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Research paper

Productivity of harvesting dense birch stands for bioenergy

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ABSTRACT

Marginal lands could be utilized for increasing energy biomass production independent of industrial roundwood procurement. Dedicated energy biomass production systems on such sites would be based on low stand establishment cost, clear-cutting at an early stage, and coppice regeneration. Harvesters designed for the processing of industrial roundwood are inefficient or too costly to use in small-diameter and dense stands, while insufficient cutting capacity and uneven space distribution of trees limit the use of modified agricultural harvesters developed for short-rotation woody-crop plantations (e.g. willow). We constructed time consumption models for clear-cutting and forwarding of whole trees from unthinned, small-diameter stands. The data originated from naturally afforested downy birch-dominated stands located in a cutaway peat production area in northern Finland. Stand age varied from 14 to 29 years and stand density was 5150–160,250 trees per hectare. In clear-cutting, a medium-sized forest harvester equipped with an accumulating felling head fitted with a circular saw disc was used, and subsequent forwarding was done using a modified medium-sized forwarder. Cutting productivity was 3–11oven-dry tons (ODt) per effective hour (E_0-h), and was highly dependent on stand characteristics (e.g. mean whole-tree volume). At a distance of 300 m, for example, the productivity of forwarding in the time study plots was 6.7–10.4 ODt E_0-h^{-1}. Our study indicates that energy biomass can be harvested from young downy birch thickets efficiently by clear-cutting with appropriate machinery.

1. Introduction

Mitigation of climate change by reducing greenhouse gas (GHG) emissions is the main target of international climate policy [1,2]. In Nordic countries, substituting fossil fuels with wood-based fuels plays a significant role in the reduction of GHG emissions. In Finland, for example, the consumption of forest chips is to be increased up to 13.5 million m^3 (ca. 25 TWh) by 2020 [3]. In 2014, 8.2 million m^3 of forest chips were consumed in Finland [4]. Wood biomass used in energy generation is harvested for the most part as a by-product of industrial roundwood (e.g. small-diameter thinning wood, logging residues), and uneven regional distribution of energy biomass potential may hinder reaching the target set for forest chip consumption [5]. Dedicated bioenergy production in non-industrial sites could increase energy wood potential independently of the demand for industrial roundwood.

Downy birch (*Betula pubescens* Ehr.) shows potential for profitable short-rotation energy biomass production on cut-away peatlands without the need for government subsidies [6]. After afforestation these stands would sequester atmospheric carbon [7,8], and vegetation also retards soil erosion [9]. Biomass production would be based on natural afforestation followed by an early clear-cut and coppice regeneration. Also, set-aside areas such as roadsides, field margins and power line corridors, offer the potential for increasing the production of energy biomass [10].

The stand data for the feasibility study above [6] was collected from six naturally regenerated 15–26-year-old downy birch thickets. Clear-cutting of such stands or coppicing is not traditional Nordic forest management practice, and the cost of harvesting was considered an important source of uncertainty in the profitability calculations. Cut-to-length harvesters designed for industrial roundwood are inefficient or too costly to be used in small-diameter and dense stands. They also have unnecessary features for the harvesting of energy biomass [11,12], and handling small-sized and crooked trees may also present technical limitations [13,14]. Most machines used in short-rotation coppice (SRC) willow and poplar plantations encounter difficulties when harvesting trees with a butt diameter larger than 10 cm [15]. In SRC systems, there is

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strong interest in increasing rotation lengths and diversifying tree species, and therefore scaled-up forage harvester prototypes capable of handling trees up to 15 cm at stump have been developed [16]. Uneven and dense space distribution, however, limits their use in naturally afforested stands. Fuel chips produced with such one-process operation are wet, which results in low heating value and greater material losses during storage phase [17]. Furthermore, investing in purpose-built machinery with a narrow field of application involves an economic risk to the harvesting entrepreneur [6]. In the feasibility study about short-rotation biomass production with of downy birch [6], time consumption of whole-tree cutting was calculated by extrapolating a clear-cut model based on data from power line corridors, where an average basal-area weighed breast-height diameter (DBH$_{(BA)}$) of the trees was only 2–4 cm [10]. The 15-ton harvester used in the time consumption study above [10] was equipped with a Bracke C16.b felling and bunching head. The studies from the clear-cuts of natural coppice stands in southern Europe e.g. Refs. [18–20] are not applicable to coppice stands in the Nordic countries, due to great differences in stand properties, harvesting conditions, and forest management and harvesting practices. Also applicable models are lacking for estimating the productivity of forwarding small-diameter whole trees in clear-cuts of in birch coppice stands.

In the present study, we measured the productivity of whole-tree cutting and forwarding of small-diameter trees from clear-cuts of mixed birch-dominated stands with machinery used in conventional energy wood harvesting. The data were used for constructing time consumption models for cutting and forwarding to be used as a basis for cost calculations.

2. Materials and methods

2.1. Stand data

The studies were performed in a former peat production area in Liminka, northern Finland (64°48′N, 25°24′E). In all, 17 rectangular time study plots with an average area of 794 m^2 were established in seven naturally afforested downy birch-dominated stands (Table 1). The age of the stands varied from 14 to 29 years and density was 5150–160,250 trees per hectare. Width of the time study plot was determined by ditch spacing, which was on average 20 m (17–27 m). The average length of the time study plots was 40 m (35–41 m). Stand data was measured from four circular sample plots placed systematically in each time study plot. The size of the plot was either 50 m^2 or 20 m^2, depending on stand density. Diameter at breast height (DBH) was measured from all trees $\geq$ 10 mm. In addition, height (h) and diameter at stump height (10 cm from the ground) were measured from 5 to 8 sample trees representing the DBH distribution in the sample plot. Sub-sample plots with a radius of 1.0 or 2.0 m were placed in the center of the sample plots above. In these plots, the total number of undergrowth trees ($\text{DBH} < 10$ mm, $h > 1.3$ m) was recorded, and the mean height and DBH were measured from a representative tree. The estimates of stand age are based on the biological ages of two dominant trees on each main sample plot. They were determined from discs cut from stumps after harvesting and by adding two years to the number of annual rings. The number of standing trees was inventoried after forwarding from the main sample plots. Stump diameters for the tally trees were calculated with linear regression equations with DBH as an independent variable. The equations were constructed separately for conifers (Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), $R^2 = 0.988$), birches (downy birch and silver birch (*B. pubescens* and *Betula pendula*), $R^2 = 0.981$) and other tree species ($R^2 = 0.854$).

The wood harvested from the time study plots was weighed by a crane scale of the forwarder (Ponsse LoadOptimizer) within an accuracy of 1 kg. Mean lengths of the extracted tree sections were measured at the roadside from the piles accumulated from each time study plot. From each forwarder load, a moisture sample of 15–41 kg (fresh mass) was taken from a grapple load representing the diameter distribution of the tree sections in the load. Three sections of ca. 30 cm in length were cut with a chainsaw from the grapple load. One section was taken from the middle of the bunch, another 0.5 m from the butt end, and one 1.0 m from the top. The samples representing each time study plot (1–3 per plot) were combined, crushed into smaller particles with a hammer mill, and

Table 1
Properties of the time study plots.

Plot no.	Harvested area (m^2)	Inventoried area (m^2)	Stand age (a)	DBH$_{(A)}$[a] (mm)	DBH$_{(BA)}$[b] (mm)	h$_{(A)}$ (m)	h$_{(BA)}$ (m)	h$_{dom}$ (m)	Density (Trees ha^{-1})	Species distribution Bi/Br/Co[c]	Basal area (m^2)	Recovered biomass (ODt ha^{-1})	Residual biomass (ODt ha^{-1})[e]	Mean whole-tree volume (dm^3)
1[e]	757	80	13.8	10	42	2.6	4.7	10.1	160,250	69/25/6	23.3	40.3	3.6	0.6
2	674	80	14.8	13	32	3.3	5.4	6.5	129,000	67/16/16	25.0	47.2	2.9	0.8
3	679	80	15.3	13	29	3.4	5.4	8.4	109,750	81/19/0	22.2	42.0	–	0.8
4	744	80	20.9	19	54	3.8	7.7	11.5	28,000	86/14/0	14.7	65.3	–	5.0
5	829	80	20.3	24	82	4.2	8.1	10.8	30,125	56/2/43	26.9	66.2	8.1	5.1
6	778	80	21.4	25	77	4.5	7.8	10.0	31,750	46/1/53	29.8	67.1	–	5.0
7[d]	743	80	22.6	26	99	4.5	9.9	12.3	27,250	70/4/26	32.3	79.7	4.1	6.5
8	1023	200	25.5	45	96	7.0	12.0	15.1	12,850	78/22/0	33.8	113.5	–	19.5
9	1078	200	24.6	46	86	7.9	11.0	14.3	12,100	91/7/2	28.2	91.9	–	16.3
10	1028	200	25.1	51	79	8.5	11.2	14.9	11,050	90/8/2	29.2	95.5	5.5	18.6
11	694	200	25.4	61	98	9.0	12.4	13.8	7600	98/1/0	28.7	88.9	–	24.7
12	751	200	26.4	63	105	9.1	12.2	14.3	6550	90/10/0	27.5	89.7	–	29.4
13[d]	747	200	23.1	63	94	9.1	12.0	15.2	6750	97/2/0	26.7	90.0	–	28.2
14	798	200	24.8	57	86	9.4	11.9	15.3	7800	99/0/1	25.5	92.3	5.7	25.0
15	793	200	23.8	58	89	9.5	12.6	15.2	6950	88/4/8	23.5	97.1	–	30.1
16[d]	739	200	29.3	85	112	11.5	13.6	17.6	5800	99/1/0	38.6	153.1	5.5	55.7
17	639	200	28.4	98	136	12.2	14,8	17.7	5150	100/0/0	46.7	173.3	–	70.8
Average	794	151	22.7	44.5	82.1	7.0	10.1	13.1	35,200	–	28.4	87.8	–	20.1

[a] An arithmetic mean.

[b] A mean weighed by basal area.

[c] Birch/Other broadleaved/Conifers, % of biomass.

[d] Unit was not included in the forwarding study.

[e] Inventory was not carried out on plots with missing data (–).

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