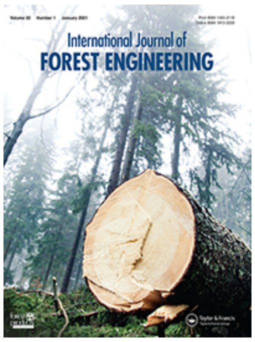

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Productivity and profitability of harvesting overgrown roadside verges – a Swedish case study

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ABSTRACT

Despite the large biomass potential, current management practices for roadside verges (ditch backslopes, foreslopes and bottoms, possible parking lots and other lateral land) consist of regularly cutting the vegetation manually with motorized brush saws or flail mowers and leaving it to rot in situ. Regular vegetation clearing is crucial for safety reasons and to maintain road functionality. This study considered the cost-efficiency of a mechanized harvesting system, using a harvester and a forwarder (as an alternative to current clearing practices), to maintain the verges of a forest road in northern Sweden. Cutting a 2.5-m wide swath on each verge removed between 32 and 112 dry t ha^{-1} (16–56 dry t km^{-1} of road) of biomass. Analyses showed that the use of forest machinery to cut and extract biomass from roadside verges can be cost-competitive compared with motor-manual clearing when the average tree height is above 7 m (~26-year-old trees), and profitable for average heights above 8 m (~29-year-old trees). As the overgrown biomass has to be cleared anyway, a mechanized harvest could partially or fully offset maintenance costs. When setting cutting intervals, a trade-off needs to be made between larger biomass production and maintaining a clear and safe road. Future research needs to investigate how size, density of vegetation and width of the cleared swath affects the long-term quality and safety of roads.

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Bioenergy; biorefinery; wood; small-diameter trees; maintenance; time study

Introduction

If the transition toward a forest-based bioeconomy continues, the demand for underutilized biomass sources such as small-diameter trees within forests and on other types of land (e.g. overgrown agricultural land, power line corridors and roadside verges) is expected to increase (Ebenhard et al. 2017; Fernandez Lacruz 2019). The overall techno-economical harvesting potential from other lands is estimated to be ~1–2 M dry tonnes (t) year^{-1} in Sweden, corresponding to 5–10 TW h year^{-1} of energy (Emanuelsson et al. 2014) or ca. 5–10% of current forest-based bioenergy use. Of this, 0.2 M dry t year^{-1} could come from the maintenance of the Swedish road network, which comprises roads that are at least 5 m in width and include a 5-m wide swath of adjoining forest. The road right-of-way comprises the roadbed (carriageway and shoulders) and roadside verges (ditch backslopes, foreslopes and bottoms, possible parking lots and other lateral land) (Figure 1). Despite its potential, the current management practice for infrastructure such as roads, power lines and railways is to cut the vegetation regularly and leave it to rot in situ. The cutting is carried out with either flail mowers attached to farm tractors or wheel-loaders, or motor-manually with brush saws (as in pre-commercial thinning). The regular clearing of vegetation is crucial for safety reasons and to maintain functionality of the infrastructure.

The Swedish road network consists of 140,800 km of public roads (70% state-owned and 30% municipality-owned) and 430,000 km of private roads, of which 74,000 km are state-subsidized for their maintenance and open to public use (Swedish Transport Administration 2017). About half of the private roads (210,000 km) are forest roads, used primarily by the forestry industry for transporting wood, and by other stakeholders for hunting, recreation, etc. (Skogskunskap 2016a). Road owners are responsible for road maintenance to ensure safe passage for traffic. To sustain the high carrying capacity and durability of the roads, it is important to keep the roadbed dry, therefore well-functioning ditches are essential (Edlund 2009; Forsberg 2010). Cutting back any vegetation maintains ditch function by preventing physical blocking of the water-flow, preventing shading that would decrease the sun's drying and snow-melting effect, and increasing the effectiveness of snow clearance (vegetation hinders snow being pushed onto the roadside verge). Moreover, trees on back- and fore-slopes decrease visibility along the road (for oncoming traffic, wildlife and pedestrians).

Maintenance guidelines for private roads suggest a vegetation-free zone at a minimum distance of 4.6 m vertically from the roadbed, and at least 2 m horizontally, on each side (Swedish Transport Administration 2019a). Clearing the vegetation from foreslopes is typically done with flail mowers, cutting a 2–3-m wide swath on each side of the roadbed (Skogskunskap 2016b) about every 3–4 years (Edlund 2009). Clearing costs when using flail mowers depend on the number of passes and the speed of cutting, which decreases as the diameter of the woody vegetation increases. Vegetation with an average height of 1–2 m (equivalent to a stump diameter of ~2–3 cm) is

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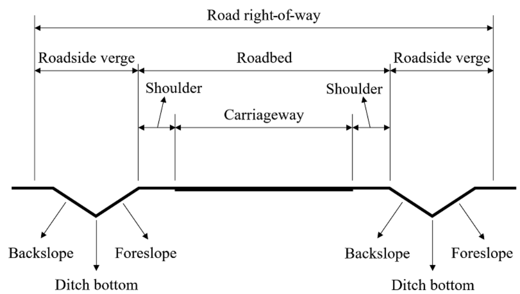

Figure 1. A cross-section of a road.

considered to be medium–difficult work for a flail mower, and a range of costs between 31 and 160 € km^{-1} (52–261 € ha^{-1}) has been reported by Forsberg (2010). Vegetation is always cut on foreslopes but not necessarily cut on backslopes, so small-diameter trees can be found on the backslopes of well-maintained roads. The cutting interval depends on factors such as road type, traffic intensity and soil fertility (affecting the growth rate of vegetation). Intervals are less regular in low-traffic forest roads, for instance between 10 and 20 years (Ebenhard et al. 2017), which therefore present a larger variation in tree size and higher biomass density when cut. Backslopes are typically cleared with brush saws, as are foreslopes that have been cut at longer intervals. This recurring cost can be considered an investment in road quality and usability.

As an alternative to current practices, the maintenance costs for infrastructures such as roads could be partially or fully offset by mechanized biomass harvest (even if it does not provide a direct economic profit per se). Fernandez-Lacruz et al. (2013) found that the use of forest machinery for harvest and extraction of overgrown vegetation along a power line corridor could be more cost-efficient than motor-manual clearing, if trees were at least 6 m high. Small-diameter trees harvesting can be challenging, however, because of the low piece-volume. Harvester productivity depends on the size of the removed trees, tree density and the intensity of removal (Eriksson and Lindroos 2014). Cutting small-diameter trees is regarded as a key barrier to achieving high cost-efficiency (Bergström and Di Fulvio 2014a), but the profitability of the whole supply chain also depends on factors such as comminution strategy, trucking distance to the end-user(s) and current market prices.

There have only been a few studies of harvesters with accumulating felling heads (AFHs) and forwarders when working in roadside verges (Iwarsson Wide 2009b, 2009c; Di Fulvio et al. 2011). Harvesting of roadside verges has several advantages compared with harvesting during conventional forest operations (final fellings and thinnings). For example, the roads offer a flat and easily traveled surface, which enables comfortable and fast repositioning of machinery, and all the trees within the roadside area should be removed, so there is no need for silvicultural decisions. These factors can result in larger volumes per hectare and more efficient working compared with other operations aimed at harvesting trees of similar size. However, the variation in biomass density along roadside verges and other land-use types can be large, and the roads or other land-use types can be scattered across the landscape, necessitating frequent relocation of the machinery (Fernandez-Lacruz and Bergström 2015). To address those challenges, integrating the management of forest and other land-use types has been suggested, to increase the utilization of machine capacity and decrease supply costs (Fernandez-Lacruz et al. 2020). Moreover, to be able to manage roadside verges effectively for both maintaining road functionality and biomass production, there is a need to balance the negative effects of allowing the vegetation to grow versus the income it may generate. Hence, the financial trade-off is between long-term road-quality-related costs, and the operational costs and benefits of harvesting. There will be a threshold where the benefits of allowing the vegetation to grow to a profitable size are lower than any potential damage to the road.

Despite the prevalence of road maintenance activities, and the largely unutilized potential of the biomass left in situ during these operations, there have been few studies on the mechanized harvest and extraction of this biomass. This study aimed to analyze the cost-efficiency of mechanized biomass harvesting (as an alternative to conventional motor-manual clearing) while maintaining the roadside verges of a forest road in a case study in northern Sweden. The study consisted of three parts: characterization of the roadside vegetation; measurement and modelling of the efficiency of mechanized biomass harvesting (with a harvester and a forwarder); and an economic comparison of the observed biomass harvesting with the modeled cost of conventional motor-manual clearing.

Materials and methods

Study site and experimental design

The fieldwork was performed in Björna (63°33′N, 18°35′E), northern Sweden. A forest inventory and time study of harvesting operations were conducted in July–August 2008. A swath of ~1.5 m on each shoulder of the forest road had previously been cleared of vegetation using a flail mower. A total of nine study units was marked out along one side of the road (behind the vegetation-free swath), to establish a gradient for the average diameter at breast height (DBH, i.e. at 1.3 m above ground level). The width of the study units was 2.5 m, the length 20 m for units 1–3, and the length 50 m for units 4–9, resulting in surface areas of 0.005 ha and 0.0125 ha for units 1–3 and 4–9, respectively. In order to streamline the inventory and harvesting operations, the start and end point of each unit was marked with poles, and the outer border (toward the adjoining forest) with labeling tape.

Prior to cutting, a systematic stand inventory was carried out in each of the marked units, by laying down transects (width = 1 m, length = 2.5 m) every 5th meter along the units' long side (transects were perpendicular to the direction of the road). The sampling position of the first transect was randomly defined within 5 m from the beginning of the unit. Thus, 25% of the study unit area was inventoried for units 1–3 (5 transects each) and 20% for units 4–9 (10 transects each). In each transect, the DBH, height and species of all the trees that had reached breast height were recorded. In order to determine the age of the biomass, and thus the period of time since the vegetation was last cut, the annual growth rings of at least eight trees per study unit were counted after harvest.

Time study

A time study was conducted on a harvester and a forwarder working in the inventoried units (each unit was studied separately). The harvester was a Rottne H8 (Rottne Industri AB, Rottne, Sweden), with a crane reach of 7 m. It was equipped with an AFH Naarva-Grip 1500-25EH (Pentin Paja Oy, Joensuu, Finland), with a guillotine, three-jawed cutting arms, two-jawed accumulating arms, a weight of 430 kg and maximum cutting diameter of 25 cm. The harvester operator had 4 years of experience, of which 5 months were spent with the study machine cutting forest roadside verges. Neither the seat nor the cabin of the harvester could rotate. Therefore, every time the harvester moved along the roadside, the machine was positioned toward the ditch to prevent the operator from working non-ergonomically, adding extra working time (Figure 2). Trees were felled as whole undelimbed trees and bunched on the ditch perpendicular to the road's direction. Longer trees were bucked to ease forwarding operations and reduce the risk of damaging the remaining forest stand.

After cutting, the biomass was forwarded to the landing area in distinct windrows from each unit. The forwarder was an eight-wheeled Timberjack 1710D (John Deere Forestry Oy, Tampere, Finland), with a load capacity of 17 t, equipped with a purpose-built load carrier Hultdins Biokassett (Hultdin System AB, Malå, Sweden) (Eliasson and Lundström 2013). According to the manufacturer, the load carrier enlarges the volume in the bunk from 28 to 75 m^3, compared with the standard machine configuration. The operator had 1 year of experience with the study machine and forwarding logging residues.

The work time of the machines was recorded using continuous time study methodology (Magagnotti et al. 2012) with work elements as defined in Table 1. A Husky Hunter FS3 handheld computer equipped with Siwork 3 software (Kofman 1995) was used. The time study of each machine began when it reached the start point of the unit and concluded when it reached the end point. If subsequent units were spatially separate from each other, the driving time between units was excluded. In the time study for the forwarder, machine work time while driving empty or driving loaded (from or to the landing, respectively) was not recorded, but empty and loaded driving speeds were measured.

Figure 2. The cutting position of the studied harvester on the studied forest road.

Measurements of harvested biomass

In November 2008, the biomass was transported by a loose residue truck to a recycling center outside Örnsköldsvik (63° 18′N, 18°46′E), with a haul distance of ca. 50 km. The truck was scaled on a weighbridge (resolution: 10 kg, maximum 60 t), keeping the biomass from different study units separate. Directly after scaling, the material was chipped using a Bruks 805 CT (Bruks AB, Arbrå, Sweden), mounted on a John Deere 1710D forwarder (John Deere Forestry Oy, Tampere, Finland). Wood chips from each study unit were sampled, filling three 1-liter buckets from the chip pile. Moisture content was determined following CEN (2009), and averaged 40.8% (standard deviation, SD, 4.5%, range 35.6–48.3%,) at the time of chipping. Calculations assumed that the fresh weight of biomass at the moment of harvest was the same as at the moment of chipping (i.e. no changes in moisture content from August to November were taken into consideration).

Statistical analyses

Normality tests performed on fieldwork data revealed a normal distribution. Regression analyses were performed using Minitab™18, and results deemed significant if the p-value was <0.05. Regression models were built deductively, choosing

Table 1. Definition of work elements in the harvester and forwarder work cycle.

Machine	Work element	Definition	Priority[1]
Harvester	Boom out	Started when the crane with empty felling head moved toward a tree to be felled and stopped when the tree was reached.	1
	Felling	Started when the first tree was reached and stopped when the last tree was felled. Included crane movements to successive trees in the same crane cycle.	1
	Boom in	Started when the last tree in the crane cycle was felled and stopped when the tree bunch was dropped on the ground. Included work to adjust the bunch.	1
	Moving	Started when the harvester wheels were turning and ended when they stopped. Included machine positioning toward the ditch.	2
Forwarder	Loading	Started when the crane moved from its base position in the empty bunk to a bunch of trees. Stopped when the last bunch had been loaded in the bunk, the crane was returned to its base position and the machine started to move to the landing. Included moving while loading.	1
	Unloading	Started when the crane moved from its base position to grab the first bunch of trees in the bunk, and ended when the empty crane was returned to its base position in the empty bunk.	1
Both machines	Miscellaneous	Other activities such as trees being dropped and then picked up again, cutting of roots of uprooted trees, bucking of long trees.	2
	Delay	Time not related to effective work time e.g. personal breaks, phone calls, machine breakdowns, etc.	3

1. If work elements were performed simultaneously, the element with the highest priority (lowest number) was recorded.

linear and non-linear functions commonly used to describe machine work that fit the fieldwork data best.

Economic analyses

The inventory and time study were used to model the biomass removal and work efficiency (time consumption per biomass output) achieved by the forest machines. Based on the derived models, the net income of roadside clearing using the mechanized harvesting system was calculated as the difference between the revenue from selling the undelimbed small-diameter trees and the cost of harvesting and forwarding, including a relocation cost for the forest machinery. The calculated net income for the mechanized system was compared with the cost of motor-manual clearing reported in the literature. The economic analysis was conducted for a theoretical roadside unit with a rectangular size of 1 ha (2.5 m × 4,000 m), assuming a one-way forwarding distance of 250 m (the biomass would be forwarded to multiple landings along the road), and presented as a function of the average height of felled trees (as found during fieldwork). An exchange rate of 1 € = 9.6 Swedish kronor (SEK) was used. Estimated revenues were based on the prevailing market price for uncomminuted, undelimbed trees at the roadside in Sweden in 2012, which amounted to 22 € solid m^{-3}, equivalent to 44 € dry t^{-1}, using a basic density of 497 dry kg solid m^{-3}, as in Fernandez-Lacruz et al. (2013).

Harvesting costs were calculated by multiplying the hourly operating cost of the machinery by the time required to harvest and forward the biomass from the modeled unit. Machine operating costs were calculated according to Ackerman et al. (2014), considering similar fixed, variable and operator costs as Fernandez-Lacruz et al. (2013), with an extra cost of 14,580 € (Eliasson and Lundström 2013) included for the forwarder's load carrier. The machine operating costs amounted to 90 and 81 Euro (€) per scheduled machine (SM) hour (h) for the harvester and the forwarder, respectively. The modeled efficiencies of the harvester and forwarder were used to calculate the productive machine (PM) time (i.e. delay-free) required to work in the theoretical unit. PMh was converted into SMh by adding delays and indirect work that supported completion of the work task, based on a technical utilization of 78% for the harvester and 84% for the forwarder, as indicated by Eriksson and Lindroos (2014). A relocation cost of 208 € per machine was included in the cost calculations, to accommodate the cost of bringing the machines to the site on a truck with a low-bed trailer.

The cost of motor-manual clearing was calculated by multiplying the hourly operating cost by the SMh required to clear the vegetation in the modeled unit. The cost of the operator was set to 31 € SMh^{-1} based on the reference cost in Sweden in 2012. The required PM time for motor-manual clearing was calculated using Equation (1) (SLA-Norr 1991), a function used for pre-commercial thinning in conventional forestry. T denotes PM minutes (min) ha^{-1}, RA the tree density in the unit (×10^3 trees ha^{-1}, with DBH ≥1 cm) and h_{baw} the mean basal area-weighted tree height (m). RA was calculated using fieldwork observations of tree density, as a function of h_{baw}. An extra time consumption of 5% was added to account for terrain roughness, as in Fernandez-Lacruz et al. (2013). PMh was converted into SMh by applying a technical utilization of 75%.

$$T = 0.765 \times ((15.08 \times RA) + (9.5 \times RA \times h_{baw}) - (0.15 \times RA^2 \times h_{baw}) + 91) \quad (1)$$

Results

Characteristics of forest roadside verges

The inventory of harvesting units (Table 2) revealed a dominance of broadleaved trees (82% of measured trees), a high tree density (on average 31,244 trees ha^{-1}, Figure 3), an average h_{baw} of 6.5 m (range 3.9–9.5 m) and an average biomass removal (i.e. above-ground biomass density) of 74.1 dry t ha^{-1} (range 32.0–111.8 dry t ha^{-1}). The mean concentration of biomass per km of forest road (with 2.5 m harvested on each side) was 37.1 dry t km^{-1} (range 16.0–55.9 dry t km^{-1}). The annual growth rings in the study units revealed an average age of 24 years (range 14–34 years) for the harvested biomass.

Regression analyses showed that the biomass removal from the units (dry t ha^{-1}) depended linearly on h_{baw} (m) and biomass age (years), yielding Equation (2) (R^2 = 0.767; p = 0.002) and Equation (3) (R^2 = 0.911; p < 0.001), respectively.

$$Biomass\ removal = -11.017 + (13.061 \times h) \quad (2)$$

$$Biomass\ removal = -21.167 + (3.916 \times age) \quad (3)$$

Harvester work

The harvester was studied for 2.51 h, with no delays. Efficiency averaged 28.2 PMh ha^{-1} (SD = 4.3 PMh ha^{-1}, range 21.8-34.2 PMh ha^{-1}) and 27.99 PMmin dry t^{-1} (Table 3). Felling (and bunching) work represented 64% of PM time. The number of crane cycles per PMh averaged 94 (SD = 21, range 63–123), which was equivalent to 1091 trees PMh^{-1} (SD 390 trees PMh^{-1}, range 475–1,741 trees PMh^{-1}). An average of 14.1 PMh (SD 2.3 PMh, range 10.9–17.1 PMh) would be required to harvest 1 km on both verges of the road studied.

The harvester's efficiency (PMmin dry t^{-1}, all work elements) was modeled on field observations (n = 9). First, as a function of h_{baw} (m), yielding Equation (4) (R^2 = 0.952; p < 0.001) (Figure 4); second, as a function of the mean basal area-weighted DBH (DBH_{baw}, cm), yielding Equation (5) (R^2 = 0.897; p < 0.001).

$$Harvester's\ efficiency = e^{6.1603} \times (h_{baw})^{-1.6144} \quad (4)$$

$$Harvester's\ efficiency = e^{5.1033} \times (DBH_{baw})^{-1.0267} \quad (5)$$

Forwarder work

The forwarder was studied for 0.53 h, with no delays. The average forwarder load contained 1.38 fresh t (equivalent to 0.83 dry t, considering an average moisture content of 40.8%,

Table 2. Main parameters of the harvesting units.

Unit	Number of measured trees	Species[1]% b:o:s:p	Mean tree DBH[2] (cm)		Mean tree height (m)		Stand density (trees ha^{-1})		Biomass removal		Age (years)
			Arithmetic	Basal area-weighted	Arithmetic	Basal area-weighted	All trees	$DBH^2 \geq 1$ cm	(fresh t)	(dry t ha^{-1})	
1	42	24:62:14:0	1.9	3.6	2.7	3.9	33,600	25,600	0.34	35.2	15
2	54	19:74:7:0	2.1	3.4	3.1	4.4	43,200	33,600	0.40	46.0	16
3	55	4:85:11:0	2.2	4.3	3.2	4.6	44,000	36,800	0.28	32.0	14
4	99	89:1:10:0	3.4	6.2	4.4	6.6	39,600	39,200	1.84	94.7	28
5	65	77:8:15:0	3.6	6.0	4.4	6.5	26,000	24,800	1.85	94.1	29
6	110	56:13:31:0	2.6	5.9	3.4	6.1	44,000	37,600	1.44	73.0	26
7	29	69:3:24:3	5.7	12.2	5.5	9.5	11,600	10,400	2.08	104.3	28
8	36	14:53:33:0	3.7	12.2	3.4	8.9	14,400	11,200	2.54	111.8	34
9	62	34:53:13:0	3.0	9.8	3.5	8.2	24,800	18,800	1.66	76.1	29

1. % of number of trees: b = birch (*Betula* spp.), o = other broadleaves (mostly gray alder, *Alnus incana*, and willow, *Salix* spp.), s = spruce (*Picea abies*), p = pine (*Pinus sylvestris*). 2. DBH = diameter at breast height, i.e. at 1.3 m above ground level.

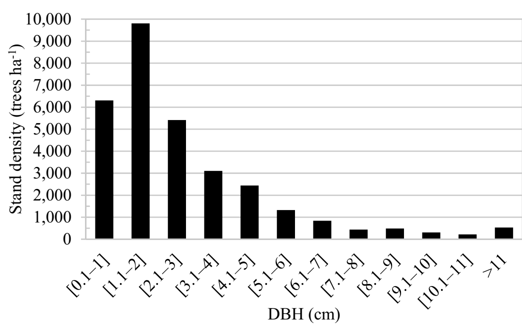

Figure 3. Average distribution of diameter at breast height (DBH) classes (cm) in harvested units (all measured trees, i.e. those that had reached 1.3 m above ground level).

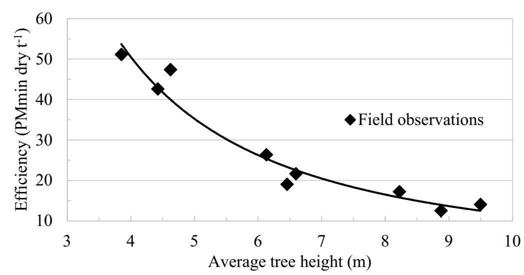

Figure 4. Field observations (points) and modeled efficiency (curve) of the harvester as a function of the average basal area-weighted height (h_{baw}) of felled trees.

as measured during chipping); no full load was achieved. Of the time studied, 65% was spent with the work element *Loading* (which included moving while loading) and 35% with *Unloading*. The time for *Loading* averaged 3.83 PMmin dry t^{-1} (SD = 2.11 PMmin dry t^{-1}, range 1.80–7.19 PMmin dry t^{-1}), while *Unloading* averaged 1.74 PMmin dry t^{-1} (SD = 0.74 PMmin dry t^{-1}, range 1.00–3.33 PMmin dry t^{-1}).

Loading (PMmin dry t^{-1}) was modeled as a function of the measured removal of biomass per unit (Table 2), denoted *b* (dry t ha^{-1}), yielding Equation (6) ($R^2 = 0.878$; $p < 0.001$).

$$\text{Loading (incl. moving while loading)} = e^{2.435} \times e^{-0.01648 \times b} \tag{6}$$

Empty and loaded driving speeds of 133 and 117 m min^{-1} (8 and 7 km h^{-1}) were measured during the fieldwork. The time consumption for *Driving empty* and *Driving loaded* was modeled as a function of forwarding distance (one-way), denoted *d* (m), and observed driving speeds, assuming a full forwarder load of 4.8 dry t, using the load carrier Hultdins Biokassett as in Eliasson and Lundström (2013).

The forwarder's efficiency (PMmin dry t^{-1}) was therefore modeled (Equation (7)) on the sum of modeled *Loading, Driving empty* and *Driving loaded* time consumption, and the average value for *Unloading* (1.74 PMmin dry t^{-1}). Additionally, Equation (7) included a *Miscellaneous* time component (complementary activities in the forwarder's work cycle, for example bunches that were dropped and then picked up again, load adjusting, etc.) which averaged 0.51 PMmin dry t^{-1}, as shown by Fernandez-Lacruz et al. (2013).

$$Forwarder's\ efficiency = e^{2.435} \times e^{-0.01648 \times b} + \frac{\left(\frac{d}{133} + \frac{d}{117}\right)}{4.8} + 1.74 + 0.51 \tag{7}$$

When considering a one-way extraction distance of 250 m, a biomass removal of 74 dry t ha^{-1} (the average value in this study) and a full load (4.8 dry t), Equation (7) returned

Table 3. Observed harvester efficiency, distributed over work elements.

Work element	Relative distribution (%)	Time consumption (PMmin dry t^{-1})				
		Mean	Standard deviation	Median	Minimum	Maximum
Boom out	11.5	3.22	1.02	2.90	2.22	5.30
Felling	64.1	17.94	11.36	13.81	5.16	34.15
Boom in	16.5	4.63	2.41	3.85	2.78	10.91
Moving	6.5	1.81	0.96	1.28	1.07	3.69
Miscellaneous	1.4	0.38	0.69	0.20	0	2.19
All work elements	100	27.99	14.99	21.64	12.52	51.14

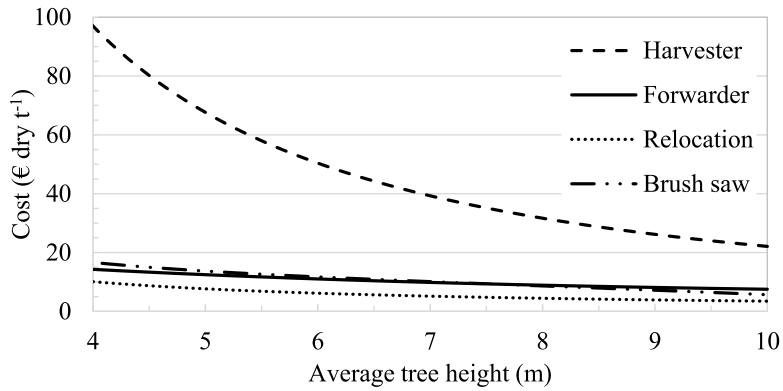

Figure 5. Costs of the mechanized harvesting system (harvester, forwarder and relocation) and motor-manual clearing (brush saw) as a function of the mean basal area-weighted height (h_{baw}) of felled trees.

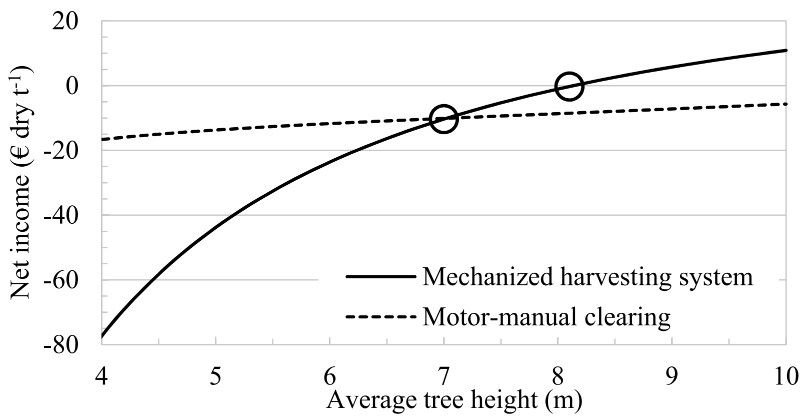

Figure 6. Net income of the mechanized harvesting system (i.e. harvester and forwarder) and costs of motor-manual clearing (brush saw) as functions of the mean basal area-weighted height (h_{baw}) of felled trees. The circles indicate the heights at which the net income of the mechanized system equals the cost of motor-manual clearing (left) and the mechanized system yields a net income of zero (right).

a forwarder efficiency of 6.45 PMmin dry t^{-1}, with a distribution over work elements according to Table 4.

Economic results

For the modeled unit size of 1 ha and a one-way extraction distance of 250 m, as the h_{baw} of felled trees increased from 4 to 10 m (a similar range as observed in the field, Table 2), the total harvesting cost per ha decreased by 21% (from 5,003 to 3,959 € ha^{-1}), while the costs per dry t decreased by 73% (from 121 to 33 € dry t^{-1}) (Figure 5). Cutting represented 67–80% of the total harvesting costs, averaging 73%. The cost per dry t of motor-manual clearing decreased by 66% as h_{baw} increased from 4 to 10 m, and the average cost per ha was 763 €. The calculated stand density (of trees with a DBH ≥1 cm) for motor-manual clearing decreased from 36,700 to 12,300 trees ha^{-1}, as h_{baw} increased from 4 to 10 m.

Table 4. Modeled forwarder efficiency for a one-way extraction distance of 250 m, distributed over work elements.

Work element	Relative distribution (%)	Time consumption (PMmin dry t^{-1})
Loading (incl. moving while loading)	52.2	3.36
Driving empty	6.1	0.39
Driving loaded	6.9	0.45
Unloading	27.0	1.74
Miscellaneous	7.9	0.51
All work elements	100	6.45

For the modeled unit of 1 ha and considering an h_{baw} in the range 4–10 m, the net income for the mechanized harvesting system was negative until an average h_{baw} of 8.1 m was reached (equivalent to an average DBH_{baw} ~9 cm), giving a net income of zero (Figure 6). The net income of the mechanized system and the cost of motor-manual clearing reached the same (negative) value for an average h_{baw} of 7 m (average DBH_{baw} ~8 cm). Therefore, for roadside verges with a h_{baw} of trees above 7 m, the mechanized harvesting system would be a more cost-efficient alternative than conventional motor-manual clearing.

Discussion

Harvester work

Harvester efficiency was modeled as a function of h_{baw} (Equation (4)) and DBH_{baw} (Equation (5)). In forestry studies, it is common to use DBH or stem volume to model harvester efficiency; however, h_{baw} was primarily considered in subsequent calculations because of its greater coefficient of determination (R^2 = 0.952) than DBH_{baw} (R^2 = 0.897). Additional analyses found that h_{baw} was positively correlated with DBH_{baw} ($p < 0.001$, Pearson correlation coefficient = 0.975). Another reason for using height is that it is an important variable when planning maintenance operations for roads and other linear infrastructures such as power lines. Height can be measured rapidly by airborne laser scanning or drone-based photogrammetry (Iwarsson Wide 2013; Wallace et al. 2016). This can be crucial for implementing an efficient and large-scale management of biomass in these land-use types, because of the extent of linear infrastructure across the Swedish landscape: ca. 570,800 km of roads, ca. 15,600 km of railways (Swedish Transport Administration 2019b) and ca. 15,000 km of power lines (for the national grid) (Svenska Kraftnät. 2017).

Fernandez-Lacruz et al. (2013) studied a harvester during power line corridor clearing, equipped with a Bracke C16.b AFH (with a cutting chain mounted on a saw disc). Considering a h_{baw} in the range of 3–10 m, the modeled harvesting efficiency for the guillotine-based AFH Naarva-Grip 1500-25EH in our study was on average 28% lower than that of the Bracke C16.b. Iwarsson Wide (2009b) found a cutting efficiency of 31.93 PMmin dry t^{-1} using a Bracke C16.a AFH, when cutting roadside verges with an average tree height of 5.5 m and biomass removal of 37.0 dry t ha^{-1}. This is in line with our results (Figure 4), despite the different cutting technology. In another study of roadside clearing (Iwarsson Wide 2009c), the cutting efficiency of a shear-based AFH Ponsse EH25 (Ponsse Oyj, Finland) averaged 14.96 PMmin dry t^{-1} (considering an average height of 9 m and biomass removal of 51.8 dry t ha^{-1}), also in line with our results.

In general, cutting work is slower with shear/guillotine-based than circular saw blade- and sword-based AFH, but shear/guillotine-based AFH are normally cheaper and more resilient against stone damage (Iwarsson Wide 2009a). Compared with thinning dense forests with a Naarva-Grip 1600-40 AFH (which is similar to the cutting technology as our study) and similar tree sizes (Ovaskainen et al. 2008), the observed efficiency in our study was on average 6–29% higher. This difference might be because the roadside operations comprised clear-cutting work, resulting in larger removals and more efficient crane movements, compared with the thinning work presented in Ovaskainen et al. (2008). Cutting represented 65–82% of the total harvesting costs (Figure 5) and can be considered a bottleneck to achieving a high cost-efficiency in the supply chains of small-diameter trees. Downstream activities in the supply chain (comminution and transport) also affect overall profitability, but cutting represents the dominant cost in small-diameter tree supply chains (Routa et al. 2013).

Forwarder work

The full work of the forwarder was modeled using field observations in combination with data from another study. The recorded driving speeds of the forwarder (133 and 117 m min^{-1}, empty and loaded, respectively) were 60–74% higher than corresponding average terrain driving speeds in power line corridor clearing (Fernandez-Lacruz et al. 2013), and 135–142% higher than average terrain driving speeds in conventional forestry operations (57 and 48 m min^{-1}, empty and loaded, respectively), as shown by Manner (2015). The difference in driving speeds was expected, because the driving occurred exclusively on a forest road, whereas in other studies it was on off-road terrain. However, the reliability of the speed measurements in our study is limited by few observations and the lack of full loads. The modeled forwarder's efficiency (Equation (7)) assumed full forwarder loads of 4.8 dry t (using the load carrier Hultdins Biokassett), similar to the payload when forwarding bundles, and 85% larger than a full load (2.6 dry t) of undelimbed small-diameter trees in a conventional thinning forwarder (Bergström and Di Fulvio 2014a). Because of the relatively high speeds and payload, the modeled work of the forwarder was on average 36% more efficient than corresponding work in power line corridor clearing (considering an extraction distance of 250 m and h_{baw} in the range 3–10 m). Even though the considered load carrier can be rapidly installed and removed to switch between fuel- and roundwood forwarding, the potential of implementing this solution may be limited because it requires a forwarder with active load space (which allows adjustment of the bunk size via a hydraulic system). Other alternatives for increasing payloads during forwarding of bulky biomass such as undelimbed small-diameter trees or logging residues can be purpose-built forwarders with load-compression devices or bunk modifications in conventional, roundwood forwarders (Bergström et al. 2010b; Frisch 2018).

Because of the closeness of the felled tree bunches to the forest road, the forwarding stage could perhaps be omitted, and instead the biomass chipped with a forwarder-mounted chipper or chipper-truck. This could decrease overall supply costs, but the profitability of the whole operation would be sensitive to the spread of bunches along long forest roads, which would increase the moving time to the detriment of chipping during the overall machine work time. Moreover, for safety reasons, this option would only be feasible in low-traffic forest roads.

This study only examined one operator per machine, but operators have been found to affect a system's productivity significantly (Purfürst and Erler 2011; Häggström and Lindroos 2016). The relatively short time period studied (2.51 and 0.53 h of the harvester's and forwarder's work, respectively), compared with their theoretical annual operation (for instance 3,200 h, considering 200 machine days per annum and two 8-h shifts per day), also limits the representativeness of the derived models.

Biomass removal

The removal of biomass during roadside clearing averaged 74.1 dry t ha^{-1}. In contrast, removal during power line corridor clearing (Fernandez-Lacruz et al. 2013) averaged 25.6 dry t ha^{-1}. The range of values in our study is in line with those in Fernandez-Lacruz and Bergström (2015) during harvesting of roadside verges and overgrown farmland. The biomass removal during first thinning of biomass-dense forests would be similar to that in study units 1–3 (Bergström et al. 2010a; Petty 2014; Bergström and Di Fulvio 2014b).

The harvester cut a fixed swath of 2.5 m on each roadside, yielding an average biomass removal of 37.1 dry t km^{-1}. The average removal per km was somewhat lower than that of Iwarsson Wide (2009c) (46.6 dry t km^{-1}, a 4.5 m wide swath) and Iwarsson Wide (2009b) (51.8 dry t km^{-1}, a 7 m wide swath) because of the comparatively narrower swath in our study. The average biomass removal of our study would increase to 66.7–103.7 dry t km^{-1} if a swath of 4.5–7 m could be cut (equivalent to an increase in removal of 80–180%). A higher biomass removal would increase harvesting efficiency, as there would be an increase in the share of crane work versus moving time along the road. On a road 5 km long, an increase in the width of the cleared swath of 1 m (into the adjacent forest) would reduce the area of productive forest land by 1 ha. However, that area could provide an additional ~74 dry t of biomass (the average from this case study) within relatively short rotations (14–-34 years), similar to the management of coppice forestry in other parts of Europe (Dimitriou et al. 2018).

Overall results

This study has addressed the problem of managing overgrown vegetation along roadside verges, and studied a mechanized alternative to current management practices. The overall results (Figure 6) show that the use of forest machinery to cut and extract biomass from forest roadside verges can be cost-effective compared with motor-manual clearing when the average h_{baw} is above 7 m (~26-year-old trees), and can be profitable for an average h_{baw} above 8 m (~29-year-old trees). Thus, in the practice, the use of a mechanized harvesting system to carry out roadside clearing is restricted to roadside verges containing relatively large trees (as found in study units 7–9). For roadside verges with vegetation below 7 m (as in units 1–6), motor-manual clearing with brush saws, and flail mowers for the lowest vegetation, should prevail because of the comparatively lower costs. However, the break-even tree height depends on current costs of machinery and market prices for energy biomass. To reduce the effect of fluctuations in the energy market, the use of small-diameter trees (and other residual woody biomasses) could be increased by creating new industries, such as biorefineries, to convert these biomasses into high-value products (Bergström and Matisons 2014).

Future work

Our results suggest that, if trees are allowed to grow taller than at the present, the net income from mechanized roadside clearing would notably increase, allowing more profitable harvests. For the specific conditions of this case study, annual growth rings revealed that a profitable harvest is possible with a clearing interval of ~29 years. However, letting roadside vegetation grow to these profitable sizes may have a negative effect on the maintenance and use of the roads. Future research needs to investigate how the size and density of roadside vegetation, as well as the width of the cleared swath, affects the long-term quality and safety of roads. Cost-benefit analyses should be carried out to determine how dense/tall should vegetation be allowed to grow (i.e. how larger biomass production can be achieved) without compromising long-term road quality and safety, nor incurring costs in road reparations that are larger than the expected income from the biomass.

The base machines used in this study (a harvester and forwarder) represent the most common machine system used in Swedish forestry, but the use of alternative systems along forest roadside verges could also be evaluated, in particular to increase the use of vegetation below 7 m in height. One possibility might be the BioBaler (Anderson Group Co., Canada), a harvester-baler of shrubs that attaches to farm tractors (González-González et al. 2017). The development of innovative technologies such as new felling-bunching heads and feller-bundlers (Bergström and Di Fulvio 2014b; Grönlund et al. 2015; Bergström et al. 2016; Manner et al. 2017; Bergström 2019) will also increase the cost-efficiency of small-diameter tree harvesting operations, both in forests and other operational environments such as roadside verges.

Conclusions

This study has shown that relatively long clearing intervals can yield relatively large biomass production along roadside verges, thus allowing profitable, mechanized harvests (compared with current practices using brush saws/flail mowers, which leave biomass to rot in situ). However, when setting the intervals for roadside clearing, a trade-off needs to be made between allowing larger biomass production and ensuring the long-term quality and safety of the roads.

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