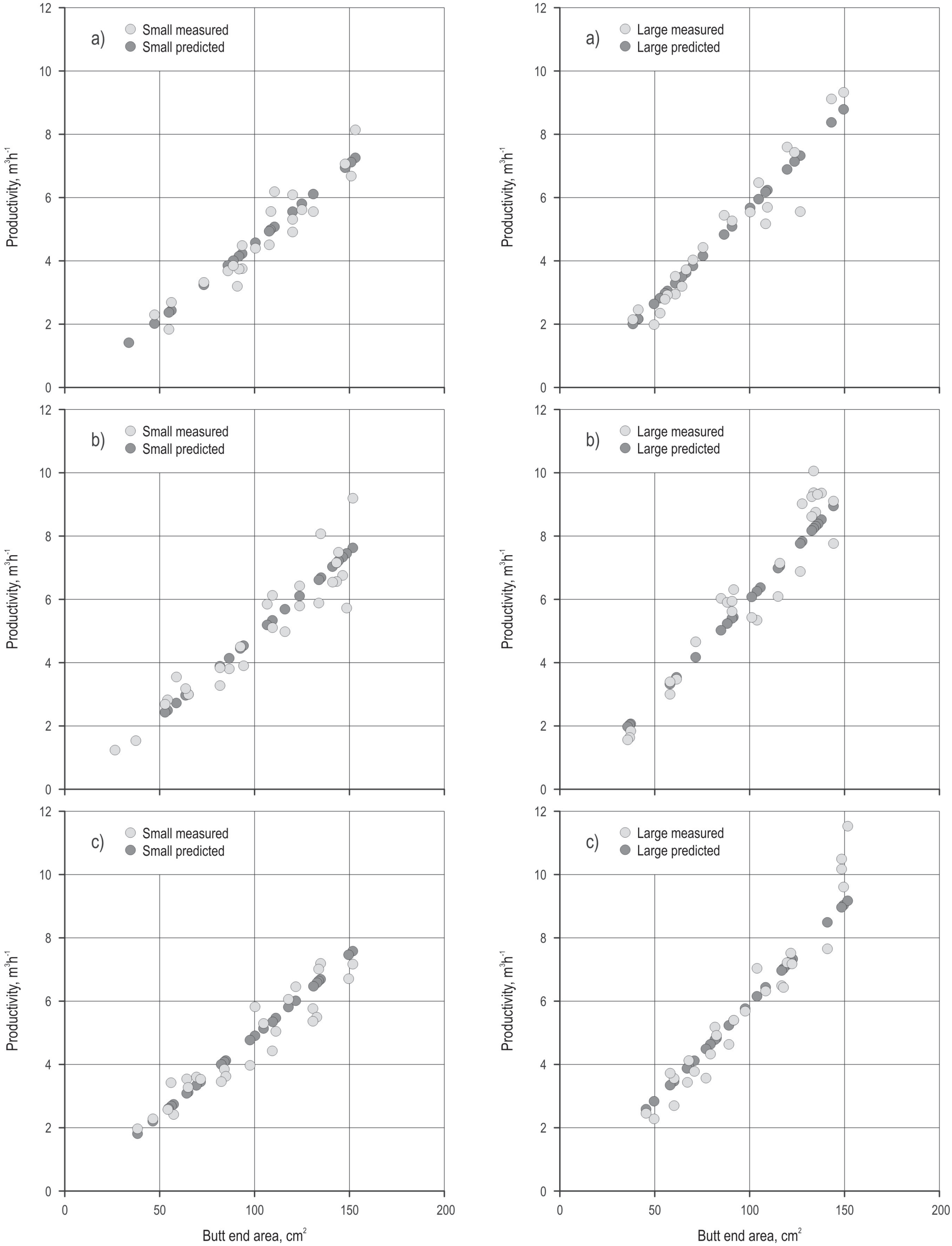

Fig. 5 Chipping productivity as a function of butt area; a) birch, b) pine, c) spruce

Table 4 Analyses of variance table for the productivity (*Pr*) as a function of significant factors and variables included in the models

Birch	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
Ln (*Pr*), OD t h^{-1}	Chip length, mm	1	0.232	0.232	14.89	0.001
	Ln (Butt area, cm^2)	1	8.009	8.009	514.83	<0.001
	Residual error	44	0.685	0.016		
Ln (*Pr*), m^3 h^{-1}	Chip length, mm	1	0.521	0.521	36.88	<0.001
	Ln (Butt area, cm^2)	1	8.253	8.253	583.91	<0.001
	Residual error	44	0.622	0.014		
Pine	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
Ln (*Pr*), OD t h^{-1}	Chip length, mm	1	0.592	0.592	26.96	<0.001
	Ln (Butt area, cm^2)	1	11.745	11.745	534.56	<0.001
	Residual error	54	1.186	0.022		
Ln (*Pr*), m^3 h^{-1}	Chip length, mm	1	0.607	0.607	28.89	<0.001
	Ln (Butt area, cm^2)	1	13.241	13.241	630.25	<0.001
	Residual error	54	1.135	0.021		
Spruce	Variables	*DF*	Adj *SS*	Adj *MS*	*F*	*p*-value
Ln (*Pr*), OD t h^{-1}	Chip length, mm	1	0.527	0.527	37.88	<0.001
	Ln (Butt area, cm^2)	1	8.109	8.109	582.65	<0.001
	Ln (Density, OD t m^{-3})	1	0.711	0.711	51.12	<0.001
	Residual error	51	0.710	0.014		
Ln (*Pr*), m^3 h^{-1}	Chip length, mm	1	0.505	0.505	35.86	<0.001
	Ln (Butt area, cm^2)	1	8.287	8.287	588.57	<0.001
	Residual error	52	0.732	0.014		

Table 5 Influence of species and chipper knife settings on the particle size distribution as percentage of total sieved mass

Particle size interval, mm	Birch		Pine		Spruce	
	Long ($n = 5$)	Short ($n = 5$)	Long ($n = 5$)	Short ($n = 5$)	Long ($n = 5$)	Short ($n = 5$)
<3.15	4.8 bc*	4.5 c	4.9 bc	6.2 a	5.7 ab	6.1 a
3.15–8	23.4 c	42.7 ab	32.1 bc	47.3 a	33.9 bc	45.7 a
8–16	65.9 a	48.4 bc	58.9 ab	44.8 c	55.5 abc	46.2 c
16–31.5	5.5 a	4.3 ab	4.0 abc	1.6 c	4.8 a	2.0 bc
>31.5	0.4 a	0.1 a	0.1 a	0.0 a	0.1 a	0.0 a

*The values in rows that do not share any letters are statistically different ($p \leq 0.05$) according to Tukey's test

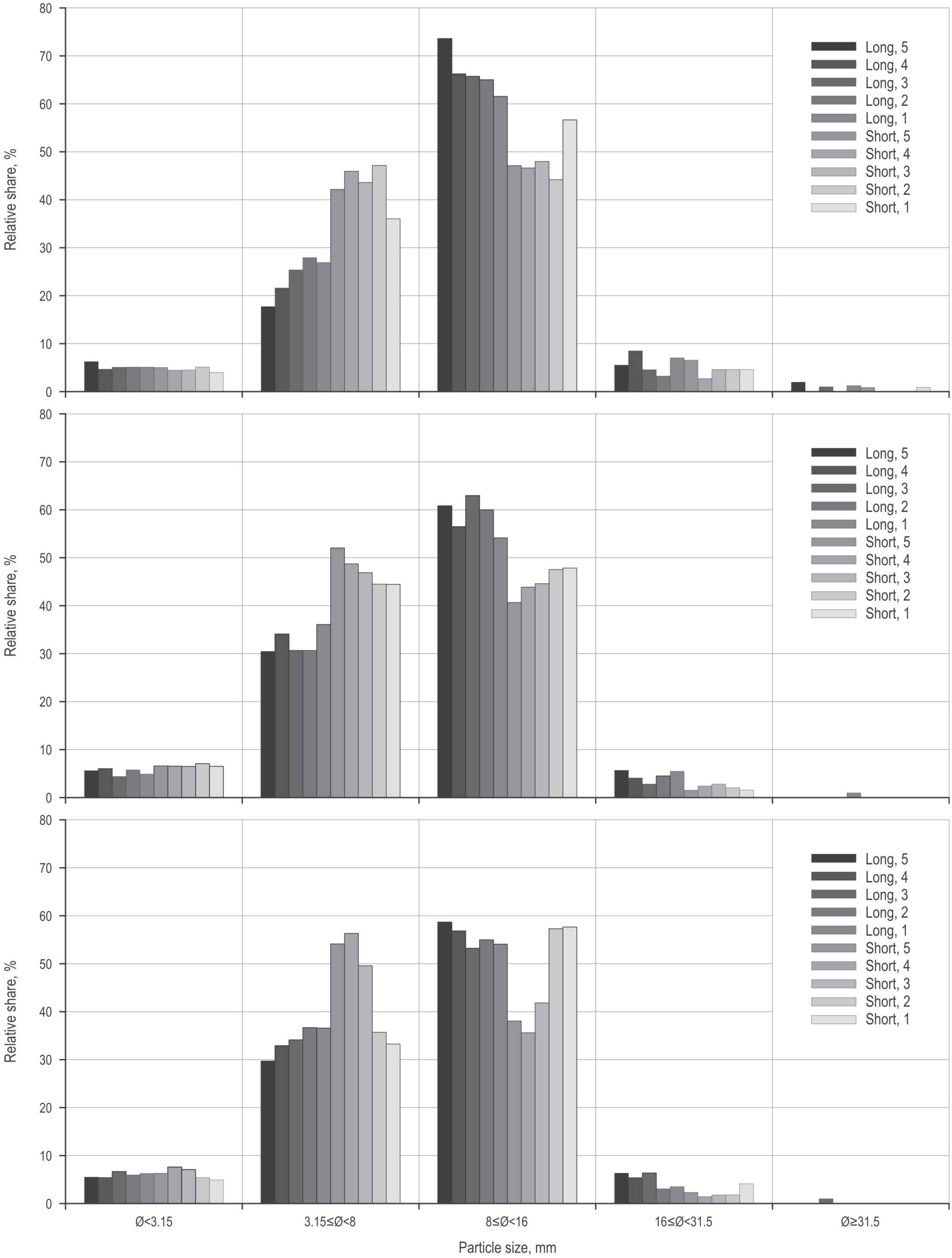

Fig. 6 Size distribution of the chips from birch (top), pine (middle) and spruce (bottom) for the two chippers settings (long/short chips) and tree butt-end diameter class (1–5)

maximum power required for chipping is not strongly affected by the chip length, but is mostly related to the diameter of a log's butt end. One explanation for this is that the butt end of a log causes the maximum »absorption« of power during the chipping process; the peak chipping power was 24–125% higher than the average absorbed when chipping the rest of the log. If the power required to run the chipper empty was removed from the total (i.e. when the chipper was idling), the net power for chipping was proportional to the butt area. This is in agreement with the results of Nurmi (1986) and Liss (1987), while Van Belle (2006) found an exponential relationship with the diameters of wood parts when chipping logging residues.

The productivity was significantly lower when producing shorter chips and more energy was used. This is due to the increased number of required cuts per wood piece, which slows down the process. These findings agree with Liss (1987, 1991), Nurmi (1986), Facello et al. (2013) and Spinelli and Magagnotti (2012). The energy consumption for the production of small chips (8 mm; 1.3–4.5 kWh m^{-3}) was in line with results found by Liss (1987), who studied tree species, similar stem sizes and similar feeding inclination angle (50°). However, Liss' (1987) measurements were made directly on the shaft connecting the tractor and the chipper, which means that it did not include additional energy losses in the process. In the present study, these losses amounted to 8.1% of the total energy requirements.

The energy requirements for chipping in this study corresponded, on average, to 0.085% of the produced fuel energy content (lower heating value). In most other studies, losses in the diesel engine are included in the measured values, which change the results considerably. For example, Liss (1987) estimated that the amount of energy produced by the diesel fuel was a factor of 3.3 larger than the resulting power on the tractor PTO shaft. He also considered that the fuel consumption under operational conditions would be doubled when the waiting time is included.

In this study, the productivity (ODt h^{-1}) increased with butt end area by up to a power of 1.04–1.09, whereas Van Belle (2006) found it to be 1.05. It seems that the productivity increase is almost proportional to the volume feeding rate and that the specific energy requirements can be reduced with more efficient feeding. Thus, an efficient use of the feed opening and available chipping time are both important. For very small trees and logging residues, feeding of many stems at a time should increase the efficiency. One way to reduce the waiting time could also be to have a larger feeding board. Nurmi (1986) found that, for a given cross-sectional area, bunches required less power when compared to single stems. This fact indicates that there are advantages to having the biomass compressed/bundled to diameter sizes that match the feeding inlet of the chipper in comparison to loose material (cf. Nurmi 1986).

As birch wood had a lower MC than the softwoods in this study, only the combined influence of OD density and MC could be estimated. However, for the studied three species, the experiment was representative for chipping fresh wood.

Although wood logs were all sampled from one stand, different levels of variability in wood densities were observed for the three species due to their different growth characteristics. This study made it possible to observe some of the effects due to this variability, but a larger sampling could have made it easier to investigate the effect of densities to a larger extent. Tree species seems to have some effect on the energy demand, due to the higher density of hardwood (birch), which corresponded to a 3–4% higher energy demand per m^3 than for softwood (i.e. pine and spruce) at a butt diameter of 10 cm (a butt-end area of 80 cm^2).

The feed to the chipper used in the present study had a disc side angle of about 45° and should be rather energy efficient compared to feeding the logs in perpendicular (90°) to the plane of rotation of the disc. Papworth and Erickson (1966) found that an increasing side angle decreased the specific energy consumption. In addition to reducing the waiting time for the chipper, the energy efficiency of the process can be improved, if it is possible to reduce the energy demands of the hydraulic system and the fan when no chipping takes place. Compared to a tractor-driven »Farmi« chipper of similar size studied by Van Belle (2006), the chipper used in the present study required about 3.5 kW when no feeding took place, below the 4.6–4.9 kW measured by Spinelli et al. (2013), but above the mechanically required minimum of 1.4 kW as measured by Van Belle (2006). Thus, it seems that the Edsby chipper could be improved. For example, Liss (1987) suggested using a conveyor instead of a fan for removing the chips and suggested that the waiting periods during crane movements could be used for emptying the chips as a way to reduce the power requirement.

The energy used to start-up the chipper was about 0.050 kWh, which is comparable to the chipping energy required for a single log. From the mass and diameter of the disc, and from the rotational speed of 540 rpm, it can be roughly estimated that accelerating and breaking the disc requires about 0.016 kWh. A disc with a larger inertial momentum would require less power; on the other hand, this would increase the energy needed for start-up. These observations give an idea of how much energy is wasted when starting or turning off a similar machine. In addition, it was observed that the idling power decreased when the chipper had warmed up. This was not expected for an electric engine and was probably due to the warming of the hydraulic oil, which affected the results (on average 1.3% of the maximum power demand).

During the experiments, some wood pieces about 10 cm long, from previous chipped logs, remained in the chipper in each run (i.e. wood pieces stayed between the feed rollers and the disc). This could also have generated some errors in the recording of absolute power; however, the error was almost constant between repetitions. Nevertheless, this could have had some influence on the quality of the chips. For this reason, we avoided sampling chips immediately at the starting of a new run. Different bouncing disturbances were observed in case of different species and chip lengths, thus a variable threshold was used to identify the starting of chipping process, and this could have also introduced some marginal uncertainty in the analyses.

With regard to the prospects of using hybrid power systems for chipping and grinding equipment, several basic decisions have to be made. The system may consist of only a chipper/grinder, or be a more complex system including other components such as a crane used for loading. Depending on the actual system, the engine load pattern will be different. The amount of energy to be stored and the required power will have to be estimated. When optimizing such a system, the cost of additional components such as an electric motor and a battery must be compared to the efficiency gains.

5. Conclusions

This study provides models which could be used for estimating the power and energy requirements, along with the chipping productivity, of a 30 kW electric disc chipper for chipping small diameter pine, spruce and birch trees from early thinnings in the north of Sweden.

The following factors have a significant effect on the power requirements and productivity when chipping small logs from thinnings: chip length, butt area and density.

The maximum power required for chipping was roughly proportional to the butt cross-sectional area of the stems, which explained most of the variability; it was almost independent of the chip length.

The energy needed per m^3 decreased by 4% for each centimetre increase in stem butt diameter. The chip size also had a significant effect, and the chipping energy per m^3 was about 20% less for a nominal chip size of 12 mm, compared to 8 mm. Increases in OD density increased the energy demand per m^3.

The productivities were roughly proportional to the cross-sectional area of the logs fed into the chipper. As the chip length increased from 8 to 12 mm, the productivity increased, and the difference between the two sizes was 20% at a cross-sectional area of 80 cm^2.

The chipping of hardwood (birch) corresponded to a slightly higher (3–4%) energy demand per m^3 than for softwood (i.e. pine and spruce).

These findings are in line with previous studies and the results could be used for designing small hybrid chippers.

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