Utilization, Cost, and Landowner Return from Whole-Tree Chipping Young Loblolly Pine Thinnings

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Abstract – Nacrtak

In the southern United States thinning loblolly pine to produce whole-tree and clean chips for energy is likely to compete with thinning for roundwood pulpwood as bioenergy markets expand. Since chip harvests have higher yields per hectare and can tolerate smaller tree size, comparisons between harvesting costs and associated landowner returns are difficult to make. We completed a gross and continuous timing study on a 67 hectare whole-tree chip harvest (skidder, 2 feller-bunchers, disk chipper, and tracked loader) in southern Alabama in order to compare production rates, harvest costs, and landowner returns. The stand was 12 year old loblolly pine established on retired crop land with an average total biomass volume of 195 green tons (gt) ha^{-1} and average stem volume 0.22 gt tree^{-1} and 0.19 gt tree^{-1} for harvested trees. The whole-tree pine chip harvest totaled 98 gt ha^{-1} compared to estimated roundwood stem volume of 48 gt ha^{-1} and clean chip volume of 73 gt ha^{-1}. Machine production averaged 49.5 gt PMH^{-1} for felling and 61.7 for skidding and 72.8 for loading, but loader production was limited by transportation and market availability. On average the crew produced 332 gt each 10 hour shift and skidding would have limited production at 392 gt PMH^{-1}. Simulations generated from continuous timing data were used to compare harvest costs and potential landowner revenue from the site for whole-tree chips, clean chips and roundwood pulpwood.

Keywords: whole tree, chipping, biomass, logging, economics, thinning, loblolly pine

1. Introduction – *Uvod*

Opportunities for early thinnings in loblolly pine are available due to interest by landowners in shortening rotation length and increasing early stand revenue. Lower density planting (South 2003) and early thinnings (Stiff and Stansfield 2003) may lead to earlier sawlog harvests. While landowner guides indicate that stands may be thinned once they average DBH greater than 15 cm, height greater than 12 m, and basal area more than 22 m^{2}ha^{-1}, lower harvesting revenue may result from early thinning due to reduction in harvesting efficiency (Traugott and Dicke 2006). Lower harvest efficiency of roundwood is produced primarily by the small volume per tree. Truck payloads are reduced and handling of more stems per unit volume increases harvesting cost. In-woods chipping may increase transportation efficiency by ensuring maximum payloads. In-woods whole-tree chipping reduces harvest cost by effectively increasing net volume per stem by harvesting tops, limbs and some needles. In-woods clean chipping effectively increases the value of the material through improved yield of acceptable chips to the mill when compared to roundwood (Stokes and Watson 1991). While markets are available for both whole-tree chips for energy (cogeneration facilities at pulp and paper mills) and clean chips for pulp and paper, they are much smaller than the roundwood market. Many proponents of bioenergy believe that the market for whole-tree chips or clean chips might expand to include electric power generation and eventually production of transportation fuels. Currently pellet mills purchase roundwood pulpwood directly in competition with pulp and paper.

Differences in end product value, thinning yield, and harvest costs of the merchandizing options make it difficult for both procurement and landowners to evaluate the choices. The net yield of acceptable chips was slightly greater for in-woods chips vs roundwood because some of the forest residue from roundwood production would be delivered as clean chips (Stokes and Watson 1991). Logger's ability to add value through chipping may also provide an incentive for in-woods clean chipping. In the region whole-tree chipping is generally limited to stands where the merchantable volumes are low due to tree size or species, but the total volume per hectare and per stand are high. Delivered prices for energy wood do not usually provide enough income for competitive stumpage prices, but energy wood harvest may provide a landowner service by increasing management alternatives and reducing site preparation costs. In addition harvesting roundwood residuals may provide a landowner service or increase utilization of the harvesting system (Bakeret et al. 2010). Integrated harvests of roundwood and biomass chips (Baker et al. 2010; Bolding and Lanford 2005; Han et al. 2004; Puttock 1995) and round-wood and clean chips (Greene and Carruth 1994; Shrestha and Lanford 2002; Spinelli et al. 2008) are possible when it is desirable to merchandize higher value material, but the low chipper utilization results in higher chipping costs.

Since chipping capital costs are high, one of the largest factors in maintaining the competitiveness of in-woods chipping versus roundwood harvest will be the potential to increase and maintain chipper utilization. While the harvesting system plays some role in chipper utilization, the dominant effect is the availability of trucking resources and market. Often modeling of harvesting systems assumes that a truck will be available when a load is produced at the landing. Trucking and markets constraints are among the most important limits to system production (Greene et al. 2004), so modeling that does not address that scarcity in a complex way will overestimate system production. The objectives of this study were to describe the production of whole-tree chips from an early thinning of a loblolly pine plantation and use those productions and stand data to simulate the harvest of a similar stand by whole-tree chipping, in-woods clean chipping, and roundwood pulpwood.

2. Methods – *Metode*

We monitored the thinning of 67 hectare, 12 year old loblolly pine (*Pinus taeda*) stand. The stand was established by planting 1600 trees per hectare on retired cropland that was grassland at the time of planting. The site is in Conecuh County, Alabama, USA, in the lower coastal plain physiographic region. Soils had clayey surface and subsurface horizons from marine parent materials and were mapped as a Vertic Hapludalf. Slopes were gentle (< 5%) with occasional hills with chalk outcrops. Most of the rock outcrops were in hardwood or grass cover because they were not planted or the seedlings did not survive in the thinner soils.

The thinning occurred in October and November 2011 with a plan to remove every 5th row and select small trees and trees with defects from the remaining rows to yield a post-harvest basal area of 13 m^{2}ha^{-1}. The stand was sampled prior to harvest with 46–0.02 hectare plots (0.05 acre) set on a rectangular grid. Measurements in the plots included DBH for each tree and a subsample of total height from three trees closest to the plot center. A model of height to diameter was developed from those subsampled height data. Regionally developed tree weight equations (Clark and Saucier 1990) were used to estimate total biomass and merchantable stem mass to a top diameter of 6.3 cm (2.5 in). Mass per stem expected to yield clean chips was estimated at 62% of total green weight (Watson and Stokes 1994). Following the harvest, we sampled the same plots to determine the distribution of both the thinned trees and the residual stand. Post-harvest sampling included an assessment of the woody debris in the stand that resulted from breakage and loss during the harvest. The volume of debris piles at the landings was also estimated.

The logging system was equipped to produce whole-tree chips delivered to pulp and paper cogeneration facilities. The crew consisted of two 720 Tigercat feller-bunchers, a 620 Tigercat skidder and a T250B Tigercat tracked loader. There was an older model wheeled loader at the landing to clear debris. The chipper was a Precision Husky model 3086. The logger equipped the chipper with an in-feed conveyor manufactured on the frame of a log trailer. The conveyor increased chipper production since the in-feed conveyor was full consistently during chipping. Trucking was shared among the contractor's two chipping crews and the principle markets for this harvest were 48 and 61 km from the harvest site. The markets limited production to about 1400 gt per week. The feller-buncher and skidder were equipped with MultiDat data recorders with Garmin GPS 15 receivers that were set to collect a position every 30 seconds. The loader was equipped with a MultiDat without a GPS receiver. We placed a monitor on the chipper that subsequently malfunctioned so no direct chipper use data were available. On November 8 and 17 we visited the site to collect video of all the machines on the site. The chip-

Table 1 Element and variable descriptions from continuous timing of the whole-tree chipping operation
Tablica 1. *Opis radnih zahvata i varijabli pri iveranju cijeloga stabla*

Machine *Stroj*	Element *Zahvat*	Description – *Opis*
Felling *Obaranje*	Move and Cut *Kretanje i sječa*	From approach of 1st tree cut to the cut of the last tree in the felling head *Od primicanja prvomu stablu, sječe do sječe zadnjega posječenoga stabla*
	Move and Dump *Kretanje i odlaganje*	From the cut of the last tree in the felling head to the release of trees from the felling head *Od sječe zadnjega stabala do otpuštanja stabala iz sječne glave vozila*
	Cycle time *Turnus vremena*	Begins and ends with release of trees from the felling head *Počinje i završava otpuštanjem stabala iz sječne glave vozila*
Skidding *Privlačenje*	Travel empty *Prazno vozilo*	Movement away from the landing to the forest until the machine stops near the first load *Kretanje s pomoćoga stovarišta do sastojine sve dok se vozilo ne zaustavi radi utovara*
	Load *Utovar*	From the time the machine stops near the load to forward motion after the trees are in the grapple *Od vremena zaustavljanja vozila blizu oborenih stabala radi utovara do ponovnoga kretanja vozila s punim hvatalom*
	Travel loaded *Utovareno vozilo*	From forward motion after the trees are grappled to include all forward motion until the grapple is opened at the landing *Od kretanja vozila s punim hvatalom sve do pražnjenja hvatala na pomoćnom stovarištu*
	Pile *Uhrpavanje*	Activity on the landing after the grapple is opened until motion to the forest *Radnje na pomoćnom stovarištu nakon pražnjenja hvatala pa sve do povratka vozila u sastojinu*
	Cycle time *Turnus vremena*	Begins and ends with beginning of travel unloaded element *Počinje i završava kretanjem praznoga vozila*
Loader *Utovarivač*	Load *Utovar*	Grapple swings from the pile to to in-feed deck and return *Zamah hvatala od složaja do utovarnoga prostora i nazad*
	Delay *Kašnjenja*	Loader stationary with engine running for less than 9 minutes *Stanka utovarivača s upaljenim motorom duže od 9 minuta*
	Pile *Uhrpavanje*	Grapple swings from the skidder unloading area to the tree pile *Zamah hvatalom od mjesta istovara skidera do složaja drva*
	Clean-up *Čišćenje*	Loader activity to move limbs or broken tops from the in-feed area to the tree pile or slash (discard) pile *Radnje micanja dijelova stabala s utovarnoga prostora do složaja otpada*
Variable – *Varijable*		Description – *Opis*
Felling *Obaranje*	Total stems *Ukupno oboreno*	All trees cut in the cycle *Sva stabla posječena u radnom turnusu*
	Hardwood stems *Oblovina*	All hardwood stems cut in the cycle *Sva pridobivena oblovina u jednom turnusu*
Skidding *Privlačenje*	Distance *Udaljenost*	Straight line distance (m) from active landing center to largest load in cycle Pravocrtna udaljenost (m) od pomoćnoga stovarišta do mjesta utovara
	Load Number *Broj utovara*	Number of loading elements in the cycle *Broj utovarnih elemenata u radnom turnusu*

per and loader were observed using a video camera on a tripod just off the landing. We mounted VIO POV cameras on the feller-buncher and the skidder. The work captured on the video was analyzed using TimerPro software and cycle and element data were exported for further analysis. For the skidder we synchronized the time study data with the GPS positions from the MultiDat and imported them into ARCMAP 10 to determine the straight line distance from the landing to the pile collected during each cycle. Element definitions and independent variable descriptions are presented in Table 1. For each of the time study periods we counted trees in sample of piles built by the feller-buncher to develop a distribution of pile sizes. Tree count in piles varied due to tree size because the feller-buncher attempted to build piles of equivalent mass.

2.1 Simulations – *Simulacije*

We used the regressions and means from the cycle time, production data, and stand parameters from this harvest to develop parameters for a harvest simulation of a whole-tree chipping operation. Simulations of a clean chipping operation and a roundwood pulpwood operation were developed using parameter estimates from published sources. Simulations were developed and run in Stella 9.03. Stella is a dynamic simulation program, which was used to incorporate regression equations and stochastic events to generate production flow on an hourly basis. Each of the simulations harvested 11 140 trees over 20 hectares. Felling production (trees pmh^{-1}) was determined by the felling regression model and that used a bunch size from a normal distribution of bunch sizes from study data and pile size selected from a normal distribution from study data. Skidding productivity was based on a distribution of skid distances from a circular harvest area with the landing at the center. Tracts feasible for chipping are usually 50 ha or larger and would have access roads through the tract to enable landing densities often less than 20 ha per landing. Skidding productivity (trees pmh^{-1}) was determined from regression equations using skid distance and load number. Skid distance was selected randomly from zones of equivalent area (4 hectare) in concentric circles around the landing. Pile size was selected from normal distribution of pile sizes from study data. If landing volume exceeded four truck loads of trees, skidding production ceased for that period. For landing processes production was stimulated by truck arrival based on Poisson distributions with means of 1.2, 1.5, and 1.75 trucks per hour. Production rate of the loader or chipper could be limited by truck arrival, wood available on the landing, or production capacity of chipping or delimbing.

For chipper production rate for whole-tree chipping we used the estimate from this study. Clean chip production rates have been estimated for softwood, 26 and 31 gt pmh^{-1} (Lambert 1987), 31 gt pmh^{-1} (Raymond and Franklin 1990), but those production rates may be limited by harvesting rates or truck supply. Detailed measurement from a clean chipping operation showed that about 62% of productive time was involved in chip production that resulted in a rate of 53 gt pmh^{-1} (Franklin 1992). The resulting specific flail and chipping rate would be 85 gt pmh^{-1}, and we used 80 gt pmh^{-1} for the maximum rate. For roundwood production, the production rate of a Chambers Delimінator was assumed to be normally distributed with a mean of 414 trees pmh^{-1} with a standard deviation of 150. These estimates were based on published data (Mooney et al. 2000) and unpublished data used in (Folegatti et al. 2007). The loading rate for the roundwood operation was determined by truck arrivals, the presence of delimbed trees on the landing, or a maximum rate of 4 truckloads pmh^{-1}.

Machine costs for the simulation were prepared using a before tax cash flow cost that developed costs for a similar firm with equipment that ranges in age and presents capital for the current year (Smidt et al. 2009). Variable costs estimates were developed using standard rules of thumb (Brinker et al. 2002; Caterpillar 1996). Overhead costs were assumed to be 4% of total costs and a capital return of 10% was estimated. Variable and fixed costs estimates are presented in Table 2.

3. Results with Discussion – *Rezultati s raspravom*

3.1 Harvesting study – *Studija sječe i privlačenja*

We estimated that the stand had 892 trees ha^{-1} and 26 m^2ha^{-1} of basal area prior to thinning (Table 3). Stand data indicate that it was available for thinning (Traugott and Dicke 2006). Average total biomass (stem branches and foliage) per tree of pre-harvest, post-harvest, and harvested trees were estimated at 0.21, 0.26, and 0.18 gt, respectively. Post-harvest basal area was estimated at 12 m^2ha^{-1}. Post-harvest sampling estimated biomass removal volume at 88 gt ha^{-1} while the total removal mass from load data was 6 668 gt or 99.5 gt ha^{-1}. With a standard error of 4.5 gt ha^{-1} the sample mean was significantly different from harvested volume. The difference could be related to a combination of sampling error, the biomass equation, or harvest of small hardwood stems (< 7.5 cm dbh) that were not sampled in the plots.

Line transects sampled following the harvest (3.30 m transects at each plot center) found a very little volume per hectare of live branches lost from trees during the harvest (standing or harvested trees). Approximately 1 500 m^3 of loosely piled slash remained on the landing following the harvest, which may sum to 300 m^3 of solid wood or about 270 gt (Hardy 1996). The slash piles were tree parts that had significant contact with the soil (piled up with blade or driven over) and were not chipped to maintain lower ash content in delivered whole-tree chips. If added to the yield of whole-tree chips, the apparent error of the sample increases.

On weekdays operators worked 10 hour days from 6 AM to 5 PM with a total break time of about 1 hour. On some weekends, when markets were open, operators worked on-site long enough to load the available trucks and/or set up the equipment or wood for the following workday. While at least one crew member worked one Sunday, no chips were produced. The crew worked 3 Saturdays over 5 weeks and produced just 2 loads of chips. Production from Wednesday and Thursday accounted for nearly 50% of total production. Gross machine time rates were 49 gt pmh^{-1} for the feller-buncher; 61.7 for the skidder and 72.8 for the loader. Utilization rates for the three machines were 36%, 49%, and 42%, respectively. Utilization rate for the feller-buncher was lower because there were two machines on site for most of the harvest. Chipper utilization rate was not measured directly but would be even lower than the loader since the loader was active on the landing when the chipper was idle. The summary of the element and cycle time analysis is presented in Table 4. We observed the production of 18 loads of chips with an average time of 9 minutes per load. Load sizes averaged about 24.5 gt. Skid distances were the straight line distance between the landing and the pile and were well distributed during the observation period. The feller-buncher averaged about

Table 2 Cost estimates for three harvesting systems
Tablica 2. *Procjene troškova sustava pridobivanja ivera*

Component – *Sastavnica*	Description *Opis*	Roundwood *Oblo drvo*	Whole-tree chipping *Iveranje cijelih stabala*	Clean chipping *Čisto iveranje*
Fixed Cost ($ smh^{-1}) *Fiksni troškovi* ($ smh^{-1})	Feller-buncher – *Sječno vozilo*	31.22	31.22	31.22
	Skidder – *Skider*	20.48	20.48	20.48
	Loader – *Utovarivač*	35.69	35.69	35.69
	Chain flail delimber – *Sječna transportna traka*	10.77	–	–
	Chipper – *Iverač*	–	56.86	–
	Chipper with Flail – *Iverač s transportnom trakom*	–	–	89.79
	Wheeled loader – *Kotačni utovarivač*	–	0.15	0.15
Variable Cost ($ pmh^{-1}) *Varijabilni troškovi* ($ pmh^{-1})	Feller-buncher – *Sječno vozilo*	39.56	39.56	39.56
	Skidder – *Skider*	36.21	36.21	36.21
	Loader – *Skider*	28.21	28.21	28.21
	Chain flail delimber – *Sječna transportna traka*	22.46	–	–
	Chipper – *Iverač*	–	117.35	–
	Chipper with Flail – *Iverač s transportnom trakom*	–	–	154.03
	Wheeled loader – *Kotačni utovarivač*	–	36.91	36.91
Labor and fringe cost ($ smh^{-1}) *Trošak radnika* ($ smh^{-1})	1 Feller-buncher – *1 sječno vozilo*	69.78	92.19	92.19
	2 Feller-bunchers – *2 sječna vozila*	92.19	114.59	114.59
Overhead ($ smh^{-1}) *Operativni troškovi* ($ smh^{-1})	1 Feller-buncher – *1 sječno vozilo*	17.61	21.03	23.62
	2 Feller-bunchers – *2 sječna vozila*	18.97	22.78	25.37
Capital return ($ smh^{-1}) *Povrat ulaganja* ($ smh^{-1})	1 Feller-buncher – *1 sječno vozilo*	20.68	29.91	35.30
	2 Feller-bunchers – *2 sječna vozila*	23.35	32.58	37.97
Beginning of year capital value ($) *Vrijednost na početku rada* ($)	1 Feller-buncher – *1 sječno vozilo*	500 000	740 000	881 000
	2 Feller-bunchers – *2 sječna vozila*	569 000	810 000	951 000
Expected book value decline ($) *Funkcionalna amortizacija* ($)	1 Feller-buncher – *1 sječno vozilo*	116 000	174 000	209 000
	2 Feller-bunchers – *2 sječna vozila*	133 000	191 000	226 000

5.2 trees per minute in the stand and it took 3 or more cycles or more than 4.8 minutes to produce one pile for the skidder.

The load sheets kept by the loader operator recorded the departure time, destination and product for each load. Load sheets were used to generate a distribution of loading times and compared to the time study data. Given the expected low precision in time recording intervals by the loader operator, the intervals were estimated in 10 minute classes. Interval data were similar for time study and load sheet (Fig. 1). Since both time study periods were Thursdays, the longer between truck intervals were eliminated. The truck departure frequency was 0 trucks for 31% of operating hours, 1 for 33%, 2 for 24%, 3 for 9%, and 4 for 3% resulting in an average rate of trucks at the landing of 1.2 per hour (variance 1.15). Assuming that arrival and departure rates were similar, the mean time between trucks would be (1/arrival rate) about 50 minutes per truck.

For the sake of comparison, the mean time between trucks from the data in Fig. 1 was 37 minutes. With a service rate equal to the mean loading time of 6.7 trucks hr^{-1} (9 minutes per load), the average utilization would be 18% (1.2/6.7). Since the skidder is only capable of 61.7 t pmh^{-1} the maximum service rate was 2.5 loads hr^{-1} (24.5 t $load^{-1}$). Utilization rate would then be (1.2/2.5) or 48% which is approximately the utilization rate of the skidder. Using 70% of the system capacity would require a truck arrival rate of 1.75 hr^{-1} and service time per truck would go from 46 minutes to 80 minutes yielding potential time lost at the landing of 16.5 hours per shift (17.5 * (1.33 – 0.4)).

Skidder and feller-buncher model statistics for the delay free cycle and element times are presented in Table 5. The regression of the feller-buncher cycle time was significant but with low R^2. Any significance of the feller-buncher cycle time was due to strong relationship between Move and Cut time and the dependent variable. Both skidder models were significant, as they were both dependent variables (straight line distance and loads per cycle). Model parameter estimates for the models used in the simulation are given in Table 6. To simulate skidding roundwood to a landing with a flail delimber, we used skidding data from another study in a similar stand with similar data collection methods (Video and GPS) (Folegatti et al. 2007). The skidder in the roundwood system was required to move the delimbing debris, which increased cycle time.

Table 3 Stand table compiled from pre-harvest and post-harvest sampling; Harvest mass is given in tons ha^{-1} on a green weight basis; DBH classes are presented in inches since they were collected in 1 inch classes

Tablica 3. *Prikaz istraživane sastojine prije i poslije sječe stabala*

DBH (inches) *Prsni promjer u inčima*	Preharvest *Prije sječe*		Biomass, t ha^{-1} – *Biomasa*, t ha^{-1}			Post Harvest *Prije sječe*		Harvest, t ha^{-1} *Sječa*, t ha^{-1}
	Trees, ha^{-1} *Broj stabala*, ha^{-1}	m^2 ha^{-1} *Temeljnica* m^2 ha^{-1}	Total *Ukupno*	Stem only *Debla*	Merchantable (6.3 cm SED) *Tržišna vrijednost* (6.3 cm SED)	Trees, ha^{-1} *Broj stabala*, ha^{-1}	m^2 ha^{-1} *Temeljnica*, m^2 ha^{-1}	Total *Ukupno*
3	27	0.1	0.5	0.4	0.2	1	0.0	0.0
4	46	0.4	1.8	1.5	1.2	2	0.0	0.1
5	86	1.1	5.8	5.0	4.7	12	0.1	0.8
6	132	2.4	14.4	12.3	11.9	30	0.5	3.3
7	163	4.1	26.5	22.3	22.0	64	1.6	10.5
8	183	5.9	41.6	34.5	34.3	81	2.6	18.3
9	129	5.3	39.2	32.2	32.0	64	2.6	19.6
10	81	4.1	31.4	25.5	25.5	54	2.7	20.9
11	28	1.7	13.5	10.9	10.9	15	0.9	7.3
12	9	0.6	5.0	4.0	4.0	6	0.5	3.8
13	9	0.7	5.9	4.6	4.6	5	0.5	3.7
Total *Ukupno*	892	26	186	153	151	335	12	88

Table 4 Machine element and cycle times in minutes and independent variables from analysis of machine video; Standard deviations are given () for the skidder and feller-buncher

Tablica 4. *Radni zahvati vozila*

Machine – *Stroj*	Element – *Radni zahvat*	Mean – *Aritmetička sredina*	Max – *Maks.*	Min – *Min.*	N – *Broj*
Loader *Utovarivač*	Load – *Utovar*	9.01	17.20	7.43	18
	Delay – *Kašnjenje*	13.5	26.42	0	–
	Pile – *Uhrpavanje*	14.19	33.94	0	–
	Clean-up – *Čišćenje*	3.05	7.32	0	–
	Total – *Ukupno*	28.88	78.62	7.60	18
Skidder *Skider*	Total – *Ukupno*	4.10 (2.00)	11.48	0.48	89
	Travel unloaded – *Vožnja praznoga vozila*	1.73 (0.88)	4.97	0.25	–
	Travel loaded – *Vožnja natovarenoga vozila*	1.87 (0.94)	5.47	0	–
	Load – *Utoar*	0.49 (0.48)	2.5	0.05	–
	Bunches/cycle – *Snopova / turnus*	1.7 (1.1)	6	1	–
	Skid Distance, m – *Udaljenost privlačenja,* m	196 (129)	544	8	–
Feller-buncher *Sječno vozilo*	Total – *Ukupno*	1.59 (1.03)	8.71	0.31	70
	Move and Cut – *Pomicanje i sječa*	1.28 (0.55)	2.65	0.18	–
	Move and Dump – *Pomicanje i ispuštanje*	0.29 (0.13)	0.68	0.09	–
	Trees per cycle – *Br. stabala po turnusu*	8.3 (2.8)	14	1	–
	Trees per bunch – *Br. stabala po složaju*	28 (7.1)	53	13	63

3.2 Simulations – *Simulacije*

The results of the simulations are presented in Table 7. For the whole-tree chipping, the feller-buncher productivity in the simulation was considerably lower than the gross production estimates. Differences could be due to differences in average tree size between that estimated from the cruise versus actual. The differences could be caused by a combination of sampling error or the tree weight equation. In addition, the simulation added more time per pile by making the feller-buncher produce the exact pile size. So some small bunches were produced to make most piles, which reduced machine efficiency. Finally we had only time study data for one of the two feller-buncher operators and the other one might have been more productive. Lower estimates for skidding productivity could be attributed to the way landing limits were imposed. If some landing space was available the skidder produced enough trees to resupply the landing and that hour was counted as completely productive. The method probably overestimated productive hours compared to the Multidat which would not record idle time.

Most the difference in productivity among the scenarios was produced by the change in volume per tree related to the harvesting system. Additional productivity gains were produced by removing bottlenecks from both felling and trucking. Whole-tree chipping was able to use most of the trucking resources provided. Clean chipping required fewer trucks since residue remained in the woods and roundwood systems were limited by loading and delimbing rather than trucking. Increased trucking resources (increased arrival rate) generally had more improvement from 1.2 to 1.5 than 1.5 to 1.75. While trucks were made available based on the Poisson arrival rate, on some occasions there was not enough wood on the landing to use all of the available trucks. The ratio of truck loaded to trucks available (departure:arrival) ranged from 0.43 to 0.96 with the greatest ratio for whole-tree chipping, where the greatest mass per tree was converted into product. Extra felling capacity was able to reduce harvest scheduled hours for each system and arrival rate combination. Total system costs for roundwood and whole-tree chipping were similar in spite of differences in component costs (Fig. 2). Total cost differences within the roundwood and whole-tree chipping system varied by as much as \$4 gt^{-1}. Clean chipping costs had a much larger variation of over \$10 gt^{-1}.

Some studies in the region have also addressed whole-tree chipping from pine thinnings. An under-

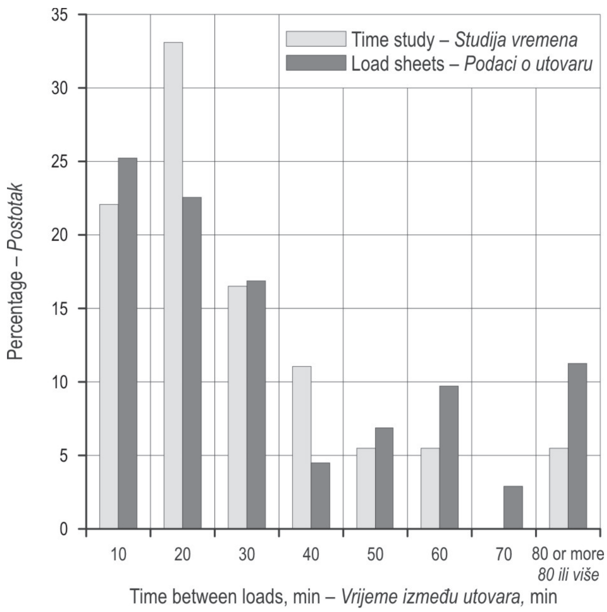

Fig. 1 Distribution of time between loads in 10 minute intervals from video data and load sheet data

Slika 1. *Prikaz vremena između utovara u 10-minutnim intervalima iz videozapisa te baza podataka*

story removal in loblolly and longleaf pine stands was estimated to have a production rate of 60 gt pmh^{-1} and a harvest cost of \$10.10 gt^{-1} even though trucking limited the chipper to 25% utilization (Mitchell and Gallagher 2007). A comparable cost from the simulation (less overhead and capital return) would have been nearly \$12 gt^{-1}. In similar conditions in loblolly pine thinnings in Alabama, productivity of both skidders (30 gt pmh^{-1}) and feller-bunchers (15 and 23 gt pmh^{-1}) (Klepac et al. 2011) were less than those in the simulation and the gross production study. A comparison of clean chip to roundwood system cost showed that clean chipping costs were about 35% greater than roundwood costs and the cost of acceptable chips to the digester were within 2% for both harvesting systems (Watson et al. 1991). In the simulations with higher clean chipping productivity, the difference was almost the same here (38%).

Stumpage and delivered product prices were south wide average prices from 4th quarter 2011 TimberMart-South (TimberMart-South 2012). Prices used were FOB at landing of \$17.05 gt^{-1} for pine whole-tree chips, \$31.00 for clean chips, and \$20.31 for roundwood pulpwood. The average stumpage value for pine pulpwood was \$9.02 gt^{-1} for the same time period. From a landowner perspective revenue per unit area would be a critical comparison and controls for the differences in harvest volume. Residual value per hectare (value FOB – Harvesting cost to roadside) ranged from \$287 to \$564 ha^{-1} for roundwood. Whole-tree chipping resulted in negative residual value when arrival rate was 1.2. The highest revenue was \$246 ha^{-1} at the low end of the roundwood system. Clean chipping was the most highly variable and ranged from \$40 to \$656 ha^{-1}. The second feller-buncher was critical for lowering system costs and increasing residual value. The arrival rate had a smaller impact. In order to compete with roundwood pulpwood value (the highest residual value for roundwood) prices for whole-tree chips would have to be similar to pulpwood value at about \$22 gt^{-1} (Fig. 3). Clean chipping was competitive with roundwood when the production rates were high, but had the largest deficit at lower production rates.

Average whole-tree chip prices resulted in negative net revenue when a typical stumpage price was paid. To determine the potential for roundwood and clean chip harvesting we estimated net income per schedule hour using a stumpage fee equivalent to \$5 gt^{-1} for roundwood and the high value the whole-tree chips (\$19.21 gt^{-1}) (Fig. 4). A lower stumpage fee might be justified since the early harvest may provide a service

Table 5 Model statistics for selected regression models; All times are delay free; Skidder – Roundwood data was from a previous study

Tablica 5. *Statistička obrada podataka (podaci o skideru s oblovinom iz prijašnjega su istraživanja)*

Model – *Model*	R^2	*N*	*DF* model	*MSE*	*F* value F *vrijednost*	*P* value P *vrijednost*
FB, Move and Cut – *Sječno vozilo, micanje i sječa*	0.890	70	2	0.20	273.73	< 0.0001
FB, Move and Dump – *Sječno vozilo, micanje i odlaganje*	0.009	69	2	0.02	0.29	0.7494
FB, Total Cycle – *Sječno vozilo, ukupni turnus*	0.161	70	2	0.93	6.42	0.0028
Skidder, chipping – *Skider, iveranje*	0.420	77	2	2.42	27.13	0.0001
Skidder, roundwood – *Skider, oblovina*	0.784	110	2	0.76	194.3	0.001

Table 6 Parameter estimates for delay free cycle time regression models for the feller buncher and the skidders from the whole-tree chipping operation and a roundwood pulpwood operation; *P* values of the *T*-test, showing that the estimate is not different from 0, are indicated by <0.1a, <0.05b, and <0.01c

Tablica 6. *Regresijski modeli za turnuse bez vremena kašnjenja*

	B_0 (Intercept)	B_1		B_2	
Model – *Model*	Estimate – *Procjena*	Name – *Naziv*	Estimate – *Procjena*	Name – *Naziv*	Estimate – *Procjena*
Felling – *Obaranje*	0.343	Total stems *Ukupno debala*	0.148[c]	Hardwood stems *Oblovina*	0.050
Skidding – Chipping *Privlačenje – Iveranje*	1.687[c]	Distance *Udaljenost*	0.007[c]	Load number *Br.utovara*	0.571[c]
Skidding – Roundwood *Privlačenje – Oblovina*	1.376[c]	Distance *Udaljenost*	0.014	Load number *Br. utovara*	0.516[c]

to the landowner and improve stand return in spite of the reduced thinning revenue. Even with more favorable terms only the most productive whole-tree chipping scenarios resulted in a positive income per SMH. Clean chipping had the greatest potential for earnings per SMH but also included the largest losses. As expected most of the roundwood scenarios had positive net revenue per SMH. Among the scenarios with loss-

Table 7 Simulation productivity for 20 hectare harvest with changes in feller-buncher number (N) and truck availability (Arrival rate) and the trucks loaded (Departure rate)

Tablica 7. *Simulacije proizvodnosti*

System *Sustav*	N *Broj*	SMH	Productivity, gt pmh^{-1} – Produktivnost, gt pmh^{-1}					Arrival rate *Stopa dostupnosti*	Departure rate *Stopa izvršenosti*
			Feller-buncher *Sječno vozilo*	Skidder *Skider*	Loader *Utovarivač*	Delimber *Rezno vozilo*	Chipper *Iverač*		
Roundwood *Oblo drvo*	1	84	26	47	21	32	–	1.20	0.82
	1	71	26	44	23	33	–	1.50	0.97
	1	69	26	44	24	34	–	1.75	1.00
	2	78	26	53	22	34	–	1.20	0.88
	2	70	26	51	24	34	–	1.50	0.99
	2	67	26	53	26	41	–	1.75	1.03
Whole-tree chipping *Iveranje cijelih stabala*	1	76	32	53	38	–	38	1.20	1.03
	1	66	32	35	40	–	40	1.50	1.18
	1	67	32	31	37	–	37	1.75	1.17
	2	72	31	53	38	–	38	1.20	1.08
	2	58	32	70	44	–	44	1.50	1.34
	2	55	32	65	48	–	48	1.75	1.42
Clean chipping *Čisto iveranje*	1	70	19	18	28	–	28	1.20	0.75
	1	68	19	18	27	–	27	1.50	0.76
	1	69	19	18	25	–	25	1.75	0.75
	2	53	19	38	36	–	36	1.20	0.98
	2	43	19	38	40	–	40	1.50	1.19
	2	40	19	38	42	–	42	1.75	1.30

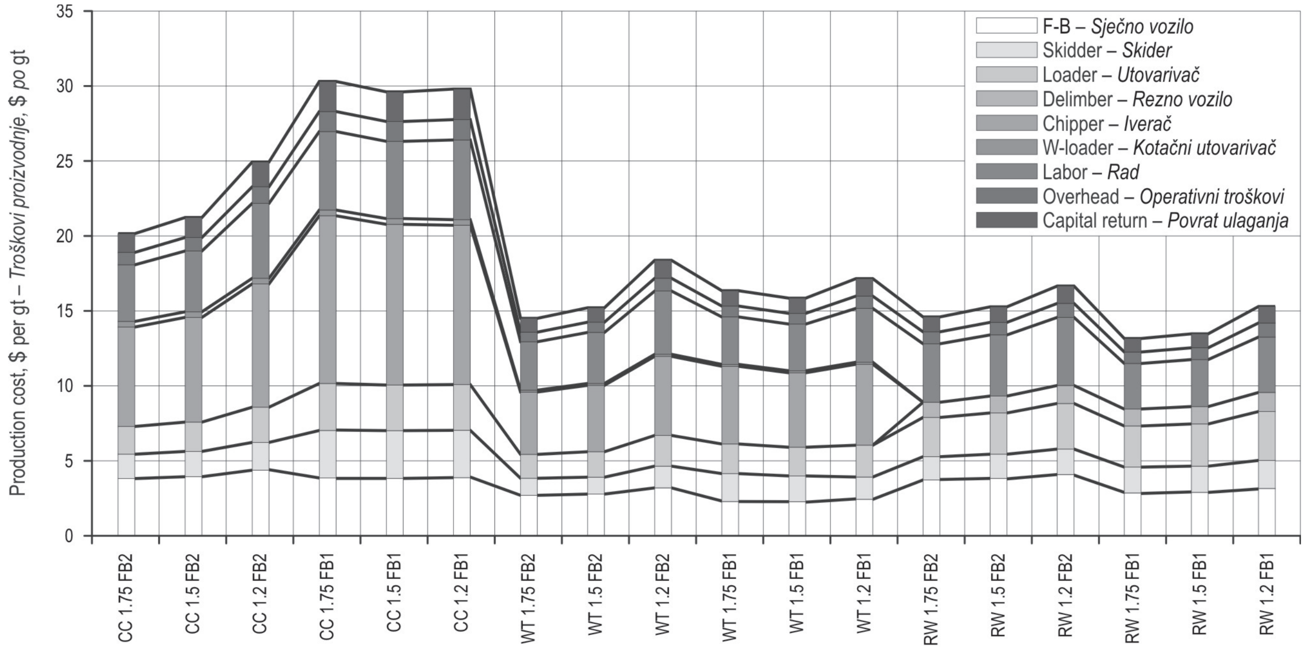

Fig. 2 Production cost from simulation of roundwood (RW), whole-tree chipping (WT), and clean chipping (CC) systems at different truck arrival rates (1.2; 1.5, and 1.75) and feller buncher number (1 or 2)

Slika 2. *Troškovi proizvodnje iverja*

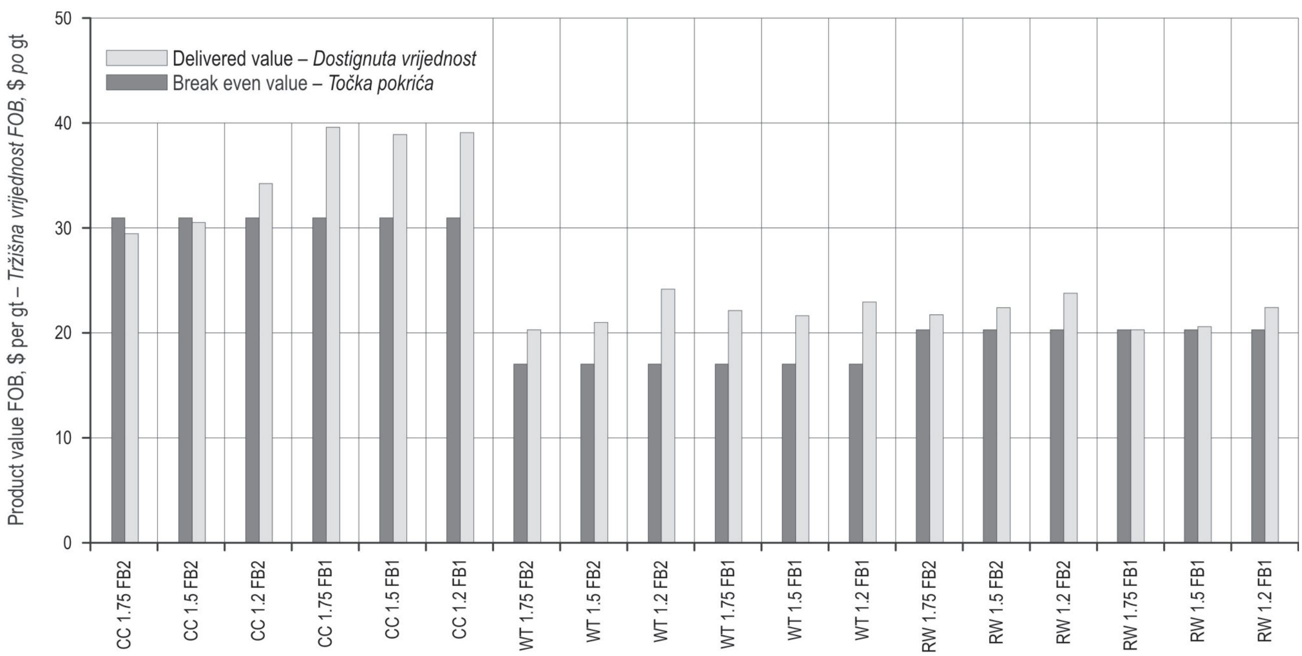

Fig. 3 Product value (FOB) for each system and the break even value to yield the same residual value per hectare compared to the highest value roundwood harvest, Values are from simulation of roundwood (RW), whole-tree chipping (WT), and clean chipping (CC) systems at different truck arrival rates (1.2; 1.5 and 1.75) and feller-buncher number (1 or 2)

Slika 3. *Tržišna vrijednost svakoga sustava i točke pokrića*

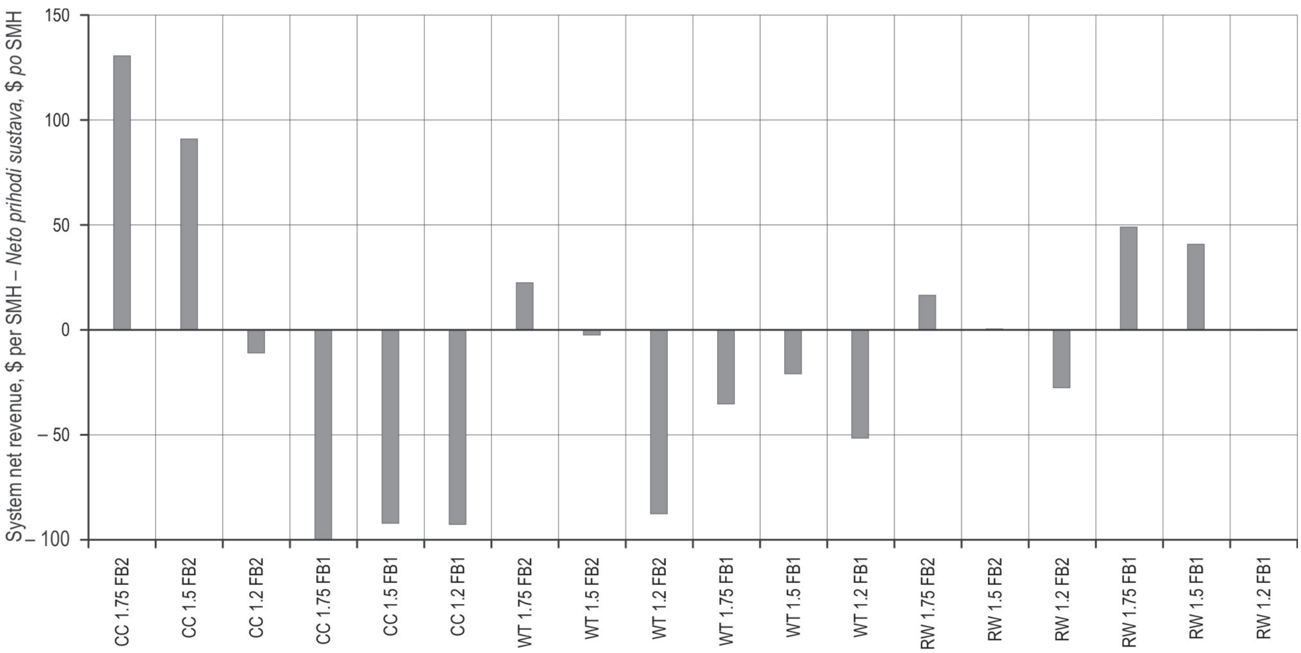

Fig. 4 System net revenue with a stumpage value of \$5 per gt and a high value for whole-tree chips (\$19.21 per gt), Values are from simulation of roundwood (RW), whole-tree chipping (WT), and clean chipping (CC) systems at different truck arrival rates (1.2; 1.5 and 1.75) and feller-buncher number (1 or 2)

Slika 4. *Neto prihodi sustava*

es, the roundwood and whole-tree chipping scenarios (\$ smh^{-1}) had losses similar in magnitude to estimated capital return (\$20 to \$38 smh^{-1}). Contractors that chose to forgo capital return could still pay all their expenses especially if they use the firm to employ themselves.

4. Conclusion – *Zaključak*

Gross time study of a whole-tree chipping system showed that the system productivity was severely limited by truck or market availability. Both detailed timing and gross time study data showed that with 2 feller-bunchers active the skidder would be limiting and would limit overall production to just over about 67 gt pmh^{-1}. Even at low levels of available markets, truck availability is seldom regular and the loss of some productive hours for the harvesting system is likely. If trucking is considered simply as variable cost there is no burden adding trucking capacity to reduce gaps without trucks at the landing. The cost may be transferred to contract haulers as they may wait at the landing to be loaded. An expansion of contractor trucking capacity means that each truck added will lower the utilization of the fleet and lead to higher fixed costs per unit of trucking. Analysis is needed to rationalize to optimal utilization of both the trucking fleet and the in-woods capacity.

It appears unlikely that the whole-tree chipping system described here could compete with roundwood or clean chip harvesting for pulpwood until tree size makes it impractical to load roundwood. Rising prices for energy wood would not reduce the deficiency since those price increases would be reflected in pulpwood prices as well. Limited markets and constrained unloading capacity at mills are also likely to lower the profitability even if prices rise. Many Southern US contractors including the one in the study operate equipment that is nearly completely depreciated so net income can be produced even at low levels of market availability. Large expansion in woody bioenergy production will require a large expansion in demand and large jump in price since investment in in-woods systems and trucking capacity will be required. Prices now often require contractors to forgo capital return. While the practice makes harvesting feasible, it is unlikely to attract the capital investment needed to expand the industry. Since the opportunity for net revenue was so small, especially with limited truck availability or quota, there would be little rationale to select chipping over roundwood harvest.

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Sažetak

Iskoristivost, troškovi i povrat sredstava u pridobivanju iverja iz mladih sastojina teda-bora

U južnom dijelu Sjedinjenih Američkih Država prorede u kulturama teda-bora za proizvodnju iverja u budućnosti vode prema proizvodnji oblovine za industriju celuloze. Troškovi su pridobivanja iverja visoki, a najvažniji su utjecajni čimbenici prijevoznici (dostupnost kamiona) i kretanja na tržištu. Cilj je istraživanja bio troškovno opisati proizvodni lanac iverja od cijelih stabala teda-bora, posječenih u proredama te usporediti prihode dobivene od iveranja cijelih stabala, čistoga iveranja u sastojini i celuloznoga drva.

*Bruto proizvodnja i studij rada i vremena provedeni su na površini od 67 ha, u dvanaestogodišnjoj sastojini teda-bora (*Pinus taeda*). Nakon sječe temeljnica sastojine iznosila je 12 m^2ha^{-1} (26 m^2ha^{-1} prije sječe), a gustoća stabala 335 po ha (892 po ha prije sječe). Ukupna je biomasa procijenjena na 195 tona svježe tvari po hektaru, a ukupno je pridobiveno 98 gt ha^{-1}drvnoga iverja. Iverje je potom dostavljeno pogonu za proizvodnju celuloze i papira.*

Upotrijebljena su ova vozila: dva sječna vozila 720 Tigercat, skider 620 Tigercat, gusjenični utovarivač T250B Tigercat, stariji model kotačnoga utovarivača, iverač Precision Husky 3086. Udaljenost prijevoza kretala se od 48 do 61 km. Tržišne potrebe za iverjem iznosile su oko 1400 gt/tjedno. Bruto stope proizvodnje iznosile su: za sječno vozilo 49 gt pmh^{-1}, za skider 61,7 gt pmh^{-1}, za utovarivač 72,8 gt pmh^{-1}.

Simulacije pridobivanja provedene su pomoću dinamičkoga simulacijskoga programa Stella 9,03. Program simulira svaki sat proizvodnje na temelju proizvodnih jednadžbi i raspodjele iz trenutačne studije te u nekim slučajevima iz prethodnih studija sa sličnim uvjetima.

Ovdje opisan sustav iveranja cijelih stabala nije se mogao natjecati sa sustavima pridobivanja oblovine ili čistoga iveranja za potrebe industrije celuloze zbog nepraktičnosti utovara oblovine. Rastuće cijene energijskoga drva vjerojatno će dovesti i do rasta cijena drva za proizvodnju celuloze. Mnogi izvođači radova na jugu SAD-a, uključujući i one u ovom istraživanju, koriste se opremom koja je gotovo u potpunosti amortizirana, pa neto dobit može biti proizvedena čak i pri niskim razinama tržišne dostupnosti. Veliko širenje proizvodnje bioenergije zahtijevat će veliko širenje potražnje te povećanje cijene jer će biti potrebna ulaganja u sustave pridobivanja i prijevoza. Neto prihodi bili su izrazito mali (pogotovo s ograničenom dostupnošću kamiona) pa su slaba opravdanja za odabir iveranja nasuprot pridobivanju oblovine za proizvodnju celuloze.

Ključne riječi: stablovna metoda, iveranje, biomasa, sječa, ekonomija, prorede, teda-bor

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