Evaluating productivity, cost, chip quality and biomass recovery for a mobile chipper in Australian roadside chipping operations

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ABSTRACT: The Bruks mobile chipper was tested for chipping extracted non-merchantable stemwood at the roadside in Pine plantation in Victoria. The elemental time study method was used to evaluate the system productivity. The productivity, cost, biomass yield, remaining slash, chip quality (size classification and energy content), and fuel and energy consumption were analysed. Chipping extracted small logs at the roadside yielded a productivity of 43.88 GMt·PMH$_0^{-1}$ (19.4 BDT·PMH$_0^{-1}$). The average cost was about 16.96 USD·GMt^{-1} (38.36 USD·BDT^{-1}).

Keywords: mobile chipper; biomass; productivity; harvest residues; energy content; *Pinus radiata*; Australia

Biomass use has become an increasingly important part of the global effort to mitigate the effects of climate change, and forest biomass has been used extensively for renewable energy generation (DPI 2010). In the European Union (EU), biofuels are a growing source of electricity generation, of which more than 50% comes from wood and wood waste. In Sweden, as much as 90% of bioenergy comes from wood and wood waste. Europe produces 696 million m^3 of woody biomass each year (Hetsch 2008) using several harvesting technologies. Harvesting systems differ in the machinery applied in the supply chain, the material used as a source of biomass, and the applicability of the systems in various forest stands and terrain.

There are three major sources of biomass: harvesting residues, short-rotation plantations (poplars, willows and eucalypts), and wood harvested for use as fuel for heat or electricity generation (energy wood) from purpose-grown plantations or from native stands. Some wood produced in short-rotation plantations is used as energy wood. Residues and energy wood can be harvested using whole-tree or cut-to-length (CTL) systems. Chipping operations can occur at various points in the biomass supply chain: in the forest stand, at the roadside, and in the storage yard or in the mill (Spinelli, Hartsough 2001; Kärhä, Vartiamäki 2006; Kühmaier et al. 2007).

The Bruks mobile chipper is a biomass harvesting machine developed in Sweden. It can be used to collect and chip harvest residues in thinning and clear-cut operations, or to chip concentrated residues and/or logs at the landing or roadside (Desrochers et al. 1993). The case study in Canada by Desrochers et al. (1993) reported productivity of 14 GMt·PMH$_0^{-1}$ for the Bruks 1001 CT chipper mounted on a Timberjack skidder for roadside slash-pile chipping in Canada.

Biomass harvesting has only recently started to develop in Australia, so little is known about the efficiency of chipper-harvesters in Australian pine plantations. This study aimed to evaluate the productivity-cost of a Bruks chipper for chipping piles at roadside, the quality of the biomass product, and the quantity and composition of the remaining slash (after biomass recovery for bioenergy). This paper analyses the productivity, biomass yield, remaining slash, and energy flow of biomass harvesting that can be useful for biomass utilization planning.

MATERIAL AND METHODS

Study area

The flat study site was located in a clearfelled area of a radiata pine (*Pinus radiata*) plantation (Hancock Victorian Plantations) near Mount Gambier, Victoria, that had been harvested in July 2010 using a cut-to-length system with a harvester and forwarder, yielding 449.75 GMt·ha^{-1} of logs. At harvest, the trees were 31 years old with an average diameter at breast height (DBH) of 44 cm. Residue logs were chipped in October 2010 using the Bruks chipper. The study area and number of observations is presented in Table 1. Fig. 1 presents a map of the study area.

Logs in the roadside piles ranged 1.5–6 m with diameters of 40–75 cm. In the area from which the roadside stockpiles were collected, pulpwood was cut to 10 cm SED in a fixed length of 3.95 m. The roadside stockpiles included large-diameter rough edge-tree logs from the edges of the study area. The plot area of 17.75 ha was a large representative sample of the radiata pine plantations common in the southern half of Australia. The non-industrial and residue logs had been extracted and stacked in piles by a forwarder prior to this study.

Table 1. Study area for Bruks chipper trial

Location of operation	Area of block (ha)	Number of trucks loaded by chips
Forest roadside	17.75	27

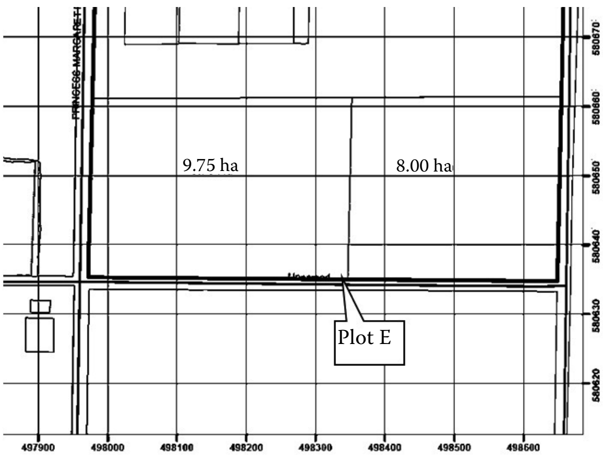

Fig. 1. Map of study area (scale: 1:5 000), plot E: extracted non-merchantable stemwood at the roadside

Equipment

In this study, a Bruks 805.2 STC mobile chipper was mounted on an Ecolog 594 C forwarder (Fig. 2). The 805.2 STC is a multi-function version based on the Bruks concept, featuring side infeed and a high-dumping chip bin. The machine can be installed on a forwarder, truck or other vehicle. A 450 HP (335.7 kW) Scania diesel engine powers the chipper, which can chip logging slash, parts of trees and roundwood up to a diameter of 50 cm. The capacity of the chip bin is 20 t. The Ecolog forwarder is 300 HP (223.8 kW) and its load capacity (chipper, bin and chips) is about 19,500 kg.

Productivity

An elemental time study method was used to evaluate productivity. The work cycle included chipping, loading into the truck and moving to the next pile. Work delays were recorded in three categories: personal, operational and mechanical. Total productivity was measured through truck weights of total green biomass delivered to the client. Productivity was calculated based on as-received tonnes and productive machine hours excluding all delays (PMH_0).

Assessment of remaining slash

To assess the remaining slash of the study treatment after biomass harvesting, 42 plots of 1 m^2 were laid out along transects within a systematic-random grid. All residues within these plots were

Fig. 2. Bruks mobile chipper for chipping residue piles at the roadside

weighed. From these, five plots in the study area were randomly selected to analyse the proportions of needles, branches, stemwood, cones and bark.

Assessment of chip quality

To assess chip quality from each treatment, a single 20 l sample was randomly collected from each load. The samples were used to measure energy content, contaminant rate (soil and sand) and chip size. The whole sample was placed on stainless steel trays and weighed, then dried in a fan-forced oven at a maximum temperature of 40°C overnight. All trays were then reweighed to determine the free moisture that had been lost on drying. The particle size distribution of each woodchip sample was analysed using a set of six square-meshed screens (sieves). The whole of each dried and weighed sample was shaken through a nest of screens with square apertures ranging from 3.36 mm to 37.5 mm, with the screen with the largest apertures on the top, decreasing to that with the smallest apertures on the bottom. The weight of the sample remaining on each screen, and the weight of material passing through the smallest screen were determined and calculated as a percentage of the whole mass of the sample used in the analysis. The size range included > 37.5 mm, 25–37.5 mm, 19–25 mm, 12.7 to 19 mm, 6.3–12.7 mm, 3.36–6.3 mm and < 3.36 mm.

The moisture content and ash yield of the dried samples were determined using a Leco MAC Analyser. The total moisture content of each sample was calculated from the weight loss on oven drying and the weight of the dried sample. The gross dry calorific value was determined using a Leco Calorimeter, according to the Australian standard coal analysis method AS1038.5.

Gross wet and net wet calorific values were calculated from the gross dry results, the total moisture and an assumed hydrogen content of 6% dry basis in the case of the net wet values.

RESULTS

Productivity

The net productivity and cost of each of the studied chipping methods are presented in Table 2 based on green metric tonnes per productive machine hour ($GMt \cdot PMH_0^{-1}$). Costs were derived from the machine owner's records and based on 75% of annual utilisation ($PMH_0 \cdot SMH^{-1}$). The hourly machine cost (without fuel consumption) was 256 $USD \cdot h^{-1}$ (PMH) based on the machine owner's records. Since the fuel consumption was recorded for the Bruks chipper and the Ecolog forwarder during this study, the machine cost was calculated by adding fuel costs to 256 $USD \cdot h^{-1}$ (Table 3).

The cost of extracting residues (non-industrial logs) by the forwarder was taken into account when computing harvest costs per green tonne. The proportions of time for each working element and delays in moisture contents are described in Table 6

Table 2. Productivity and cost of biomass harvesting using a Bruks mobile chipper based on green metric tonne (GMt) and bone dry tonne (BDT)

Chipping productivity		Chipping cost		Forwarding cost	
($GMt \cdot PMH_0^{-1}$)	($BDT \cdot PMH_0^{-1}$)	($USD \cdot GMt^{-1}$)	($USD \cdot BDT^{-1}$)	($USD \cdot GMt^{-1}$)	($USD \cdot BDT^{-1}$)
43.88	19.4	16.96	38.36	8.0	18.10

Table 3. Fuel consumption and machine cost for Bruks chipper

Fuel consumption ($l \cdot PMH^{-1}$)	Fuel cost	Hourly machine cost without fuel cost	Machine cost scheduled hours	Machine cost productive hours
	($USD \cdot PMH^{-1}$)			
54.6	38.8	256	294.8	393.0

Table 4. Biomass yield and biomass recovery from study block

Biomass yield ($GMt \cdot ha^{-1}$)	Biomass yield ($BDT \cdot ha^{-1}$)	Biomass recovery (%)
36.6	16.2	43.6

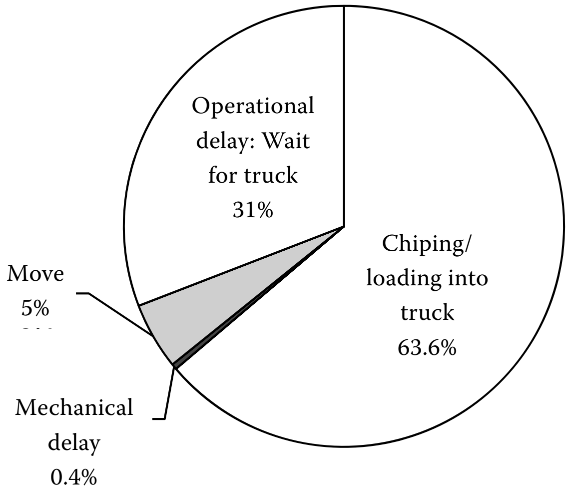

Fig. 3. Time elements for chipping the piles at the roadside Chipping time is the most time-consuming element of the Bruks work cycle

Table 5. Dried woodchip size classes

Size range (mm)	Range (%)
> 37.5	0.8
25–37.5	5.8
19–25	13.6
12.7–19	36.7
6.3–12.7	26.9
3.36–6.3	10.5
< 3.36	5.7

Table 6. Moisture, ash yield and calorific values of chip samples

Total moisture (%)	Ash yield (% dry basis)	Gross dry calorific value	Net wet calorific value
		(MJ·kg^{-1})	
55.8	0.6	19.9	7.0

moisture content is weight of water divided by weight of water plus dry wood

each work cycle for all treatments are illustrated in Fig. 3. The largest delay was waiting for trucks in the roadside chipping treatment (an operational delay).

Biomass yield

The green weight of chips delivered by the trucks was recorded for this treatment (Table 4). The biomass yield was about 36.6 GMt·ha^{-1} from the roadside chipping operation due to larger logs extracted by the forwarder to the roadside.

Quality of the biomass product

Chip samples were analysed to differentiate chip size, moisture content and calorific values of products for each of the study treatments. These assessments of chip quality were done to ensure the operations being studied met the strict chip quality requirements and to facilitate the comparison of the resulting productivity results to similar chip quality operations. The results are presented in Tables 5 and 6. For this case study, most chips ranged from 6.3 to 25 mm.

Moisture content varied among the samples. Chip samples from the roadside chipping treatment had moisture content of 55.8% with net wet calorific value of 7 MJ·kg^{-1} (Table 6).

Assessment of remaining slash

The quantity of slash remaining after biomass recovery by the Bruks chipper was 47.4 GMt·ha^{-1}. Within the harvest residue samples, the percentage by weight of the following components was evaluated: needles, bark, branches, cones and stemwood (Table 7). Branches, stemwood and needles comprised the largest proportion of the remaining slash.

Table 7. Remaining slash after biomass recovery

Remaining slash		Depth of slash (cm)	Needles	Bark	Branches	Cones	Stem-wood
(GMt.ha^{-1})	(BDT.ha^{-1})				(%)		
47.4	20.9	16	21.2	4.9	59.1	1.5	13.3

Table 8. Fuel consumption and emissions caused by the study treatment

Fuel consumption		CO_2	N_2O	CH_4	CO	NO_X
(l·PMH^{-1})	(kg·GMt^{-1})			(g·GMt^{-1})		
54.6	1.66	5751.0	3.7	8.7	38.1	85.8

Table 9. Energy flow for the study treatment

	Energy flow ($MJ \cdot GMt^{-1}$)
*Energy input (fuel consumption)	75.6
**Energy output (calorific value of chips)	7,000
Net energy	6,924.4

*the energy input is calculated from fuel consumption for slash collection, chipping and unloading into chip vans at the roadside

**energy output is calorific value of the chip including the reduction in energy value due to its moisture content

Fuel consumption and energy flow

The fuel consumption of the Bruks chipper was recorded. Energy consumed, energy created and emissions generated were analysed, taking into account working time and biomass yield (Tables 8 and 9).

DISCUSSION AND CONCLUSIONS

The harvesting treatment in which chipping was conducted at the roadside was more productive than collecting and chipping residues in the clearfelled area (Ghaffariyan et al. 2011a). For roadside chipping operations, the Bruks chipper did not travel onto the site to collect residues, which reduced the total work time per tonne. The chipper was also able to chip residues directly into the truck when available at the roadside. The small logs and stemwood were well-concentrated at the roadside, which improved chipping productivity (Table 2). During early tree felling and log extraction, some edge trees were heaped to the roadside piles, which may have increased the productivity. High moisture content in this treatment (Table 6) increased the green weight of each load, which might increase productivity when measured in green tonnes per hour.

The productivity of the Bruks chipper in the roadside piles in this study is higher than that reported for the Bruks 1001 CT in Canada (Desrochers et al. 1993), and may indicate greater efficiency of the Bruks 805.2 STC. It was also noted that the Canadian operation was chipping slash piles rather than stemwood logs resulting in a significantly smaller average piece size. According to the chipping model developed by Spinelli and Magagnotti (2010) and updated later by Ghaffariyan et al. 2012, the larger piece size will result in higher productivity.

The Bruks mobile chipper's net productivity (43.88 $GMt \cdot PMH_0^{-1}$) is lower than the recorded productivity of 58.18 $GMt \cdot PMH_0^{-1}$ for Husky Precision chipper working at the roadside to chip Eucalypt trees in Western Australia (Ghaffariyan, Sessions 2012) and is lower than that of Morbark chipper working at the roadside (59.4 $GMt \cdot PMH_0^{-1}$) to chip logs from first thinning in Pine plantation in South Australia (Ghaffariyan et al. 2012). Spinelli and Hartsough (2001) reported a productivity range from 11.2 to 27.4 $GMt \cdot PMH_0^{-1}$ for chipping stems and branches of softwood and hardwood by a trailer-mounted Pezzolato PTH 900/660M mobile chipper in Italy. The differences in all these cases can be attributed primarily to the difference in chipper power or size. The productivity recorded in our study is higher than reported for a Peterson Pacific chipper tested in whole Eucalypt tree chipping for biomass (33.90 $GMt \cdot PMH_0^{-1}$) in Western Australia, due to the smaller tree size of 0.10 m^3 in the latter study (Ghaffariyan et al. 2011b) and roadside chipping of logging residues with a mobile chipper in Turkey (Eker 2011). The differences in these cases are primarily attributed to the difference in piece size being chipped. The difference in productivity across these studies due to chipper size or piece size are supported by the Spinelli and Magagnotti (2010) and Ghaffariyan et al. (2012) infield chipping model mentioned above.

The roadside chipping treatment yielded the high amount of biomass per hectare. This might be due to a number of factors: (a) large edge-trees added to the residue logs when the site was harvested; (b) some industrial logs left in residue piles during primary extraction; or (c) higher site productivity for the roadside chipping block.

The high moisture content for extracted non-industrial logs at the roadside (Table 6) may have resulted from stacking the large non-industrial logs and stemwood (fibre-plus materials) into large piles which slowed drying. High moisture content resulted in low energy content (net wet calorific value).

The assessment of remaining slash (Table 7) showed that the percentage of branches and needles was larger than the percentage of stem, bark and cones in the harvest residues.

The average weight of remaining slash per hectare for this case study (extracted non-merchantable stemwood at the roadside) was similar to the 52 $GMt \cdot ha^{-1}$ reported by Smethurst and Nambiar (1990) for a clearfelled *Pinus radiata* plantation in Mount Gambier in which the residues were measured after CTL harvesting without any residue recovered for biomass.

The results of this study indicated that chipping extracted non-merchantable logs and residues at the roadside was a productive harvesting alternative. However, given the cost of biomass harvesting, future studies could compare the Bruks chipper with ordinary infield chippers (such as the Husky Precision) and less mobile roadside chippers to find the cheapest alternative.

While this study was limited to biomass collection and chipping, future studies could also investigate the impact of residue log recovery on establishment costs, fertilisation requirements depending on the level of slash removal, soil compaction and site sustainability. The effect of chipping method (roadside chipping or in-terrain chipping) on truck transport efficiency, such as the effect of moisture content and differences in trailer load compaction efficiency (dumping versus blowing chips into vans) offer further directions for future research.

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