Productivity and Profitability of Forest Machines in the Harvesting of Normal and Overgrown Willow Plantations

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Abstract – Nacrtak

Forage harvesters used in Short Rotation Willow Coppice (SRWC) plantations in Sweden suffer from an inability to efficiently harvest stems thicker than 6 – 7 cm at stump height. An alternative, when harvesting in such plantations, might be to use forest machines fitted with accumulating felling heads. This study aimed to measure the time consumption and to compare the costs of two forest machine systems in a normal (N) and an overgrown (O) SRWC, where the respective biomass densities were 36 and 56 Oven-Dry tonnes (OD t) per ha. The first machine system included a harvester and a forwarder and the second consisted of a harwarder (one-machine system). When harvesting and forwarding the biomass for 250 m, the productivity of the two and one-machine system was on average 2.3 (sd = 0.6) and 0.9 (sd = 0.2) OD t/Productive Work hour, respectively. Biomass density or stem sizes had a marginal effect on the time consumption per hectare for the two-machine system, but were significant for the one-machine system. The productivity for the two-machine and one-machine system in the O area, compared to the N area, was 40% and 36% higher, respectively. The net income was positive when using the harvester–forwarder system but it was negative for the harwarder. Increases in biomass density or stem sizes increased the profitability of the machine systems studied. Thus, if dealing with more overgrown plantations than those studied, forest machines, and especially a harvester-forwarder system, may offer an efficient and economical alternative to conventional forage harvesters.

Keywords: System analysis, time study, productivity, harvester, forwarder, harwarder

1. Introduction – *Uvod*

Current field design of Short Rotation Willow Coppice (SRWC) plantations for energy has increased the efficiency of cultural operations, allowing for fully-mechanized cultivation and harvesting (Mola-Yudego 2011, Mitchell et al. 1999). The harvesting operation accounts for about half the total cost of SRWC production; the remainder of the cost is attributable to cultivation (25%) and biomass transportation (25%) (Sims 2002). Nearly all SRWC in Sweden are harvested by direct chipping, using forage harvesters equipped with wood cutting headers and shuttles for transporting the chipped biomass to the road side (Nordh and Dimitriou 2003). The forage harvesters tend to have problems with stems and therefore the diameter at stump height (dsh) (i.e. the cutting height) exceeds 6 – 7 cm. For instance, as such thick stems are relatively inflexible, they are not readily bent to fit into and pass through the feeding and cutting unit (Nordh and Dimitriou 2003). Spinelli et al. (2008) found that when the average dsh exceeded ca. 4 cm, the mechanical stress on the machines increased and in turn reduced the machines' work availability from 94% to 84% (Spinelli et al. 2008). It is to be expected that future SRWC plantations will achieve higher biomass yields due to the breeding of new and better clones (Mola-Yudego 2011). As such, it is likely that the average dsh of the harvested trees will increase, requiring harvesters that can handle larger stems (Nordh and Dimitriou 2003). In fact, such a need already exists to some extent: the use of conventional forage harvesters can be challenging when harvesting SRWC that has become somewhat overgrown (i.e. which contains a notable amount of stems larger than 4 cm in dsh) (Magnusson 2009).

One possible way to work around these problems would be to use forest machines developed for harvesting small trees for bioenergy in first thinnings. Such forest machine systems are highly reliable and can handle stems/trees much larger than those found in overgrown SRWC plantations. In the Nordic countries, two-machine systems consisting of a harvester equipped with an accumulating felling head (AFH) and a forwarder that transports the biomass to the roadside are commonly used for such operations. However, one-machine systems are also used consisting of a machine (a harwarder) that both fells and transports the biomass to the roadside (cf. Talbot et al. 2003).

A detailed understanding of the factors affecting the productivity and operating costs of forest machines when used in SRWC plantations could facilitate the development of approaches that would make their use more profitable than that of conventional forage harvesting systems when harvesting significantly overgrown SWRC plantations.

Therefore the aim of this study was:

⇒ to study the effect of work methods and biomass density (normal and overgrown) on the work time consumption of a harvester–forwarder system and a harwarder system in willow plantations,

⇒ to compare their productivity, costs and profitability.

2. Material and Methods – *Materijal i metode*

The study site was located in Ransta, Sweden (59°49'N, 16°38'E). A *Salix viminalis* L. clone »Tora« plantation was established there in the year 2000 in a double row pattern (Fig. 2). The plantation was intended to be harvested every five years on a regular basis. At the time the study was conducted, it had been grown by six years since it had last been harvested. The plantation covered an area of 17.2 ha, of which 3.6 ha were used for the study. The study was conducted in 2010, between the 29th of November and the 9th of December. The ground surface was partially frozen and covered with a snow layer to a depth of ca. 5 cm and had a high bearing capacity. The study area was inventoried in rectangular plots with a width of 5 single rows (5 m) and a length of 4 stools (2.4 m) (i.e. a stool is a stump from which stems sprout), giving a sample area of 12 m^2. The plots were regularly distributed in the direction of the rows and separated from one another by 10 m, giving a density of 80 plots per hectare. The study area contained both normal (N) and overgrown (O) areas (Table 1). The biomasses were estimated by sampling 35 stems representing the full range of observed dsh; their dsh, height and fresh weight were measured. A sub sample of stems was then chopped into ca. 0.2 liters small pieces and their moisture content (MC, wet basis) was determined according to CEN/TS 14774-2 (2004). The MC was on average 50.4% (*sd* 1.6%). The oven-dry (OD) masses of stems with different dsh were then used to generate a biomass function [1] (cf. Verwijst and Telenius 1999):

Table 1 Average values for the properties of the two study areas. Standard deviations are quoted in parentheses. OD = oven-dry

Tablica 1. *Prosječne vrijednosti značajki dvaju istraživanih područja. Standardna je devijacija navedena u zagradama. OD = suha tvar*

	Study areas *Istraživano područje*	
Properties – *Svojstva*	Normal *Normalno*	Overgrown *Preraslo*
Density, stool/ha – *Gustoća, panj/ha*	13,815 (1,527)	12,765 (2,859)
Density, stems/stool *Gustoća,* stabljika/ha	3.5 (0.5)	3.7 (0.7)
Diameter at stump height, cm* *Promjer na panja,* cm*	2.7 (1.2)	3.1 (1.5)
Height, m* – *Visina,* m*	5.4 (2.1)	6.0 (2.2)
Biomass, OD t/ha – *Biomasa, OD* t/ha	36 (8)	56 (17)
Biomass, raw mass, t/ha *Biomasa, sirova masa,* t/ha	72 (16)	114 (35)
Mean annual increment, OD t/ha, year *Srednji godišnji prirast, OD* t/ha, *godina*	6.0	9.3

*Arithmetic mean value – *Aritmetička srednja vrijednost*

$$\text{Stem mass (OD kg)} = 0.0001 \times dsh^{2.603};\ R^2 = 0.979 \quad (1)$$

Where:

dsh diameter at stump height, mm

A harvester and forwarder system and a harwarder system were studied. The harvester was a Valmet 911.1 (Komatsu Forest AB, Sweden) with 4 wheels, a mass of 15.2 t, a power output of 129 kW and a width of 2.7 m. The harvester crane was a Cranab CRH 16 (Cranab AB, Sweden) with a maximum reach of 9.8 m and equipped with the Bracke C16.a (Bracke Forest AB, Sweden) AFH with a mass of 500 kg which cuts trees with a saw-chain attached to a rotating disc with a diameter of 795 mm. The forwarder was a Timberjack 1210B Pendo (John Deere Forestry Oy, Finland) with 8 wheels, a mass of 15.5 t, a power output of 114 kW and a width of 2.8 m. The load capacity of the machine was 14 t and the load bunk cross sectional area was 4.2 m^2. The forwarder crane was a Loglift F71 FT (Loglift Jonsered AB, Sweden) with a maximum reach of 10.0 m. The forwarder was

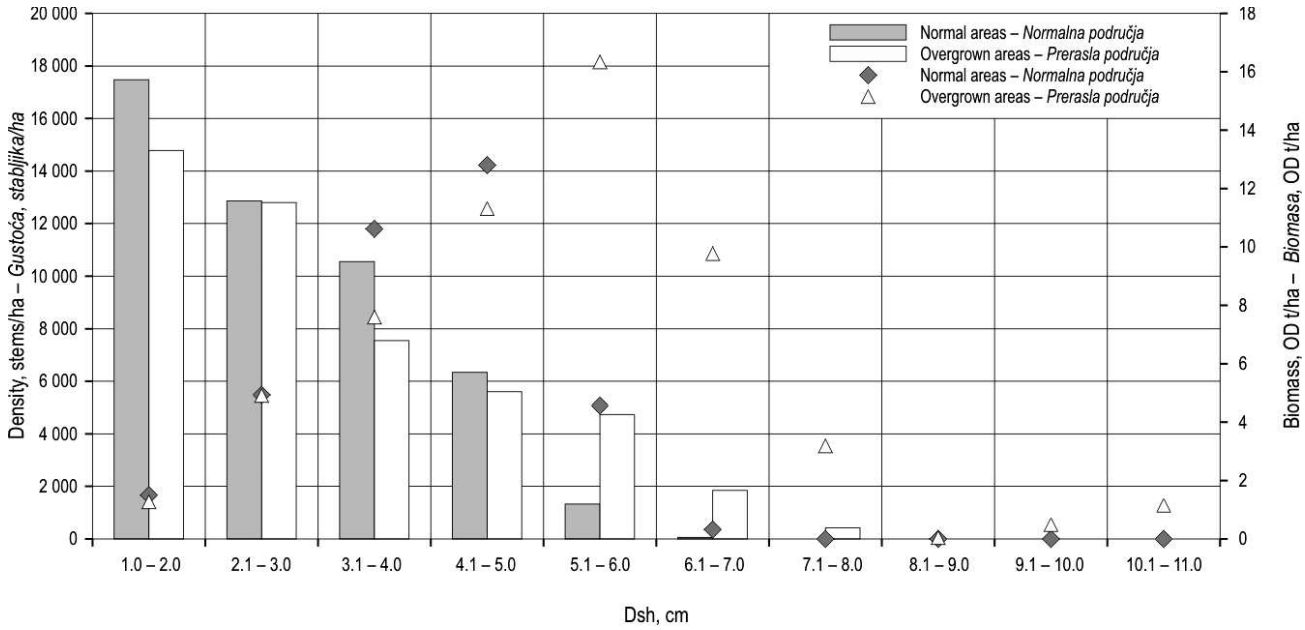

Fig. 1 The number of stems (bars) and the biomass (polygons) per ha as a function of stem diameter at stump height for the normal (N) and overgrown (O) areas. Dsh = diameter at stump height, OD = oven-dry

Slika 1. *Broj stabljika (stupci) i biomasa (poligoni) po hektaru kao funkcija promjera stabala na visini panja za normalno (N) i preraslo (O) područje. Dsh = promjer na visini panja, OD = suha tvar*

equipped with a slash grapple (Hultdins AB, Sweden) with a grapple-area of 0.36 m^2. The same forwarder was also used as a harwarder, and in this case it was equipped with the Naarva Grip 1500-25 E (Pentin Paja Oy, Finland) accumulating felling-grapple. During the experiments the harvester, forwarder and harwarder were operated by one, two and one operator, respectively. All operators were professionals and experienced with harvesting of small trees in thinning operations.

The harvester felling and bunching work was studied as a function of 3 factors, giving 8 different treatment combinations: factor α, biomass density (N and O); factor β, number of harvested double--rows (5 and 6 rows); and factor γ, working method (i.e. front and side to side; see Fig. 2 for an explanation of these terms). The cut stems were bunched in piles positioned to the rear of the machine, at an angle of ca. 45° to the strip road, on the side of the harvester with the butt ends pointing towards the machine (Fig. 2). For each treatment combination the harvester's operation was studied for at least 0.5 Productive Work hours (PW) hours (IUFRO 1995) and for at most 1 PW-hour, short delays were also recorded. A randomized block design with 3 blocks was used; in total, 24 study units were harvested in the experiment (12 in N and 12 in O) (Fig. 3). The results of the experiment were analyzed by ANOVA, using a general linear model of the form:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + c_1 + \alpha_i \times \beta_k + \alpha_i \times \gamma_k + \beta_j \times \gamma_k + \alpha_i \times \beta_j \times \gamma_k + \varepsilon_{ijkl} \quad (2)$$

Where:

- μ overall mean,
- α biomass density,
- β number of harvested double-rows,
- γ working method,
- ε error.

The forwarder loaded the piles into the bunk area until a full load was achieved (up to the full length of the stakes) and then hauled the biomass to roadside, where the stems were unloaded perpendicular to the direction of the road, with their butt ends pointing towards the road. The forwarder's work time consumption was analyzed in terms of the factors α and β (see above) using a linear ANOVA model of the form:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \chi_k + \alpha_i \times \beta_j + \varepsilon_{ijk} \quad (3)$$

The harwarder cut and directly loaded the stems until the bunk area was loaded to the capacity and then hauled the biomass to the roadside for unloading (Fig. 4). Each load corresponded to a study unit. Six study units (three blocks) were harvested in the O area and two in the N area (one block) (Fig. 3). The results of the work in the O stand were analyzed using a two-way ANOVA model:

$$y_{ij} = \mu + t_i + b_j + \varepsilon_{ij} \quad (4)$$

Where:

μ overall mean,

t_i treatment main effect (number of harvested rows),

b_j block main effect,

ε_{ij} random error term.

The average work time consumption in the O area (six study units) was compared to the average work time consumption in the N area (two study

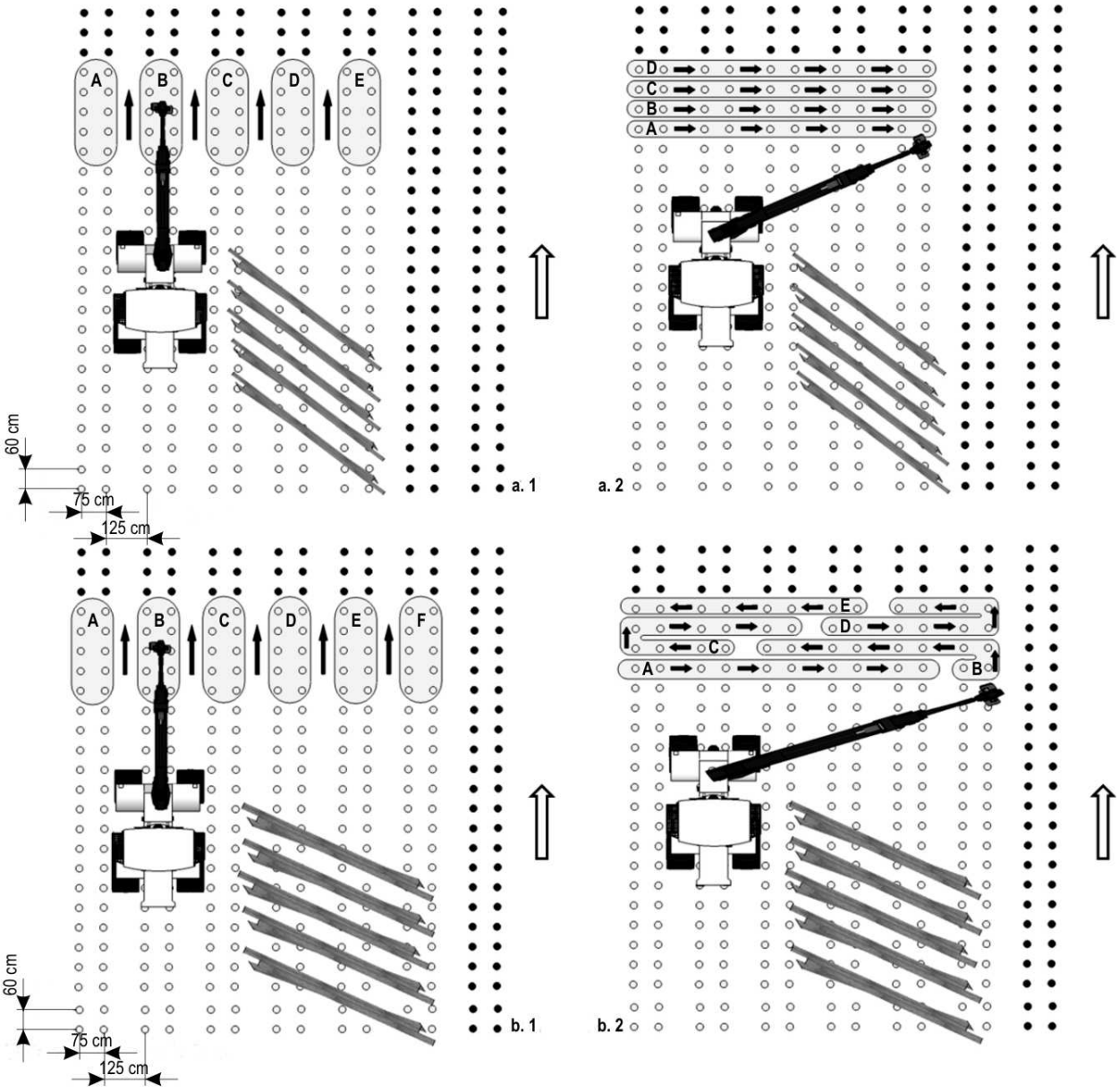

Fig. 2 The working methods used with the harvester when harvesting either 5(a) or 6(b) double-rows, in a direction parallel (a.1 and b.1) or perpendicular (a.2. and b.2) to the orientation of the machine. The large hollow arrows on the right hand side of the drawings indicate the machine's working direction. The alphabetic sequence of capital letters in each drawing shows the sequence of crane cycles (i.e. the stools in the area marked »A« were felled first, then those in the area marked »B«, etc.) The small black arrows in the drawings indicate the direction of the crane's movement during felling and bunching; the shaded oval regions denote approximately the area felled during each crane cycle

Slika 2. *Metode rada primijenjene pri radu harvestera kod sječe 5(a) ili 6(b) duplih redova, u paralelnom ili okomitom smjeru u odnosu na orijentaciju stroja. Velike prazne strelice na desnoj strani crteža prikazuju radni smjer stroja. Abecedni slijed velikih slova na svakom crtežu prikazuje slijed ciklusa krana (panjevi na površini A sječeni su prvi, zatim oni na površini B itd.). Male crne strelice na crtežu pokazuju smjer kretanja krana tijekom sječe i vezanja snopova; zasjenčena ovalna područja prikazuju približno površine koje su sječene u svakom ciklusu krana*

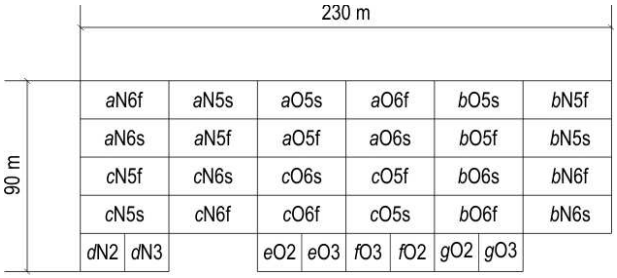

Fig.3 The spatial layout of the study units (cells), with their treatments, in the study area. The italic letter in each of the cells indicates the block affiliation (i.e. »*a, b, c*« for the harvester–forwarder and »*d, e, f, g*« for the harwarder). The capital letters indicate the biomass density (i.e. normal (N) and overgrown (O)). Numbers indicate the number of harvested double-rows (i.e. 5 and 6 rows and 2 and 3 rows). The letter positioned after the numbers indicates the harvester's working method (i.e. in front (f) and side to side (s))

Slika 3. *Prostorni raspored istraživanih jedinica (polja), s njihovim postupcima, u istraživanom području. Kurzivno slovo u svakom polju prikazuje pripadnost bloka (npr. »a, b, c« za forvarder–harvester i »d, e, f, g« za harvarder). Velika slova pokazuju gustoću biomase (npr. normalno (N) i preraslo (O)). Brojevi pokazuju broj posječenih duplih redova (npr. 5. i 6. red te 2. i 3. red). Slova iza brojeva pokazuju radnu metodu harvestera (npr. ispred (f) i sa strane na stranu (s))*

units). The data were analysed using Tukey's *t*-test; differences were considered significant if $p < 0.05$.

The work time consumption was recorded by using the Allegro Field PC® and the SDI software (Haglöf, AB). The individual work elements involved in the operation of the harvester took relatively short time and where therefore studied with frequency measurements (cf. Harstela 1991). The harvester's operational state (i.e. the work element currently in progress) was recorded once every 7 s, giving precedence to the element with the highest priority as specified in Table 2. In addition, the total time consumption was recorded in order to control for missed observations.

The individual work elements in the operation of the forwarder and harwarder took a relatively long time and they were therefore studied with snap-back timing (continuous time recording) rather than frequency registration (cf. Harstela 1991). The times were recorded in cmin (i.e. 1 cmin = 1/100 min). The work time was recorded separately for the various work elements listed in Table 3.

The harvested area was subsequently inventoried in 28 rectangular sample plots (sized to contain 20 stools) and systematically laid out and spaced 30 m along the strip roads. In each plot, the cutting height of each stool was measured, the number of damaged stumps was counted and the depth of the tire tracks (i.e. the distance between the bottom and the rim edge for each track section) in relation to the mid-section of each sample plot was measured. A stump was considered to be damaged if more than half of its radius was cracked.

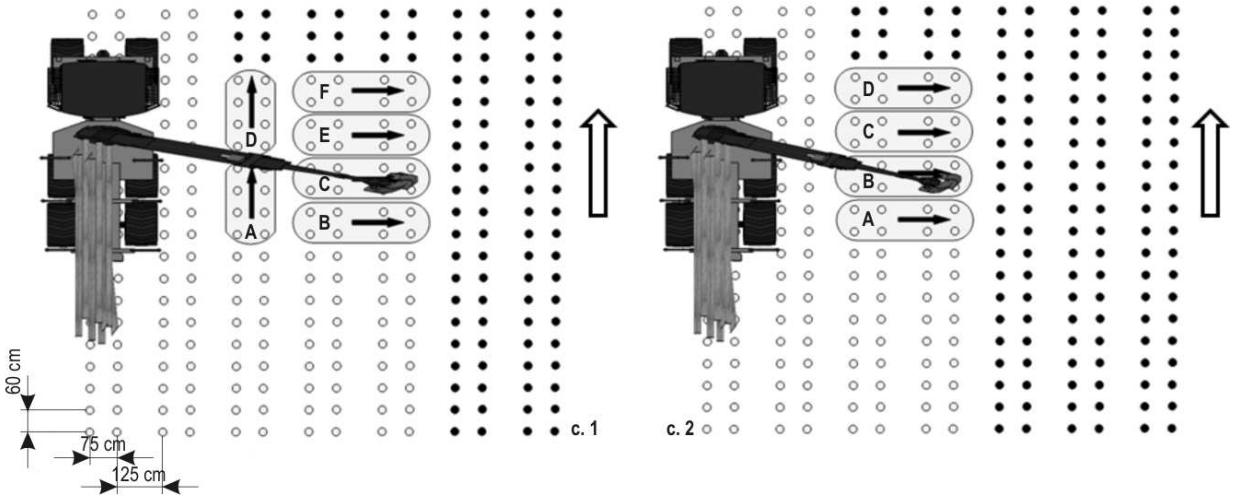

Fig. 4 The working methods used with the harwarder when harvesting either 3 (c.1) or 2 (c.2) double-rows. The large hollow arrows on the right hand side of the drawings indicate the machine's working direction. The alphabetic sequence of capital letters in each drawing shows the sequence of crane cycles (i.e. stools in the area marked »A« were felled first, then those in the area marked »B«, etc.). The small black arrows indicate the direction of the crane's movement during felling and bunching; the shaded oval regions denote approximately the area felled during each crane cycle

Slika 4. *Metode primijenjene pri radu harvardera kod sječe 3 (c.1) ili 2 (c.2) duplih redova. Velike prazne strelice na desnoj strani crteža prikazuju radni smjer stroja. Abecedni slijed velikih slova na svakom crtežu prikazuje slijed ciklusa krana (panjevi na površini A sječeni su prvi, zatim oni na površini B itd.). Male crne strelice na crtežu pokazuju smjer kretanja krana tijekom sječe i vezanja snopova; zasjenčena ovalna područja prikazuju približno površine koje su sječene u svakom ciklusu krana*

Table 2 Definitions of the work elements in the operation of the harvester
Tablica 2. *Definicije radnih elemenata u radu harvestera*

Work element *Radni element*	Description *Opis*	Priority* *Prioritet**
Boom out Prazan kran	Starts when an empty crane moves towards the first stool to be harvested and stops when the first tree has been reached *Počinje kada prazni kran kreće prema prvomu panju gdje će se sjeći i završava kada se dosegne prvo stablo*	2
Felling and accumulating Sječa i kumuliranje	Starts when the first tree has been reached and stops when the last tree has been felled *Počinje kada se dosegne prvo stablo i završava kada se zadnje stablo posiječe*	1
Boom in Puni kran	Starts when the last tree in the crane cycle has been felled and stops when trees have been dropped on the ground (includes time spent arranging the bunch) - *Počinje kada je zadnje stablo u ciklusu krana posječeno i završava kada su stabla spuštena na tlo (uključuje vrijeme uređenja svežnja)*	2
Moving Kretanje	Starts when the machine wheels begin turning and stops when the wheels stop *Počinje kada se kotači stroja počinju okretati i završava kada se kotači zaustave*	3
Miscellaneous Razno	Other activities e.g. cutting roots away from the bottom of the stems *Ostale aktivnosti, npr. rezanje korijena sa stabla*	4
Delays Zastoji	E.g. repairs and personal breaks *Npr. popravci i osobni odmori*	4

*If work elements were performed simultaneously, the element with the highest priority (lowest number) was recorded
**Ako su radni elementi izvođeni istodobno, element je s višim prioritetom (manji broj) zabilježen*

Table 3 Definitions of the work elements in the operation of the forwarder (F) and harwarder (H)
Tablica 3. *Definicije radnih elemenata u radu forvardera (F) i harvardera (H)*

Work element *Radni element*	Description *Opis*	Priority* *Prioritet**
Boom out, H *Prazan kran, H*	Starts when an empty crane moves towards the first stool to be harvested and stops when the first tree has been reached *Počinje kada prazni kran kreće prema prvom panju gdje će se sjeći i završava kada se dosegne prvo stablo*	1
Felling and accumulating, H *Sječa i kumuliranje, H*	Starts when the first tree has been reached and stops when the last tree has been felled *Počinje kada se dosegne prvo stablo i završava kada se zadnje stablo posiječe*	1
Loading, H *Utovar, H*	Starts immediately after the felling of the last tree in the crane cycle and stops when the bunch of trees has been transferred to the log bunk *Počinje odmah nakon sječe zadnjega stabla u ciklusu krana i završava kada je svežanj stabala prenesen u utovarni prostor*	1
Loading, F *Utovar, F*	Starts when the empty crane move from its base position in the bunk area and stops when the crane returns to the load bunk *Počinje kada prazan kran krene sa svoje osnovne pozicije u području ležišta i završava kada se vrati u utovarni prostor*	1
Moving while loading, F–H *Kretanje pri utovaru, F–H*	Starts when the machine wheels begin turning and ends when the wheels stop moving to allow cutting/loading *Počinje kada se kotači stroja počinju okretati i završava kada se kotači zaustave da omoguće sječu/utovar*	2
Moving loaded, F–H *Puna vožnja, F–H*	Starts when the machine moves from the study unit and ends when the machine stops at the landing *Počinje kada stroj kreće s istraživane jedinice i završava kada se zaustavlja na stovarištu*	2
Unloading, F–H *Istovar, F–H*	Starts when the machine stops at the landing and ends when the base machine starts to move from the landing *Počinje kada se stroj zaustavi na stovarištu i završava kada krene sa stovarišta*	1
Moving unloaded, F–H *Prazna vožnja, F–H*	Starts when the machine moves from the landing and ends when the machine stops at the cutting/loading area *Počinje kada stroj kreće sa stovarišta i završava kada se zaustavlja na mjestu sječe/utovara*	2
Miscellaneous, F–H *Razno, F–H*	Other activities, e.g. picking up dropped bunches, etc *Ostale aktivnosti, npr. podizanje ispalih svežnjeva*	3
Delays, F–H *Zastoji, F–H*	E.g. repairs and personal breaks *Npr. popravci i osobni odmori*	3

*If work elements were performed simultaneously, the element with the highest priority (lowest number) was recorded
**Ako su radni elementi izvođeni istodobno, element je s višim prioritetom (manji broj) zabilježen*

The system analysis boundaries were defined to include harvesting and forwarding of the biomass piled at roadside. The plantation size was set to 10 ha (cf. Rosenqvist et al. 2000), giving a forwarding distance of 250 m. The analyses were based on the average productivity of the harvester and harwarder when harvesting six and three double rows, respectively. The conversion of PW into Work Time including delays shorter than 15 min (WT) (IUFRO 1995) was based on the maximum proportion of delay time recorded in the field study for each system. The interest rate was set to 6% and the calculation was made according to Harstela (1993). The purchase prices were set for the harvester, forwarder and harwarder to €285,000, €225,000 and €270,000, respectively (cf. Laitila 2008). The annual utilization time (AU) for the harvester, forwarder and harwarder were set to 2,361 WT-hours/year, 2,500 WT-hours/year and 2,430 WT-hours/year, respectively (cf. Nurminen et al. 2009). The AU for the harwarder was calculated as an average of the harvester and forwarder values. The economic lifetime was set to 6 years and the salvage value was set to 20% of the purchase price. The operator costs were set to 20 €/WT-hour. The calculated hourly operating costs of the harvester, forwarder and harwarder were 85.2 €/WT-hour, 70.4 €/WT-hour and 79.6 €/WT-hour, respectively. The relocation cost was set to 200 € per machine and relocation. The gross income was based on current market price for un-comminuted tree parts delivered at road side of 21.0 €/m^{3}solid (Anon 2010). A conversion rate of 397 OD kg/m^{3}solid was used (cf. Nurmi 1995). The net income of the removal was calculated as the difference between the roadside gross income and the harvesting costs (including relocation costs).

3. Results – R*ezultati*

The harvester was studied for 19.67 WT hours, of which delay time accounted for 0.3%. The harvested area was 1.46 ha. The PW time consumption per ha in the N and O area was 13.2 (sd = 1.4) and 13.5 (sd = 1.2) hours, respectively, which corresponds to respectively 0.36 and 0.24 PW-hours/OD t. The average productivity of the harvester was 3.5 OD t/PW-hour. The biomass density (factor α) and the number of harvested rows (factor β) had significant effects on productivity ($p < 0.001$ and $p = 0.036$, respectively). Consequently, the productivity was 54.4% higher in the O area than in N, and it was 9.3% higher when harvesting five rather than six rows. The working method (factor γ) had no significant effect on productivity ($p = 0.132$). No significant block or interaction effects on PW time consumption per hectare were found.

The average number of felled and accumulated stools per crane cycle in the N and O areas was 13.2 and 8.8, respectively, and the difference was significant ($p < 0.001$). The average amount of biomass harvested in a full crane cycle in the N and O areas was 34.3 and 39.6 OD kg, respectively, and the difference was significant ($p = 0.018$). The total time consumption per stool did not differ significantly for any of the eight examined combinations of the tree factors (Table 4). However, the greater biomass density (factor a) in O areas (relative to N areas) resulted in a 10.6% and significant increase ($p = 0.019$) in the PW time consumption per stool. Harvesting five rows instead of six (factor β) caused an 8.9% significant reduction ($p = 0.029$) in PW time per stool.

The forwarder was studied for 7.64 WT-hours, of which delay time accounted for 8%. In total 25 full loads were loaded, forwarded to roadside and un--loaded. At a hauling distance of 250 m, the time required for forwarding averaged 21.8 PW-min per load, which corresponds to a productivity of 7.2 OD t/PW-hour. The corresponding PW time consumption per hectare in the N and O area is then 5.0 (0.5) and 7.8 (0.7) hours, respectively. A full load averaged 2.6 OD t (5.3 fresh t), which corresponds to 38% of the machine's load capacity. The load size reached 2.5 and 2.7 OD t (4.8 and 5.7 fresh t), respectively, in the N and O area, the difference in load size was not significant ($p = 0.100$). To reach a full load in the N and O area, in average 15 and 13 crane cycles were required, respectively. The average forwarding distance was 163 m (min. 32 and max. 317 m). An average strip road length of 47 m was required to achieve a full load. The forwarder's average moving speed during productive work was 1.2 m/s when unloaded and 1.0 m/s when loaded. The average calculated bulk density of a full load was 109 OD kg/m^3 (220 fresh kg/m^3). Unloading took 4.66 PW-min per load on average (1.79 PW-min/OD t) and required an average of 10.8 crane cycles; the mass handled per crane cycle was 0.25 OD t. Miscellaneous time accounted for 0.58 PW-min per load on average (0.22 PW-min/OD t). Loading and moving while loading accounted for 7.39 and 1.36 PW-min per load (2.84 and 0.52 PW-min/OD t), respectively. The biomass density and number of rows (factors α and β) did not significantly affect the total time spent in loading and moving while loading in terms of PW-time/OD t. However, in the O area, the loading work element took 18% longer than was the case in the N area, and this difference was significant (p = 0.026) (Table 5).

The harwarder was studied for 15.09 WT-hours, of which delay time accounted for 4%. It harvested an area of 0.29 ha. In total, 8 full loads were produced. At a hauling distance of 250 m, the producti-

Table 4 Productive work time (PW) consumed per stool (s/stool) during harvester operation
Tablica 4. *Proizvodno radno vrijeme (PW) utrošeno po panju (s/panj) za vrijeme rada harvestera*

Factor, α *Faktor,* α	Normal, N *Normalno, N*				Overgrown, O *Preraslo, O*			
B	5 rows – *5 redova*		6 rows – *6 redova*		5 rows – *5 redova*		6 rows – *6 redova*	
Γ	Forward *Ispred*	Side to side *Strana na stranu*	Forward *Ispred*	Side to side *Strana na stranu*	Forward *Ispred*	Side to side *Strana na stranu*	Forward *Ispred*	Side to side *Strana na stranu*
	n = 3	n = 3	n = 3	n = 3	n = 3	n = 3	n = 3	n = 3
Boom out *Prazan kran*	0.304^{a}	0.341^{a}	0.341^{a}	0.310^{a}	0.434^{a}	0.471^{a}	0.461^{a}	0.530^{a}
Felling and accumulating *Sječa i kumuliranje*	2.415^{ab}	2.241^{b}	2.704^{ab}	2.758^{ab}	2.591^{ab}	2.338^{b}	2.907^{a}	2.466^{ab}
Boom in *Puni kran*	0.461^{a}	0.466^{a}	0.521^{a}	0.420^{a}	0.593^{a}	0.556^{a}	0.621^{a}	0.632^{a}
Moving *Kretanje*	0.120^{ab}	0.120^{ab}	0.080^{b}	0.082^{b}	0.121^{ab}	0.179^{a}	0.103^{b}	0.096^{b}
Miscellaneous *Razno*	0.028^{a}	0.000^{a}	0.011^{a}	0.022^{a}	0.009^{a}	0.017^{a}	0.044^{a}	0.035^{a}
Total time *Ukupno vrijeme*	3.327^{a}	3.168^{a}	3.657^{a}	3.592^{a}	3.747^{a}	3.561^{a}	4.135^{a}	3.760^{a}

Total PW time consumption per stool, *p*-values: Factor α = **0.019**, Factor β = **0.029**, Factor γ = 0.176, Factor $\alpha \times \beta$ = 0.769, Factor $\alpha \times \beta$ = 0.551, Factor $\beta \times \gamma$ = 0.866, Factor $\alpha \times \beta \times \gamma$ = 0.615, Block = 0.444
The *p*-values in bold indicate significant differences ($p \leq 0.05$). Different superscript letters row-wise indicate significant ($p \leq 0.05$) differences between treatments according to Tukey's simultaneously test of means
Ukupno PW utrošeno po panju, p-vrijednosti: faktor α = ***0.019***, *faktor* β = ***0.029***, *faktor* γ = *0.176, faktor* $\alpha \times \beta$ = *0.769, faktor* $\alpha \times \beta$ = *0.551, faktor* $\beta \times \gamma$ = *0.866, faktor* $\alpha \times \beta \times \gamma$ = *0.615, blok= 0.444*
p-vrijednosti označene poludebelo pokazuju značajne razlike (p ≤ 0.05). Različita slova u eksponentu po redovima pokazuju značajne (p ≤ 0.05) razlike između postupaka prema Tukeyevu testu

Table 5 Productive work time (PW) consumed by individual work elements in the operation of the forwarder when loading and moving while loading. The table shows the PW time consumed for different biomass densities (factor α, which can be either normal (N) or overgrown (O)) and the effects of operational factors, including the biomass concentration along strip roads, pile size, number of piles per crane cycle, and machine position. Standard deviations are given within brackets

Tablica 5. *Proizvodno radno vrijeme (PW) utrošeno po pojedinim radnim elementima u radu forvardera kod utovara i kretanja pri utovaru. Tablica pokazuje PW utrošeno za različite gustoće biomase (faktor* α*, koji može biti ili normalno (N) ili preraslo (O)) i utjecaje radnih čimbenika uključujući koncentraciju biomase pored putova, veličinu složaja, broj složaja po ciklusu krana i poziciju stroja. Standardne su devijacije dane u zagradama*

Factor α – *Faktor* α	Normal, N – *Normalno, N*		Overgrown, O – *Preraslo, O*	
	n = 12		n = 12	
	min/OD t	%	min/OD t	%
Loading – *Utovar*	$2.61\ (0.46)^{a}$	82.9	$3.07\ (0.47)^{b}$	85.8
Moving while loading – *Kretanje pri utovaru*	$0.54\ (0.13)^{a}$	17.1	$0.51\ (0.09)^{a}$	14.2
Sum of Loading and Moving while loading – *Zbroj utovara i kretanja pri utovaru*	$3.15\ (0.54)^{a}$	100	$3.58\ (0.53)^{a}$	100
Biomass concentration, OD t/100 m – *Koncentracija biomase, OD t/100* m	3.96 (0.38)		6.16 (0.59)	
Pile size, OD t – *Veličina složaja, OD* t	0.17 (0.03)		0.23 (0.02)	
No. crane cycles/pile – *Broj ciklusa krana/složaj*	1.00 (0.00)		1.08 (0.10)	
No. piles/machine position – *Broj složajeva/pozicija stroja*	1.15 (0.14)		1.12 (0.14)	

Different superscript letters row-wise indicate significant ($p \leq 0.05$) differences between treatments according to Tukey's test of means
Različita slova u eksponentu po redovima pokazuju značajne (p ≤ 0.05) razlike između postupaka prema Tukeyevu testu

vity in the N and O area was 0.75 and 1.02 OD t/PW-hour, respectively. Consequently, the PW time per ha in the N and O area was 47.8 (*sd* = 1.9) and 54.9 (*sd* = 4.7) hours, respectively. The average hauling distance was 183 m (min. 45 m and max. 280 m). On average, the harwarder moved at a speed of 1.2 m/s while unloaded and 1.0 m/s while loaded. The average load mass was 1.8 OD t (3.6 t of fresh biomass), which corresponds to 26% of the machine's load capacity. The average calculated bulk density of a full load was 74 OD kg/m^3 (148 fresh kg/m^3). Unloading took 7.08 min/load (3.93 min/OD t) on average, and required an average of 17 crane cycles; the mean handled mass per crane cycle was 0.11 OD t. Miscellaneous time accounted for 0.44 minutes per load (0.25 min OD/t). The number of harvested rows (factor β_1) had no significant effect on total PW time consumption in the O area. The biomass density (factor α) had a significant effect on PW time consumption ($p < 0.001$), and was 42% higher in the N area compared to O area (Table 6). The mean handled mass per crane cycle during felling and loading was 27 OD kg; for the N area (23 OD kg) it differed significantly ($p = 0.042$) from that for the O area (28 OD kg). The mass moved by the crane during the felling and loading cycle was 74% lower than the corresponding mass while unloading. The number of stools handled per crane cycle was 9.0 and 6.3 in the N and O area, respectively, and the difference was significant ($p = 0.034$).

Table 6 Productive work time (PW) consumed by individual work elements in the operation of the harwarder and in total, for different biomass densities (factor α; normal (N) and overgrown (O))

Tablica 6. *Proizvodno radno vrijeme (PW) utrošeno po pojedinim radnim elementima u radu harvardera i ukupno, za različite gustoće biomase (faktor α, normalno (N) ili preraslo (O))*

Factor α – *Faktor α*	Normal, N *Normalno, N*		Overgrown, O *Preraslo, O*	
	n = 2		n = 6	
	min/OD t	%	min/OD t	%
Boom out *Prazan kran*	4.88 (0.76)^a	6.8	4.23 (1.03)^a	8.4
Felling – *Sječa*	57.25 (1.36)^a	80.4	38.34 (2.58)^b	76.2
Loading – *Utovar*	6.91 (0.24)^a	9.7	5.85 (0.70)^b	11.6
Moving while loading *Kretanje pri utovaru*	2.19 (0.18)^a	3.1	1.89 (0.43)^a	3.8
Sum – *Zbroj*	71.23 (1.70)^a	100	50.32 (2.99)^b	100

Different superscript letters row-wise indicate significant ($p = 0.05$) differences between treatments according to Tukey's simultaneously test of means
Različita slova u eksponentu po redovima pokazuju značajne (p = 0.05) razlike između postupaka prema Tukeyevu testu

Table 7 Gross incomes, costs and net incomes for the two-machine and harwarder systems in normal (N) and overgrown (O) willow plantations. OD = oven-dry

Tablica 7. *Bruto prihod, troškovi i neto dobit za sustav s dvama strojevima i harvarder u normalnim (N) i preraslim (O) plantažama vrba. OD = suha tvar*

	Harvester and forwarder *Harvester i forvarder*		Harwarder – *Harvarder*	
	Normal, N *Normalno, N*	Overgrown, O *Preraslo, O*	Normal, N *Normalno, N*	Overgrown, O *Preraslo, O*
Gross income, €/ha *Bruto prihod, €/ha*	1 904	2 962	1 904	2 962
Cost, €/ha *Troškovi, €/ha*	1 721	1 934	3 987	4 572
Cost, €/ODt *Troškovi, €/ODt*	48	35	111	82
Net income, €/ha *Neto dobit, €/ha*	184	1 028	–2 082	–1 610
Net income, €/ODt *Neto dobit, €/ODt*	5	18	–58	–28

The mean height of the harvested stumps was 18.2 cm (min. 3 cm, max. 58 cm and median 17.5 cm). The proportion of damaged stumps was 29.9%. No significant differences in either stump height or proportion of damaged stumps was observed for any treatment factors or machine/felling head types. The average depth of the machines' tracks after the work was complete was 6 cm (min. 0 cm, max. 28 cm and median 1.5 cm).

Economic Analysis

In the two-machine system, the harvester operation accounted for 75% of the total cost of the work in the N area and 67% in the O area. The total operating costs per hectare for the two-machine system in the N and O areas were respectively 43% and 42% lower than those for the harwarder (Table 7). In the O area, the cost per harvested OD t for the two-machine system and for the harwarder was respectively 73% and 74% lower than the corresponding cost in the N area. The cost to gross income ratio was below 100% for the two-machine system, but above 100% for the harwarder. The net income per OD t for the two machine system was 2.6 times higher in the O area than in the N area.

4. Discussion – *Rasprava*

The harvester

The biomass density (OD t/ha) (i.e. tree size) had only a minor, non-significant, effect on the felling--bunching work time consumption per ha. The har-

vester's productivity was therefore 54% higher in the O areas than in the N areas as the biomass density in O areas was 57% higher than that in N areas. Similar results of increases in harvester productivity have been reported in the thinning of forest stands for energy-wood (Kärhä et al. 2005, Di Fulvio et al. 2011). Fewer harvested rows had a significant reduction effect on the harvester's time consumption per ha, which was due to the use of relatively shorter crane extensions (cf. Ovaskainen 2009). In this case the driver had a clearer view of the cutting device and the progress of the work, resulting in more accurate control over the felling process. The working method »forward« had no significant effect on the harvester's time consumption but with this method it was easier to grab a single stool at a time than working perpendicularly to the rows (side to side) (cf. Fig. 2). Visual inspection indicated that the felling speed during a crane cycle was slightly reduced cutting stems larger than ca. 3 cm dsh, which in turn facilitated the possibility to manage a proper accumulation of the cut stems (i.e. at higher speeds it was more difficult to manage a proper accumulation). This suggests that modification of the accumulating function might be necessary in order to fully exploit the potential of this technology when harvesting at higher speeds. To increase the potential of AFHs, the felling and accumulation of trees must be performed in a continuous movement, for instance by using the boom-corridor technique (cf. Bergström 2009, Forsberg and Wennberg 2011). The harvester operator experienced a more stressful work that required a greater degree of concentration in the current study (i.e. clear cutting of SRWC) compared to energy-wood thinning. This was mainly due to the handling of many more trees/stems per hour of work time. This problem could possibly be reduced by increasing the automation of the felling process, e.g. by having the driver control only the felling direction and speed, with grabbing, cutting and the accumulation of stems being performed automatically.

The forwarder

The biomass density and number of harvested rows did not significantly affect the work time required per load for the forwarder. However, the higher biomass concentration in the O area significantly increased the loading time consumption per OD t. This is because the pile size in the O area was 42% larger than that in the N area; the piles in the O area were thus larger than the grapple area and multiple crane cycles were required per pile. The average mass of the piles in the O area, when harvesting six rows, was 487 kg. The force required to lift such piles, when they are located ca. 3 m away from the machine, is much less than the studied machine's capacity (1500 kg at 4.5 m from the crane base). The grapple area was therefore deemed to be the limiting factor in this work; it is expected that the efficiency of forwarding in the O areas could be increased by using a grapple with a larger grapple area that would be able to load the larger piles using only one crane cycle. In this case, estimates based on the field study data suggest that the time consumption for loading and moving while loading would have been decreased by 6% if all piles had been loaded with only one crane cycle. On the basis of the field data, it was determined that each stoppage of the machine consumed 3.5 s on average, which was added to the »moving while loading« time element. Suppose that in the O area, the harvester produced piles whose sizes corresponded to either 1 or 2 full forwarder grapples (0.216 or 0.432 OD t), with the density of piles per loading position being high in the former case and low in the latter. In this case, it would be possible to describe the time spent moving while loading as a function of the spacing between the piles. The production of larger and more widely-separated piles would decrease the total time spent on loading and moving while loading per OD t forwarded by 3%. Overall, these observations indicate that the size of the piles produced by the harvester must match the capacity of the forwarder's grapple in order to maximise the efficiency of forwarding, i.e. the work of the harvester and the forwarder must be synchronized (cf. Gullberg 1997).

The harwarder

The harwarder was equipped with an accumulating felling-grapple designed for both felling and loading. However, because of its dual-purpose nature, the felling-grapple is less efficient at either task than purpose-specific heads. That is to say, the number of stools felled per crane cycle with the felling-grapple was 30% lower than the corresponding number achieved with the harvester's AFH, and the grapple load during unloading contained 57% less biomass than that achieved using the slash grapple employed in forwarding operations. In addition, the mass of a full harwarder load was 32% lower than that of a full forwarder load. The difference in load mass can be explained by the fact that the forwarder loaded pre-bunched stems, which were thus somewhat compressed, while the harwarder performed direct-loading. It might be possible to increase the harwarder payload by using load compression devices, such as flexible stakes attached to the bunk of the machine (cf. Bergström et al. 2010). The time spent on felling per stool was 3.9 times higher for the harwarder than for the harvester (9.8 s/stool com-

pared to 2.5 s/stool). It is reasonable to assume that the felling speed of the harwarder could be significantly increased by using more advanced technology that is better suited to industrial forestry, such as the Ponsse EH25 felling-grapple. If we assume that the harwarder's felling speed could be doubled in this way, the time consumption per stool would be 4.6 s and 5.2 s, respectively, in the N and O areas. Such increases in felling efficiency would in turn increase the machine's productivity in the N and O areas by 59% and 52%, respectively, relative to the results obtained in the field study.

An additional increase in productivity could also be expected with a purpose built harwarder; the one used in this work was a standard forwarder with a crane designed only for loading.

Work quality

The operators of the harvester and harwarder were instructed to cut the stools to an above-ground height of less than 10 cm. However, both felling heads produced average stump heights in excess of this level. This was partially due to the snow that covered the soil when the harvesting was performed, which made it difficult to assess the true ground level. It was also observed that when stools were cut row-wise, the stump height rose as the boom reach increased, i.e. the stumps were shorter close to the machine and taller further away from it. The average proportion of damaged stumps was 30%, which is relatively high (cf. Hytönen 1994). It was observed that, when using the harvester, it was possible to grab more than one stool at a time with the AFH, which caused the stems to bend slightly while being cut; this in turn caused the stools to split. The tracks left by the machines' wheels were relatively shallow. Harvesting was performed at a time when the soil was partially frozen, which had a positive effect on its bearing capacity. Using tracks on the forwarder's wheels (bogies) would significantly reduce the pressure it exerts on the ground, which would be especially useful on wet soils.

Economic Analysis

When using forest machines to harvest SRWC, the productivity can be expected to increase with the size of the stems up to a certain point. The two-machine system was found to be profitable in both the normal and over-gown areas, while the harwarder produced a loss in both. The conventional direct chipping system reaches an average productivity of about 16 OD t/WT hour under conditions where the crop yield is 25 OD t/ha (Danfors and Nordén 1995). It would therefore be expected to achieve greater incomes than with either of the studied forest machines systems under normal and somewhat overgrown conditions (cf. Danfors and Nordén 1995). However, as the amount of biomass harvested increases, the profitability of the forest systems increases while the convenience and ease of operation of the conventional systems is expected to decline. This suggests that the use of two-machine systems in more heavily overgrown willow plantations could be even more efficient than that of conventional direct chipping systems.

5. Conclusions – *Zaključci*

This study shows that a thinning harvester's work time consumption per hectare in the felling and bunching of stems in SRWC plantations is meagerly affected by stem sizes or biomass density, which gives a harvesting productivity increase almost proportional to the increase in biomass density. The work time consumption of the harwarder increased significantly with biomass density, while the increase was only minor for the forwarder. That suggests that a harvester-forwarder system productivity would be expected to increase significantly when harvesting stands with average diameters greater than 5 cm at stump height that are more overgrown than those studied. The net income obtained using the harvester-forwarder system under the studied conditions was positive; however, the net income achieved using the harwarder system was negative.

This study indicates that, when dealing with highly overgrown willow plantations, where ordinary forage harvesters cannot be used, current forest machines adapted for harvesting small diameter trees may offer an efficient and economically viable alternative. Further development of techniques and working methods for the use of forest machines can be expected to increase their efficiency and reduce their harvesting costs.

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Sažetak

Proizvodnost i profitabilnost šumskih strojeva u iskorištavanju normalnih i preraslih plantaža vrba

U Švedskoj se plantaže vrba u kratkim ophodnjama (PVKO) obično iskorištavaju izravno iveranjem, uz primjenu krmnih kombajna opremljenih zaglavljima za rezanje drva i prijamnim bunkerima za transport usitnjene biomase do ceste. Krmni kombajni korišteni u PVKO imaju nedostatak u tome što ne mogu učinkovito prikupljati stabljike deblje od 6 do 7 cm u visini panja. Može se očekivati da će u budućnosti plantaže vrbovih panjača postizati više prinose biomase zbog uzgajanja novih klonova te će se prosječni promjeri pridobivanih stabala vjerojatno povećati, što će stvoriti potrebu za takvim kombajnima koji mogu raditi s većim stablima. Moguća alternativa u

pridobivanju biomase na takvim plantažama mogu biti šumski strojevi s ugrađenim akumulativnim sječnim glavama (ASG) razvijenim za sječu malih stabala za bioenergiju u prvim proredama. Cilj je ovoga istraživanja bio utvrditi utrošak vremena i usporediti troškove primjene dvaju sustava šumskih strojeva u normalnim (N) i preraslim (O) PVKO, pri čemu je gustoća promatrane biomase iznosila 36 i 56 tona suhe drvne tvari po hektaru. Prvi strojni sustav uključio je harvester i forvarder, a drugi se sastojao od harvardera (sustav od jednoga stroja). Sječa i usnopljivanje pomoću harvestera istraživani su kao funkcija gustoće biomase, broja posječenih redova i smjera sječa–usnopljivanje. Potrošnja radnoga vremena forvardera analizirana je s obzirom na gustoću biomase i broj požetih redova. Potrošnja radnoga vremena harvardera analizirana je u ovisnosti o gustoći biomase i broja posječenih redova. Proizvodnost je harvestera bila 54 % veća na O površini nego na N površini, i iznosila je 9 % više pri pridobivanju pet nego što je pri pridobivanju šest duplih redova. Smjer sječa–vezanje u snopove nije imao značajan utjecaj na proizvodnost harvestera. Gustoća biomase i broj sječenih redova nisu značajno utjecali na utrošak vremena po tovaru forvardera. Kod harvardera gustoća je biomase značajno utjecala na potrošnju vremena po tovaru. Ono je u usporedbi s O površinom bilo 42 % veće na N području, dok broj posječenih redova nije imao signifikantan utjecaj. Harvarder je bio opremljen s akumulativnom sječno-hvatnom glavom koja je dizajnirana za oboje, i za sječu i za utovar, i tada je vrijeme utrošeno na sječu po panju bilo 3,9 puta veće nego za harvesterovu ASG. Pri pridobivanju i izvoženju biomase na udaljenosti od 250 m proizvodnost sustava s dvama odnosno s jednim šumskim strojem iznosila je prosječno 2,3 (sd = 0,6) odnosno 0,9 (sd = 0,2) tona suhe drvne tvari/proizvodni radni sat. Gustoća biomase ili veličina stabla imali su sporedni učinak na potrošnju vremena po hektaru za sustav s dvama strojevima, ali su zato značajni kod sustava s jednim strojem. Proizvodnost sustava s dvama strojevima i sustava s jednim strojem u O području iznosila je u usporedbi s N površinom 40 % odnosno 36 % više. Ukupni troškovi rada po hektaru za sustav s dvama strojevima na N i O površinama bili su za 43 % odnosno 42 % niži nego troškovi rada harvardera. Neto je dobit bila pozitivna kada je korišten sustav harvester–forvarder, a kada je primijenjen harvarder, neto je dobit bila negativna. Neto dobit po toni suhe tvari kod sustava s dvama strojevima bila je 2,6 puta veća u O području nego je to u N području. Zaključuje se da s povećanjem količine biomase koja se pridobiva profitabilnost šumskih sustava raste, dok se za konvencionalne sustave očekuje da pogodnost i jednostavnost njihova rada opadaju. Prema tome, ako se radi o više preraslih plantaža nego što je to u primjeru, šumski strojevi i posebno sustav harvester–forvarder mogu ponuditi učinkovitu i ekonomičnu alternativu uobičajenim krmnim kombajnima. Daljnji razvoj tehnika i radnih metoda u upotrebi šumskih strojeva može pridonijeti očekivanomu povećanju njihove učinkovitosti i smanjenju troškova pridobivanja biomase.

Ključne riječi: analiza sustava, studij vremena, proizvodnost, harvester, forvarder, harvarder

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