SYSTEM ANALYSIS OF PRODUCTIVITY AND COST OF STUMP EXTRACTION FOR BIOFUEL USING MCR 500 EXCAVATOR HEAD

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Abstract
In the 30ies of the 20th century stump extraction was identified as one of the most prospective technologies of forest sector to secure deliveries of solid biofuel. Now we are returning to the same challenges having the same targets – to secure energy independence and competitiveness of forest sector. MCR 500 is the prototype of combined stump extraction and mounding bucket for caterpillar excavator produced in Latvia by the LSFRI Silava and engineering company Orvi SIA. The device is made for extraction of stumps with diameter up to 50 cm. Additional benefit of the device is its ability to prepare soil for the forest regeneration by making mounds. The article summarizes results of productivity trials of stump extraction using the MCR 500 head and following forwarding of the material. Data from earlier studies are used to characterize comminution and road transport of stumps and chips. In total 3.5 ha were extracted during the studies. A harvested amount of stumps was estimated using biomass equations. It will be updated in further comminution studies. Average stock of extractable biomass (stumps and coarse roots) on the experimental sites was 28 tons ha^{-1}. Productivity of stump extraction was 2.4...3.4 tons per efficient hour. Consumption of efficient time for scarification of soil was 3.4...4.3 hours per ha. Forwarding took 30 min per load (2.6 tons per efficient working hour). Prime cost of chips according to biomass equations is 9.78 Ls LV m^{-3}, according to expert judgement based harvested stock is 6.38 Ls LV m^{-3}.
Key words: stump harvesting, forwarding, prime cost.

Introduction

Forest bioenergy is becoming increasingly important for the forest owners and forest industry in Latvia. Logging residues from clear-felling for biofuel production has already become widely accepted technology in state and private forests in Latvia. The demand for forest fuel is expected to grow due to increase of consumption in district heating sector and forest industries, like pellet production (Kons, 2011). Besides extraction of harvesting residues form clear-felling, a variety of other forest residues can be utilized for biofuel production. Extraction of stumps started in Finland and to some extent – in Sweden (Eriksson and Gustavsson, 2008). If cost efficiency is used to evaluate potential of potential resources, stumps are located in the next position after harvesting residues from clear-cuts, both, in terms of available resources and harvesting costs (Lazdiņš and Thor, 2009). However, stump biofuel has specific quality characteristics, making use of stumps complicated in conventional biomass boilers (Walmsley and Godbold, 2009).

Stumps consist of wood and bark of a tree below the stump cross-section. Recovery is performed with heavy machines after harvesting and removal of roundwood. Excavators equipped with a special stump extraction buckets that can pull and split stumps into smaller pieces are usually used for production. The harvestable dry mass of a stump-root system is 23...25% of the stem wood biomass, for both spruce and pine (Hakkila, 2004; Eriksson and Gustavsson, 2008). As a comparison, the crown mass and stem ratio is typically 40...60% for spruce and 20...30% for pine in Finnish and Swedish studies (Hakkila, 2004). Information about extractable biomass of stumps of deciduous trees is limited (Lazdiņš and Thor, 2009). The energy content of stumps varies in different references. About 140to160 MWh ha^{-1} can be harvested according to studies in Finland (Hakkila, 2004); in other publications 170 MWh ha^{-1} are mentioned (Nylinder, 1979); Tekes reported 200 MWh ha^{-1} (TEKES, 2004). Stump recovery can also reduce the cost of site preparation for replanting (Eriksson and Gustavsson, 2008).

Information about possibilities to merge extraction of stumps and scarification of soil is limited; however, there is scientific evidenceof improved natural regeneration, less insect damages and reduction of root rot distribution in the next generation stand (Saarinen, 2006). Therefore, the aim of the study is to evaluate productivity and prime cost of simultaneous stump extraction and soil preparation with the experimental stump extraction head MCR-500, forwarding and conventional soil preparation with a disc trencher as a control. The experiment will be continued with forest regeneration studies, which will provide information about the impact of stump extraction on the whole forest regeneration cycle.

Materials and Methods

The trials were established in 3 forest stands managed by Ltd. "Rīgas meži" nearby Ogre city (Table 1). Pine (P) dominant stand (176-18) was on naturally wet mineral soil. It was used generally to adapt to the working method. Two spruce (S) dominant stands were located on naturally dry mineral soil

Table 1

Characteristics of experimental stands

Code	Area, ha	Dominant tree specie	Stand type	Age decade	Stand composition	Harvested volume, m^3
176-18	2.7	Pine (*Pinus sylvestris* L.)	*Myrtilloso-sphagnosa*	11	7P3S	949
98-4	3.8	Spruce (*Picea abies* (L.) H. Karst.)	*Hylocomiosa*	9	6S2P2B + A, Ga	1542
104-9	1.5	Spruce (*Picea abies* (L.) H. Karst.)	*Myrtillosa mel.*	9	7S2P1B + A, Ga	293

Table 2

Work elements

No	Stump extraction	Disc trenching	Forwarding
1.	Tower turns	Preparations in the field	Driving in stand
2.	Driving in stand	Scarification	Manipulations with crane
3.	Reaching	Manoeuvring	Catching
4.	Catching	Other operations	Loading
5.	Pulling	Non-work operations	Unloading
6.	Splitting	Repairs	Sorting
7.	Shaking	-	Other operations
8.	Dropping	-	Non-work operations
9.	Scarifying	-	Weighing
10.	Other operation	-	Empty driving
11.	Non-work operations	-	Loaded driving

(98-4) and drained mineral soil (104-9). Other tree species represented in the experimental stands were silver birch (S), common aspen (A) and black alder (Ga). All stumps of Ga and other rare deciduous species were left in the stands.

All stumps were measured (species, height, diameter and visually identifiable rotting signs) and marked before extraction. The harvesting, forwarding and soil scarification trials were implemented from September to November, 2011. The time studies were implemented according to work elements are listed in Table 2. Forwarder loads was weighed using CAS scales RW-15P. Field computer with SDI software was used to record work elements. Time consumption is expressed in centiminutes (cmin.), which is 1/100 part of a minute.

Quality of soil scarification was estimated after stump forwarding using transect method – a set of 25 m^2 large sample plots located after each 25 m on the longest diagonal of the sample plot. Area and distance between mineralized spots were measured; minimal distance between suitable planting spots is at least 1.5 m.

The prime cost of production of stump chips was calculated using adapted version of the Flis cost calculation model (Thor et al., 2008). Productivity figures for stump extraction and forwarding were taken from the productivity studies. Maintenance costs and investments were considered as for new machines. Productivity figures and maintenance cost of stump truck, crusher, loader and chip truck were borrowed from earlier studies (Thor et al., 2008) using updated values for fuel cost and salaries.

Biomass was calculated using by recalculation of stump level diameter to diameter at breast height ($D_{1.3}$) and application of biomass expansion equations to estimate above- and below ground fractions of stumps (1st for spruce and pine and 2nd – for birch). For other species equation of dominant tree specie was applied. The same equations were used in previous studies (Thor et al., 2008).

$$\begin{gathered} D_{1.3} = a + b * D_0; where \\ D_{1.3} - diameter\ at\ breast\ height, cm; \\ D_0 - diameter\ of\ \ stump, cm; \\ a - coefficient, 0.7\ for\ spruce\ and\ \text{-}1.89\ for\ pine; \\ b - coefficient, 0.74\ for\ spruce\ and\ 0.87\ for\ pine. \end{gathered} \quad (1)$$

$$D_{1.3} = -6.7 + 0.916 * D_0 + \frac{50.5}{D_0} \quad (2)$$

$$M_s = exp\left(-3.36 + 10.67 * \frac{D_{1.3}}{D_{1.3}+17}\right); where$$
M_s – dry biomass, kg. (3)

$$M_s = \exp\left(-3.97 + 11.05 * \frac{D_{1.3}}{D_{1.3}+15}\right) \quad (4)$$

$$M_s = exp\left(-3.68 + 11.54 * \left(\frac{2+1.25*D_{1.3}}{2+1.25*D_{1.3}+26} + 0.02 + 0.05\right)\right) \quad (5)$$

$$M_s = \exp\left(-6.39 + 13.37 * \frac{D_{1.3}}{D_{1.3}+8}\right) \quad (6)$$

$$M_s = \exp\left(-6.34 + 13.29 * \frac{D_{1.3}}{D_{1.3}+9}\right) \quad (7)$$

Table 3

Characterization of extracted stumps according to biomass equations

Object	Number of extracted stumps per ha^{-1}	Extractable biomass of harvested stumps, kg ha^{-1}	Share of extracted stumps, %		Prepared mounds per ha^{-1}
			from number of stumps	from extractable biomass of stumps	
176-18	377	22907	90	72	315
98-4	324	27752	71	62	355
104-9	384	24970	63	53	1496

Stump biomass was calculated using exponential regression equations: spruce – 3rd equation, pine – 4th equation (Marklund, 1988), birch – the 5th equation (Repola et al., 2007). Equation for birch includes also large roots; for spruce and pine biomass of extractable roots was calculated separately usingthe 6th and 7th equation (Marklund, 1988), respectively. Above-ground part of stump is calculated separately using volume formula of cylinder and wood density factors from the guidelines for the greenhouse gas inventories (Penman, 2003). In this article.total biomass of stump and large roots (D > 5 cm) is called extractable biomass.

Results and Discussion

Average extracted biomass of stumps and roots according to the biomass calculations is 25.7 tons ha^{-1}. Average share of extracted stump biomass is 62% of total extractable biomass of the measured stumps. Average extractable biomass of stump is 73 kg (Table 3). If compared to harvested roundwood stock, share of extracted stump biomass is 7%. According to other study in Latvia, it is 12% (Thor et al., 2008). The same study also noted incongruity between the Swedish biomass equations and actually extracted biomass.

Average productivity of stump extraction is 2.7 tons per productive hour, but if soil scarification is not accounted – 3.4 tons per productive hour. Average time consumption for soil scarification is 3.4 hours ha^{-1}, when sufficient number of planting spots are prepared – 4.3 hours ha^{-1}. The most efficient stump extraction was in object No 104-9 (Table 4). In optimal working conditions an excavator can prepare 346 mounds per productive hour (10 sec per mound), if time consumption for stump extraction relevant work elements is not accounted (Table 5). According to the study results, it is possible to scarify 0.29 ha per productive hour. Notably that in the last stand (104-9) the productivity of soil scarification was 3 times

Table 4

Productivity of stump extraction

Object	Productivity of stump extraction, tons per hour		Productivity of mounding, mounds per hour	Productivity of soil preparation, ha per hour	
	total productive time	productive time for stump extraction		modelled scarification time[1]	to prepare 2000 mounds ha^{-1}
176-18	2.4	2.7	106	0.34	0.05
98-4	3.0	3.7	106	0.30	0.05
104-9	2.5	3.8	346	0.23	0.17

1 Excluding time consumption for stump extraction and treatment.

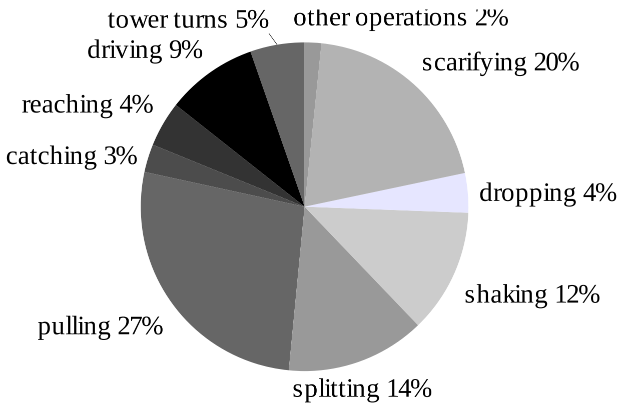

Figure 1. Share of work elements in productive time consumption.

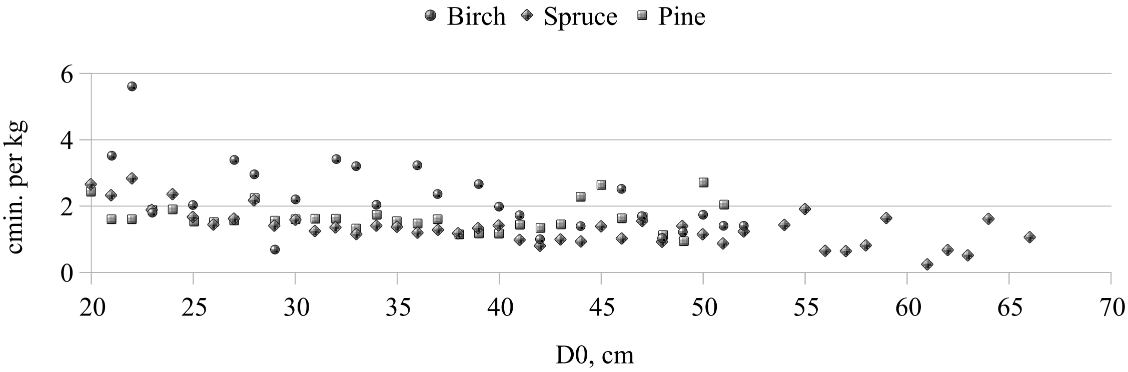

Figure 2. Productivity of stump extraction depending on dimensions of stumps.

higher than in the beginning. It is very probable that in real conditions the productivity will be similar to results obtained in the 104-9 or will be even better, if the pressure in the main cylinder of cutting knife is increased.

The most time consuming work elements are pulling, splitting and scarifying (61% of the total productive time, Figure 1). Technical improvements (increase of pressure in cylinder of the cutting knife) could increase productivity of pulling, splitting and shaking (cleaning of stumps). Productivity of scarifying can be increased by reduction of mounds per ha; however, much more studies are necessary to identify optimal number of the dedicated planting spots in different growing conditions.

Comparison of productivity of extraction of the stumps of different tree species and dimensions showsthat the MCR 500 can easily extract spruce stumps of any size and productivity constantly increases with the size of stumps (Figure 2). Productivity of extraction of birch stumps increases until D_0 reaches about 45 cm, then it becomes constant or decreases; however, productivity of large birch stumps is higher than of small stumps. Different results are obtained with pine stumps – there is no significant difference between productivity of smaller or larger stumps, but significant drop in productivity was observed, if D_0 of stumps is more than 45 cm. Productivity of the largest pine stumps is smaller than productivity of extraction of smaller pine stumps.

Comparison of work cycles, when 1 or several stumps are extracted approves hypothesis that simultaneous extraction is beneficial (Table 5), which means that in practice an operator should start pulling with the biggest stump, which will take also smaller surrounding stumps in a group of stumps, and not with smaller ones, which will be pulled out one by one.

Productivity of extraction of rotten stumps was significantly higher than average productivity figures. Time savings per stump, except time for soil scarification, was 17% on average. Most of reductions of the time consumption was in pulling and splitting operations (Figure 3). The damages by root rot may significantly reduce biomass of stumps, which is complicated to estimate using biomass equations; therefore, increase in productivity in practice might be lost in reduction of extracted biomass.

Average forwarder load was 7651 ± 272 kg. Average consumption of productive time in forwarding when calculated according to biomass equations was 22.8 ± 6.6 min ton^{-1} or 2.6 ± 0.8 tons per productive hour (Table 6). If time per load (20.3 min for loading and 10.1 min for unloading) is recalculated, results of the study are comparable with earlier stump

Table 5

Productivity of extraction of multiple stumps

Number of stumps per cycle	Share of total number of stumps	Share of total extractable biomass	Average extractable biomass of stump, kg	Average time consumption, seconds per stump
1 stump	85.9%	84.6%	69	62
2 stumps	12.4%	13.3%	76	60
3 stumps	0.9%	0.8%	62	58
≥ 4 stumps	0.8%	1.3%	41	27
More than 1	14.1%	15.4%	78	60

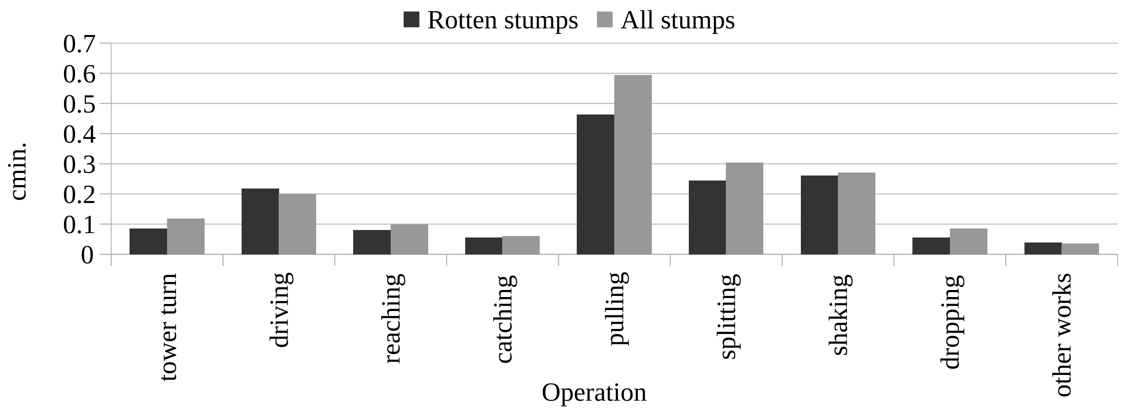

Figure 3. Productivity of extraction of rotten stumps – comparison of work elements.

forwarding studies (Thor et al., 2008); however, average load calculated by the biomass equations is 2 to 3 times smaller than in the same studies calculated according to weighed biomass. Average load according to biomass equations is 1.3 ± 0.4 tons, according to weighing data – 3.8 tons of dry mass.

The significant correlation was found between the load size and efficient time for loading ($R^2 = 0.78$). It can be expressed as a power regression (8th equation, Figure 4). It is also noticeable in Figure 5 that average load size depends on work conditions – it was considerably bigger in the object 98-4, where stock per ha was also greater than in other stands due to a larger dimensions of stumps.

$$E_0 = 1950.15 * M_5^{-1}; \text{ where}$$
$$E_0 - \text{productive time of loading, cmin.,}$$
$$M_5 - \text{biomass per load, kg} \quad (8)$$

Average productive time for scarifying of soil is 89 ± 18 min ha^{-1}. The soil preparation was more time consuming in *Myrtillosa mel.* stand type (106 min ha^{-1}).

Table 6

Productivity of forwarding

Value	Measurement unit	Numeric value
Average speed		
driving empty	km per hour	2.5 ± 0.2
driving loaded	km per hour	2.8 ± 0.2
Average load according to the biomass equations	tons	1.3 ± 0.4
Average unloading time	min load^{-1}	10.1 ± 0.6
Average loading time	min load^{-1}	20.3 ± 1.3
Average time per load, excluding driving	min load^{-1}	30.2 ± 1.3
Productivity		
total excluding driving	tons per hour	2.6 ± 0.8
total excluding driving and unloading	tons per hour	3.9 ± 2.3
unloading	tons per hour	7.9 ± 0.5

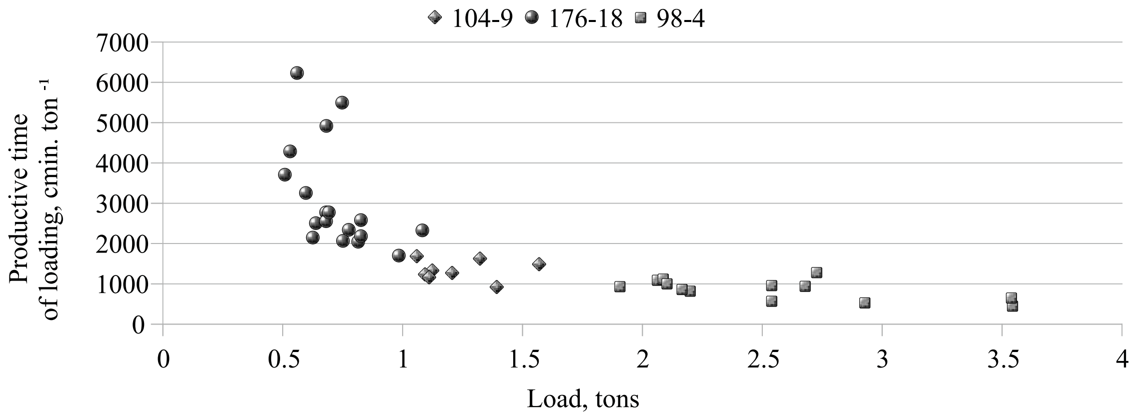

Figure 4. Productivity of loading depending on load size.

Table 7

Summary of prime cost calculation according to biomass equation figures

Position	Excavator	Forwarder	Stump truck	Crusher	Loader	Chip truck	Totals
Costs, thousands Ls year							
Investment	20.7	18.7	20.2	68.7	5.9	20.2	154.4
Staff	45.0	36.0	36.0	29.3	29.3	36.0	211.6
Operating	52.6	44.3	47.7	173.4	35.6	47.7	401.3
Total	118.4	99.0	103.9	271.4	70.7	103.9	767.3
Productivity (conversion factor ton to LV m^3 = 6), LV – loose volume							
LV m^3 per hour	12.50	7.54	18.84	60.00	250.00	25.93	-
LV m^3 yearly	217425	139640	64552	196632	768900	88875	-
Prime cost							
Ls LV m^3	2.35	3.07	1.65	1.42	0.10	1.20	9.78
Total cost, Ls ha^{-1}							1509
Proposed income, Ls ha^{-1} (price of chips assumed 7 Ls LV m^{-3})							1079
Compensation for soil scarification, Ls ha^{-1}							110
Net balance, Ls ha^{-1}							-319

Average productivity of disc trencher in the trials was 89 min ha^{-1}; cost of soil preparation with disc trencher 110 Ls ha^{-1}. Average number of planting spots in area prepared by the trencher was 1352 ± 50 per ha^{-1}, in area prepared by excavator – 1250 ± 72 per ha^{-1}.

According to the study results, prime cost of wood chips from stumps including stump extraction, forwarding, communition and road transport using the biomass equations derived values of harvested stock is 9.78 Ls LV m^3. Net balance according to average market price of wood chips is still negative (Table 7). If biomass is recalculated from forwarder loads obtained in other studies (Lazdinš et al., 2009), prime cost of chips would decrease to 6.38 Ls LV m^{-3}, if soil scarification is not included, thus, making stump extraction feasible.

Conclusions

1. The biomass equations used for calculations might underestimate biomass of stumps; therefore, the productivity figures and costs should be recalculated after comminution of stumps.
2. The experimental trials approved that simultaneous extraction of several stumps increases productivity. Extraction of rotten stumps also took less time – by 17% in comparison to average time consumption. However, it should be considered that biomass of rotten stumps might be smaller.
3. Average consumption of productive time for soil preparation, excluding loading and unloading of the device is 2.8 times less than during preparation of soil with excavator during stump extraction. This means that stump extraction, if directly compared to disc trenching is not feasible, but it might provide better growth conditions for seedlings, which can compensate additional cost.
4. Statistically significant difference between number of planting spots in extracted and control sites was found only in compartment No 176, where operator learned working method; therefore, the

result approves that stump extraction secures at least the same quality of soil preparation as disc trencher meeting national regulations on forest regeneration.
5. Productivity of forwarding per ton is twice less than estimated in other studies showing similar productivity results per load, which again points to necessity to use comminution derived data on produced biomass.
6. Prime cost of stump biofuel production, if biomass equations derived figures of productivity are used, is 9.78 Ls LV m^3; 55% of the cost relies to extraction and forwarding. Hourly cost of forwarder is significantly higher than service cost paid in trials, because old forwarder was used for the experiments and investment cost was not taken into account. The prime cost might significantly reduce after updating of the biomass figures; if expert judgement based values are used, production of chips would cost 6.38 Ls LV m^{-3}

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References

1. Eriksson L.N., Gustavsson L. (2008) Biofuels from stumps and small roundwood - Costs and CO_2 benefits. *Biomass and Bioenergy*. [Online] 32 (10), pp. 897–902.
2. Hakkila P. (2004) *Developing Technology for Large-Scale Production of Forest Chips. Wood Energy Technology Programme 1999–2003*. pp. 98.
3. Kons K. (2011) *Biomass Potential from Clear Fellings in Latvia*. Master thesis. Umeå, Sveriges lantbruksuniversitet, Institutionen för skoglig resurshushållning, pp. 44.
4. Lazdiņš A., Von Hofsten H. (2009) Technical and environmental issues of stump harvesting for biofuel production in Latvia. In: *Annual 15th International Scientific Conference Proceedings*. 2009 Jelgava, Latvia University of Agriculture. pp. 155–162.
5. Lazdinš A., Von Hofsten H., Lazdiņa D., Lazdāns V. (2009) Productivity and costs of stump harvesting for bioenergy production in Latvian conditions. In: *Proceedings*. 2009 Jelgava, Latvia University of Agriculture Faculty of Engineering. pp. 194–201.
6. Lazdiņš A., Thor M. (2009) Bioenergy from pre-commercial thinning, forest infrastructure and undergrowth – resources, productivity and costs. In: *Annual 15th International Scientific Conference Proceedings*. 2009 Jelgava, Latvia University of Agriculture. pp. 147–154.
7. Marklund L.G. (1988) *Biomassafunktioner för tall, gran och björk i Sverige*. (Biomass equations for pine, spruce and birch in Sweden) Sveriges lantbruksuniversitet, Institutionen för skogstaxering. pp. 73.
8. Nylinder M. (1979) *Relationstal, träbränslen - olja* (Conversion factors, fuelwood – oil). In: Rapport - Sveriges lantbruksuniversitet, Institutionen för virkeslära ; nr. 110. Uppsala, [Sveriges lantbruksuniversitet, Institutionen för virkeslära]. pp. 45–47.
9. Penman J., Gytarsky M., Hiraishi T., Krug T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., Wagner F. (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. 2108 -11, Kamiyamaguchi, Hayama, Kanagawa, Japan, Institute for Global Environmental Strategies (IGES), pp. 587.
10. Repola J., Ojansuu R., Kukkola M. (2007) Biomass functions for Scots pine, Norway spruce and birch in Finland. *Working Papers of the Finnish Forest Research Institute*, 53, p. 28.
11. Saarinen V.M. (2006) The effects of slash and stump removal on productivity and quality of forest regeneration operations--preliminary results. *Biomass and Bioenergy*. 30 (4), pp. 349–356.
12. TEKES (2004) *Increased use of forest fuels to expand the raw material base. Stumps – an unutilised reserve*. pp. 2.
13. Thor M., Iwarsson-Wide M., Von Hofsten H., Nordén B., Lazdiņš A., Zimelis A., Lazdāns V. (2008) *Forest energy from small-dimension stands, infra-structure objects and stumps (research report)*. Skogforsk, Uppsala. p. 75.
14. Walmsley J.D., Godbold D.L. (2009) *Stump Harvesting for Bioenergy – A Review of the Environmental Impacts*. Forestry (2010) 83 (1): pp. 17–38.