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Productivity and Cost of Processors in Whole-Tree Harvesting Systems in Southern Pine Stands

Joseph L. Conrad IV and Joseph Dahlen

Logging businesses in the US South have not adopted cut-to-length harvesting systems. Adding dangle head processors on the landing of whole-tree harvesting systems may allow southern loggers to achieve some of the advantages of cut-to-length systems (i.e., precise length and diameter measurements) while maintaining high productivity and low costs per ton characteristic of current whole-tree systems. We conducted a designed study of conventional (i.e., feller-buncher, grapple skidder, loader) and processor (i.e., feller-buncher, grapple skidder, processor, loader) systems. Four harvest sites were split, with half of each site harvested by a conventional system and the other half by a processor system. Harvesting productivity was estimated using time-and-motion studies, and costs were estimated using the machine rate method. Cut-and-load costs averaged US$13.57 and US$14.67 ton^{-1} on the processor and conventional harvests, respectively (P > .10). Cost per ton was elevated on several conventional harvest tracts because of long skidding distances, indicating harvest planning is more important than harvesting system in determining harvesting costs. Processing and loading costs were US$1.70 ton^{-1} higher on processor harvests, which, combined with restrictive mill quotas being more problematic for processor crews, suggests loggers will require a logging rate premium in order to invest in processors.

Keywords: logging, efficiency, wood supply chain

The whole-tree, feller-buncher/grapple skidder system has been the most commonly used system by logging businesses in the US South since the 1980s (Greene et al. 1988, Barrett et al. 2017, Conrad et al. 2018b). Logging crews using this system typically operate a feller-buncher, one or two grapple skidders, and one or two knuckle-boom loaders paired with pull-through delimbers and slasher saws. This system, coupled with large tracts of pine plantations, has allowed southern logging businesses to double their production over the past 30 years and harvest timber at a competitive cost internationally (Conrad et al. 2018a). Unlike logging businesses in the US Northeast, Midwest, and West, and internationally, southern logging businesses have not adopted cut-to-length systems.

Southern whole-tree systems typically harvest and deliver tree-length material (i.e., random lengths to a specified minimum top diameter) to mills with subsequent processing conducted at the manufacturing facility (Conrad et al. 2018b). This approach minimizes material handling at harvest sites and results in high volume recovery at pulp mills, which helps pulp mills minimize raw material costs. For sawmills, however, lumber is sold in standard lengths; consequently, purchasing tree-length material produces high levels of residual material that must be sold, used, or disposed. Sawmill efficiency may be increased, and process residuals reduced, if standard length logs are purchased instead of tree-lengths.

While southern whole-tree systems are very efficient when producing tree-lengths, productivity can be reduced significantly when short log lengths are processed. Cass et al. (2009) found that processing productivity was reduced by 52 percent when log lengths <20 ft were produced. In addition, approximately three-quarters of southern loggers using whole-tree systems estimate, rather than measure, log dimensions during processing (Hamsley 2008). Poor estimation may lead to low value recovery if the logger underestimates diameters and lengths. On the other hand, the logger may deliver out-of-spec timber to the mill if they overestimate log dimensions.

Affiliations: *Joseph L. Conrad (jlconrad@uga.edu), Assistant Professor of Forest Operations, Warnell School of Forestry and Natural Resources, 190 East Green Street, Athens, GA 30602. Joseph Dahlen (jdahlen@uga.edu), Associate Professor, Wood Quality & Forest Products, Director, Wood Quality Consortium, 190 East Green Street, Athens, GA 30602.*

Processing heads are capable of measuring the length and diameter of stems, quickly bucking stems to length, and performing multiple bucking cuts to minimize the impact of defects on log value. Harvesters use processing heads to fell, delimb, top, and buck stems at the stump. Harvesters are used in the harvester-forwarder cut-to-length system that is becoming increasingly popular in the Northeastern, Midwestern, and Western United States as well as internationally (Gellerstedt and Dahlin 1999, Leon and Benjamin 2012, Blinn et al. 2015, Dodson et al. 2015, Rickenbach et al. 2015, Mac Donagh et al. 2017). Although cut-to-length systems have been impractical in the US South because of pulp mills' desire for tree-length material, lack of dealer support, and other reasons (Conrad et al. 2018a), excavator-based, dangle head processors may be stationed at the landing on whole-tree harvesting crews. In this system, a feller-buncher fells trees, whole trees are delivered to the landing, the processor delimbs, tops, and bucks stems to length, and a knuckle-boom loader loads processed stems onto trailers. Such an equipment mix might allow logging crews to achieve high production and low per-ton costs characteristic of southern whole-tree systems and achieve high value recovery from precise measurements of length and diameter associated with cut-to-length systems (Gingras 1996, Gingras and Soucy 1999, Hamsley et al. 2009).

A new processor costs US$500,000 or more, whereas a loader, pull-through delimber, and slasher saw often cost less than US$300,000. In addition, whereas the loader equipped with a delimber and slasher saw is capable of processing and loading trucks, the processor is not designed to load trucks. The average Georgia logging business owner has invested US$1.97 million in equipment, including trucks and trailers (Conrad et al. 2018b), meaning a new processor represents a substantial investment for most logging businesses.

In addition to representing a substantial investment, processors may also change harvesting system balance and necessitate other changes to harvesting operations. For example, loading is the limiting factor in production for many conventional harvesting operations. When a processor is added, processing and loading capacity may increase substantially, and skidding may become the limiting factor. This may necessitate adding a skidder, revising harvest plans to reduce skidding distance, or reducing skidder tasks such as gate delimbing. Previous research found that adding a processor to a southern logging system improved value recovery, but increased harvesting costs by nearly US$1 per ton (Hamsley et al. 2009). Another study found that logging crews with processors on the landing were able to perform up to nine product separations (sorts) before production declined, compared to just six separations for conventional crews (Cass et al. 2009). Similarly, a study in New Zealand concluded that processor productivity did not decline until between nine and 12 sorts were required (Tolan and Visser 2015). However, intensive biomass sorting did reduce processor productivity in western forests (Kizha and Han 2016).

Research is necessary to evaluate how adding a processor changes the productivity and cost of southern harvesting systems. Therefore, the goal of this study was to compare harvesting productivity and cost of a conventional southern whole-tree harvesting system using a knuckleboom loader, pull-through delimber, and slasher saw for processing to a system using a dangle head processor to top, delimb, and buck stems on the landing.

Materials and Methods

Four harvest sites were selected by our industry partner and research sponsor, divided in half, with each half tract assigned to a conventional crew or processor crew. The four sites were located in the Piedmont and Upper Coastal Plain of Georgia in Hancock (33.2209°N, 83.1848°W), Jasper (33.2497°N, 83.5717°W), Warren (33.3417°N, 82.5667°W), and Washington (33.0329°N, 82.6306°W) Counties. Harvest sites ranged in total size from 76 to 100 acres, and each harvest treatment was assigned to a unit of 36–57 acres (Table 1). Each site contained between 60 and 80 tons per acre according to preharvest inventories conducted by our industry partner. Site I was predominately chip-n-saw, and Site II was mostly pine sawtimber. Sites III and IV both contained almost one load of pulpwood per acre. Site III contained patches of hardwood pulpwood and very small pine pulpwood, whereas the other tracts had a fairly consistent size and volume distribution throughout.

Harvesting crews were selected by our industry partner and/or the forest landowner. Harvesting crews were experienced with their respective harvesting system and considered top-performing crews with the goal that the analysis focus on differences between treatments rather than differences in crew efficiency. The processor operators had been operating the machine for approximately 1 year, by which time most operators will have neared the top of the learning curve for operating a given type of equipment (Purfurst 2010, da Silva Lopes and Pagnussat 2017).

Four harvesting businesses and six harvesting crews participated in the study. Three unique crews harvested processor sites and three different crews harvested conventional sites. Processor Crew I harvested sites I and III. Likewise, Conventional Crew I harvested sites I and III. The remaining crews harvested one site each. Each of the processor crews operated similar equipment, and the four conventional crews also operated similar equipment (Table 2). The processor crews generally operated one rubber-tired feller-buncher, two grapple skidders, a processor,

Management and Policy Implications

Southern logging businesses have used conventional whole-tree, feller-buncher/grapple skidder systems for decades to deliver tree-length logs to mills. Although desirable for pulp mills, purchasing tree lengths reduces sawmill productivity and yields large amounts of residual chips that must be marketed or disposed. In contrast to conventional systems, processors are capable of precise length and diameter measurements and quickly buck logs to lengths desired by sawmills. This study found that adding a dangle head processor to southern logging operations increased weekly production. Harvesting costs were lower on processor harvests in this study than on conventional harvests because of poor harvest planning and system balance on several conventional harvests. Nonetheless, logging businesses are likely to demand a US$1–2 ton⁻¹ logging rate premium to add a processor because of the high initial cost of a processor (≥US$500,000), increased costs of processing and loading, and susceptibility to mill quotas. Large landowners that negotiate prices directly with mills and/or sawmills should consider incentivizing logging businesses to add processors to increase volume and value recovery on timber harvests and increase mill efficiency. For logging business owners, harvest planning and system balance are critical to profitability, regardless of whether a processor is used.

Table 1. Preharvest inventory data for the four harvest sites in the Piedmont and Upper Coastal Plain of Georgia.

| Site and treatment | Acres | Tons acre⁻¹ | | | | Total | Trees acre⁻¹ | Tons tree⁻¹ |
		Pine pulpwood	Pine chip-n-saw	Pine sawtimber	Hardwood			
Site I								
Processor	48	<1	53	8	0	61	89	0.69
Conventional	50	<1	55	14	<1	70	84	0.83
Site II								
Processor	57	6	11	57	3	77	105	0.73
Conventional	40	5	12	46	1	64	95	0.67
Site III								
Processor	56	22	44	4	1	71	138	0.51
Conventional	44	30	31	4	<1	67	126	0.53
Site IV								
Processor	40	22	6	42	<1	70	100	0.70
Conventional	36	25	11	40	0	77	118	0.65

Table 2. Makes and models of equipment used at each harvest site.

| Site and treatment | Equipment | | | |
	Felling	Skidding	Processing	Loading
Site I				
Processor	Tigercat 718E	Tigercat 620E	John Deere 2154D with Waratah 622B processing head	Tigercat 234B
Conventional	Tigercat 718E	Tigercat 620E	Pull-through delimber, slasher saw	Tigercat 234B
Site II				
Processor	Caterpillar 573C	Caterpillar 545C, 545D	Gate delimber, Caterpillar 538 with Waratah 622B processing head	Caterpillar 622B
Conventional	Caterpillar 553C	Caterpillar 525C, 525D	Gate delimber, pull-through delimber, slasher saw	Caterpillar 559C
Site III				
Processor	Tigercat 718E	Tigercat 620E (2)	John Deere 2154D with Waratah 622B processing head, pull-through delimber, and slasher saw	Tigercat 234B (2)
Conventional	Tigercat 718E	Tigercat 620E	Pull-through delimber and slasher saw	Tigercat 234B
Site IV				
Processor	Tigercat 724G	Tigercat 620E, John Deere 648H	Gate delimber, John Deere 2154G with Waratah 622B processor head	Tigercat 234B
Conventional	Tigercat 724G	Tigercat 630E	Gate delimber, pull-through delimber, slasher saw, chainsaw processing by deckhand	Tigercat 234B

and a trailer-mounted loader. However, the processor crew at Site I operated only one skidder, and the processor crew on Site III added a second loader to process small-diameter tree-length pulpwood and load trucks. Conventional crews operated one feller-buncher, one grapple skidder, and a trailer-mounted loader with a pull-through delimber and slasher saw. The exception to this configuration was the crew harvesting Site II, which used two skidders. Three crews had spare equipment on site at times, but the extra equipment was not used consistently and was excluded from productivity and cost calculations. The equipment configuration and production capabilities of the logging crews were typical of Georgia loggers (Conrad et al. 2018b). Pulpwood, chip-n-saw, and sawtimber were harvested from each site. The conventional crews harvested tree-length pulpwood, tree-length chip-n-saw, and tree-length sawtimber as well as topwood pulpwood (Table 3). The processor treatment harvested tree-length and topwood pulpwood, but chip-n-saw and sawtimber were bucked to multiples of 16 or 20 ft.

Time-and-motion studies were conducted on each harvest unit to detect differences in productivity between treatments and develop estimates of harvesting costs per ton. Elemental time studies were conducted to estimate harvesting productivity. We recorded time per cycle, stems per cycle, and delay time for each machine in the system and combined this data with weight per stem from preharvest inventory measurements to calculate hourly productivity (Table 1).

For feller-bunchers, a cycle began when the feller-buncher placed a bunch of stems on the ground and ended when the next bunch of stems was placed on the ground. Time per cycle, stems per cycle, and delay time were recorded for each felling cycle. A skidding cycle began when a skidder dropped a turn of stems at the landing or staging area and ended when the next turn of stems was dropped at the landing or staging area. Several skidder operators regularly staged trees 100–300 ft from the landing and moved the wood to the landing at a later time. The average time to move piles from the staging area to the landing was added to each turn that ended at the staging area (Conrad et al. 2013). Skidding distance, stems per cycle, and delay time were recorded for each skidding cycle. Although several crews operated two skidders (Table 2), they were all of comparable size, and so data from all skidders in a unit were combined when estimating skidding productivity. A processor cycle began when the processor placed the last log from a tree in a pile and ended when the last log from the next tree was placed in a pile. Cycle time, number of logs processed, whether or not butt flare was removed, and delay time were recorded for each processor cycle. Processing with a trailer-mounted loader began when the last log from a tree was placed in a pile and ended when the last log from the next tree was placed in a pile. Cycle time, number of stems per cycle, use of the pull-through delimber (yes/no), use of the slasher saw (yes/no), and delay time were recorded for each cycle. A truck loading cycle began when the first stem was placed on a trailer and ended when the last stem was placed on the trailer. Time per load,

Table 3. Product specifications for pulpwood, chip-n-saw, and sawtimber product classes for the conventional and processor treatments.

Product	Treatment	Length (ft)	Minimum large end diameter (in.)	Minimum small end diameter (in.)
Pulpwood	Both	≥12	NA	3
Chip-n-saw	Conventional	16.5	8	6
Chip-n-saw	Conventional	≥25	8	5
Sawtimber	Conventional	16.5	14	10
Sawtimber	Conventional	≥25	14	8
Chip-n-saw	Processor	Multiples of 16 or 20	8	5
Sawtimber	Processor	Multiples of 16 or 20	14	8

Table 4. Machine rate assumptions for all harvesting crews.

Machine	Feller-buncher	Skidder	Loader	Processor
Purchase price (US$)	260,000	280,000	239,000	500,000
Salvage value (percentage of purchase price)	25	20	20	20
Economic life (years)	5	5	5	5
Interest, insurance, and taxes (percentage of average value invested)	10	10	10	10
Fuel consumption (gal pmh^{-1})	6.5	5.1	3.7	5.0
Maintenance and repair (percentage of depreciation)	100	100	100	100
Utilization (%)	65	60	65	65

Note: gal pmh^{-1}, gallons per productive machine hour (excluding delays).

delay time, and stems per load were recorded for each truckload. We used average truck payload from scale tickets on each site and treatment combination to calculate loading productivity.

In addition to the elemental time study, work sampling (Miyata 1981) was conducted on the landing to estimate the percentage of time the processor spent processing logs and identify bottlenecks in the system. The activity the machine was performing (e.g., processing, waiting on skidder, idle) was recorded at 45-second intervals.

Hourly costs of owning and operating harvesting equipment were estimated using the machine rate method (Miyata 1980, Brinker et al. 2002, Dodson et al. 2015). For each machine, an off-road diesel price of US$2.70 per gallon was assumed (EIA 2018). Each equipment operator and deckhand was assigned compensation of US$17.75 per hour (BLS 2018), plus 40 percent overhead and fringe benefits. We assumed 2,000 scheduled hours per year for each machine and employee. Assumptions that varied by machine are listed in Table 4. Although each crew operated slightly different equipment (Table 3), the equipment was of similar size, cost, and potential productivity. Therefore, the same machine rate assumptions were used for each feller-buncher, skidder, loader, and processor, respectively.

For each harvest unit, we assumed US$3,500 of roadwork. Initial movement of equipment to the harvest site was assumed to take 5 hours at a distance of 40 miles. One company truck was assigned to each crew at a cost of US$0.545 per mile with 80 miles driven per day. A deckhand earning US$17.75 per hour was employed on Site I Processor, Site II Conventional, Site III Processor, and both harvest units on Site IV. An owner salary of US$6,000 per month was assumed for all crews along with US$3,000 per month in overhead. Two chainsaws worth US$1,500 apiece were assigned to each crew. No profit was included in the calculations with the goal of focusing on logging costs exclusively.

Hourly productivity from the time-and-motion studies was combined with hourly cost estimates from the machine rate method to calculate the cost per ton for each machine. Individual machine productivity and cost data were combined to estimate harvesting system productivity and cost per ton using a modified version of the Auburn Harvesting Analyzer (Tufts et al. 1985). The Auburn

Harvesting Analyzer was also used for sensitivity analysis to estimate the impact of increasing skidding productivity and imposing a restrictive quota.

We compared the weight of sawtimber and chip-n-saw loads delivered from the processor and conventional systems to determine whether there were any differences in average payload between the two systems. Given the more uniform dimensions of standard length logs, we hypothesized that loggers using processors would be able to estimate payloads more accurately than loggers with conventional systems. In-woods weight scales were not used during the study.

Paired sample *t*-tests were used to compare tract-level sample means (e.g., harvesting productivity and cost) between the two harvest treatments. Average cycle times and logs processed per stem were compared using analysis of variance (ANOVA) and the Tukey HSD test. Average truck payloads for sawtimber and chip-n-saw were compared using a mixed effects model in which treatment was fixed, and site was random. Data analysis was conducted using Microsoft Excel and JMP Pro 13.2.0 software (SAS Institute 2016). Statistical analysis was conducted at $\alpha = .10$ significance level because of the small sample size and high levels of variability typical of this type of research.

Results and Discussion
System Productivity and Cost

There were no statistically significant differences in harvesting costs (cut-and-load) between processor and conventional crews ($P > .25$). Harvesting costs averaged US$13.57 and US$14.67 per ton on the processor and conventional harvests, respectively (Table 5). The processor crews produced 67 percent more timber per scheduled machine hour (including delays) than conventional crews, although because of the small sample size, these differences were not statistically different ($P = .17$). It is important to note that three of the four processor crews used two skidders, whereas only one of the four conventional crews used two skidders (Table 3). The processor crews averaged 59 loads per week, whereas the conventional crews averaged 35 loads per week ($P = .17$). Average weekly production (tons) by the conventional crews was practically identical to the

Georgia average for feller-buncher/grapple skidder crews, whereas processor crew production was 73 percent higher than the Georgia average (Conrad et al. 2018b).

These results demonstrate that business management and harvest planning have a greater impact on harvesting productivity and cost than whether a company produces tree-lengths with a conventional system or standard lengths with a processor. Poor system balance, most commonly inadequate skidding capacity, resulted in extremely high harvesting costs on the conventional harvests at sites III and IV, and the processor harvest at Site I (Table 5). For example, the processor crew on the Site I used just one skidder, which created a bottleneck and caused harvesting costs to be US$4 ton^{-1} higher than on any of the other processor harvests. Adding a second skidder to this system would have reduced harvesting costs to US$10.26 ton^{-1}, a 40 percent reduction. Similarly, the conventional crew on Site IV chose to use one skidder and one landing to harvest 36 acres, resulting in the lowest skidding productivity observed during the study. If skidding productivity were increased by 50 percent on this harvest, harvesting costs would have been reduced to US$13.84 ton^{-1}, a 27 percent reduction.

On each site, skidders were responsible for conducting initial delimbing, either by driving over tree tops or by using a delimbing gate. This approach is not necessary in most conventional systems, and it is counterproductive in a processor system. Processors are equipped with a head capable of felling, delimbing, topping, and bucking stems at the stump and are therefore capable of conducting all of the delimbing. Skidder delimbing is unnecessary in a processor system and is not recommend by processing head manufacturers (Michael Campbell, pers. comm., Waratah Area Manager, Product Support and Sales Southeast USA, August 30, 2018). Requiring the skidder to conduct initial delimbing reduces system productivity and increases costs per ton when skidding is the limiting factor in production, as was the case on all four processor treatments (Table 5). We estimated that gate delimbing and driving over tops added 1–2 minutes to each skidding cycle, which agrees with prior research that found gate delimbing increased skidding cycle time by 1.5 minutes (Greene and Stokes 1988).

We simulated the impact of reducing average skidder cycle time by 1.5 minutes per turn to analyze the impact of skidder delimbing on harvesting costs. Reducing average skidder cycle time by 1.5 minutes per turn reduced harvesting costs on the processor treatments by an average of US$1.91 ton^{-1} ($P = .03$), a 14 percent reduction (Table 6). Similarly, hourly production increased by almost 10 tons per scheduled machine hour ($P < .01$), and weekly production increased by an average of 12 loads per week ($P < .01$). Of course, these cost savings and productivity increases will not be realized if processor productivity is reduced significantly by increased delimbing responsibilities; however, given the high amounts of idle time for the processors in this study, even if the processors spent slightly more time per tree delimbing, this would not adversely affect overall system productivity. Conducting all delimbing at the landing will increase landing slash that will need to be moved by skidders, but this should not have a significant impact on skidding productivity (Soman et al. 2019) and would be preferable to the 1–2 minutes per cycle spent gate delimbing or driving over tree tops. Gate delimbing or driving over tree tops with skidders may be necessary for trees with unusually large limbs, such as when trees are harvested adjacent to a road or power line right-of-way. Nonetheless, this analysis suggests that using skidders for delimbing is quite costly in a processor system and should be avoided when possible.

The harvesting cost estimates in this study are similar to those of mechanized systems in South America (Mac Donagh et al. 2017), comparable to past studies of whole-tree systems in the US South and cut-to-length and whole-tree systems in the US West after adjusting for inflation and changes in fuel prices (Adebayo et al. 2007, Conrad et al. 2013). Previous research found that harvesting costs were US$1–2 ton^{-1} higher in processor systems than conventional systems (Hamsley 2008, Hamsley et al. 2009). In this study, the average cost of the processor system was lower than for the Conventional system (Table 5). However, this difference was the result of poor system balance on several conventional tracts. In this study, the combined cost of processing and loading was US$1.70 ton^{-1} higher on the processor tracts than the conventional tracts (Table 7), which suggests a US$1–2 ton^{-1} premium may be necessary for loggers to invest in processors, especially when restrictive quotas are likely.

Table 5. Harvesting productivity and cost (cut-and-load) on the four harvest tracts for the processor and conventional crews.

Site and treatment	Harvesting cost (US$ ton^{-1})	System productivity (tons smh^{-1*})	Loads week^{-1}	Average observed skidding distance (ft)	Limiting factor in production
Site I					
Processor	17.01	26.79	35	562	Skidding
Conventional	9.92	35.80	46	624	Loading/Processing
Site II					
Processor	12.12	51.18	64	750	Skidding
Conventional	13.24	36.04	47	588	Loading/Processing
Site III					
Processor	12.60	53.00	68	821	Skidding
Conventional	16.43	20.08	26	659	Skidding
Site IV					
Processor	12.57	53.18	70	742	Skidding
Conventional	19.08	17.83	24	1217	Skidding
Average					
Processor	13.57[a]	46.04[a]	59[a]	719[a]	–
Conventional	14.67[a]	27.43[a]	35[a]	772[a]	–

Note: The loads per week below assumes 40 hours worked per week by all employees and machines. Actual production differs slightly because some crews, or some employees or machines, worked more (or less) than 40 hours per week. smh, scheduled machine hour (including delays). Values not connected by the same letter are significantly different ($\alpha = 0.10$).

Table 6. Impact of reducing skidder cycle time by 1.5 minutes on the processor treatments.

Site	Harvesting cost after reducing skidder cycle time (US$ ton⁻¹)	Harvesting cost savings compared to study observations (US$ ton⁻¹)	Increased loads week⁻¹
Site I	13.68	3.33	11
Site II	10.49	1.63	15
Site III	10.82	1.78	15
Site IV	11.64	0.93	7
Average	11.66	1.91[a]	12[a]

Note: This analysis simulates the impact of removing delimbing responsibilities from skidder operators.
[a]Increase or decrease is statistically different from 0 (α = 0.10).

Table 7. Harvest function productivity (tons pmh⁻¹ machine⁻¹) and cost (US$ ton⁻¹) for all sites with descriptive statistics.

Function	Treatment	Function cost (US$ ton⁻¹)	Productivity (tons pmh⁻¹ machine⁻¹)			
			Mean	Min.	Max.	Standard error
Felling	Processor	1.77	123	65	163	23.3
	Conventional	2.69	108	90	159	17.0
Skidding	Processor	3.65	38	37	38	0.4
	Conventional	4.42	35	25	53	6.1
Processing	Processor	2.96	74	69	77	1.8
Processing and loading	Conventional	3.22	39	35	42	2.0
Loading	Processor	1.96	91	87	100	3.1

Note: Function productivity and costs assume each function is operating at its intrinsic production level, unconstrained by a system rate. pmh, productive machine hour.

Table 8. Impact of a 1,350-tons-per-week quota on the harvesting costs for the processor and conventional crews observed during this study.

Site and treatment	Harvesting cost (US$ ton⁻¹)	Cost increase from study observation (US$ ton⁻¹)
Site I		
Processor	17.01	0.00
Conventional	10.30	0.38
Site II		
Processor	15.77	3.65
Conventional	13.80	0.56
Site III		
Processor	17.24	4.64
Conventional	16.43	0.00
Site IV		
Processor	16.67	4.10
Conventional	19.08	0.00
Average		
Processor	16.67[a]	3.10[a]
Conventional	14.90[a]	0.23[b]

Note: Values not connected by the same letter are significantly different (α = 0.10).

Quota Sensitivity Analysis

Processor crews have higher fixed costs than conventional crews. Consequently, processor crews require higher production levels or higher cut-and-load rates, or both, in order to break even. A 1,350 tons wk⁻¹ (~45 loads) quota was applied to each crew using the Auburn Harvesting Analyzer to estimate the impact on conventional and processor crews. This quota level is 20 percent higher than median production per crew in Georgia (Conrad et al. 2018b).

The processor crews were more sensitive to the 1,350 tons wk⁻¹ quota than the conventional crews. The quota increased costs for the processor crews by an average of US$3.10 ton⁻¹, versus just US$0.23 ton⁻¹ for the conventional crews (P = .08) (Table 8). The only processor crew that did not see increased costs as a result of the quota was the crew harvesting Site I, and that crew already had one of the highest costs observed in the study as a result of inadequate skidding capacity. The conventional crews were generally less

productive, had lower capital investments, and were therefore less affected by the quota. This supports past observations that loggers should focus on matching their harvesting systems to mill demand (Stuart et al. 2010).

Function Productivity and Cost

Felling was the least expensive and most productive function, as is often the case for southern loggers (Table 7). Skidding was the least productive and most expensive harvesting function. This finding underscores the importance of harvest planning and system balance in minimizing harvesting costs. Skidder productivity ranged from 25 to 53 tons per productive machine hour (pmh; i.e., excluding delays) per machine on conventional treatments because of inconsistent skidding distances between sites and the use of gate delimbers or driving over tree tops. For example, the skidder on the conventional harvest at Site I averaged 53 tons pmh⁻¹ because the maximum skidding distance was 1,000 ft, and skidding distance averaged 623 ft. In contrast, on the conventional harvest at Site IV, the skidder produced just 25 tons pmh⁻¹ because the maximum skidding distance was 1,800 ft, and the average skidding distance was 1,217 ft. Skidding distance has long been known to influence skidding productivity and cost (e.g., Tufts et al. 1988, Baumgras et al. 1993, Kluender et al. 1997, Soman et al. 2019). In a conventional system, loading and processing may be the limiting factor in production, as was the case on two of the four sites in this study (Table 5), allowing for a somewhat long skidding distance. However, when a processor is added to the system, skidding is likely to become the limiting factor. Therefore, increasing skidder productivity will improve system efficiency and reduce costs per ton. Skidding productivity could be increased by reducing skidding distance, eliminating unnecessary tasks such as gate delimbing, adding an additional skidder, or increasing skidder size (i.e., payload capacity).

Processor productivity, excluding delays, was remarkably similar between sites, ranging between 69 and 77 tons pmh⁻¹, which is equivalent to 2–3 loads per hour (Table 9). On sites with

larger-diameter trees (i.e., greater weight per stem), the processor produced fewer stems per hour, and on sites with smaller-diameter trees (i.e., lower weight per stem) the processor produced more stems per hour, with the result being similar production across the range of sites in this study. Previous research indicates that processing costs decline rapidly as dbh increases to 7–9 in. but decline modestly thereafter up to the capacity of the harvesting head (Kellogg and Spong 2004, LeDoux 2011). The vast majority of trees in this study were large enough for the processor to handle efficiently, but loggers conducting first thinnings would be ill-advised to add a processor because the machine will not be productive with small stems, and the ability to buck precisely would be unnecessary because almost all of the timber would be delivered in tree-length form.

Actual production was far below delay-free processor productivity on three of the four sites (Tables 5 and 9). The processors on the four sites spent between 44 percent and 83 percent of time processing stems (Figure 1). The processors on sites I and II spent 25 percent of their time waiting on the skidders. The crew on these two sites did not allow the skidder to drop a turn of logs on the landing until all of the stems from the previous turn had been processed. Consequently, there were constant interactions between the processor and skidder as the skidder waited on the processor

when skidding distance was short, and the processor waited on the skidder on long skidder turns. Although a maximum of 25 percent of nonprocessing time was directly attributed to the skidder, in reality, most nonprocessing time was a result of inadequate skidding capacity. Processors often conducted busywork on the landing when there was no wood available and would even leave the machine to perform other tasks because they could catch up quickly. The delay-free productivity values in Table 9 are probably conservative. It is likely that the processor operators could have been more productive, but there was no incentive to do so because it would have resulted in additional idle time and no additional system production.

Load Weights

The average chip-n-saw and sawtimber payload was 0.25 tons higher on processor loads compared to conventional loads ($P = .18$). However, the average processor payload was higher only on Site II. Load weights were slightly more variable on conventional loads, and this trend was found at all four sites. The coefficient of variation of conventional loads was 6.1 percent, compared to 5.1 percent on processor loads. Previous research suggests that minimizing load weight variation is critical to minimizing hauling costs (Hamsley et al. 2007, Reddish et al. 2011). The consistent dimensions of standard length logs mean loggers may be able to estimate truck weights more accurately than conventional crews. Nonetheless, payload variability was lower for both types of crews in this study than for the crews analyzed by Hamsley et al. (2007).

On average, 49 percent of conventional loads received at least one scale ticket deduction compared to just 27 percent of processor loads ($P = .13$). Scale ticket deductions are assessed by the receiving mill when logs do not meet their specifications because of length, diameter, or defect (e.g., sweep, crooks, knots, etc.). On the conventional treatment, the percentage of loads with deductions ranged from 27 percent on Site I to 69 percent on Site III. In contrast, processor loads with defects ranged from 17 percent on Site

Table 9. Average processing time per stem for the processor on the four harvest sites.

Site	Tons pmh^{-1} machine^{-1}	Average delay-free cycle time (min)	Average number of processed logs per stem
Site I	77	0.54[a]	1.72[a]
Site II	74	0.59[b]	1.97[b]
Site III	77	0.43[c]	1.76[a]
Site IV	69	0.61[b]	1.88[b]
Average	74	0.54	1.83

Note: pmh, productive machine hour (excluding delays). Values not connected by the same letter are significantly different ($\alpha = 0.10$).
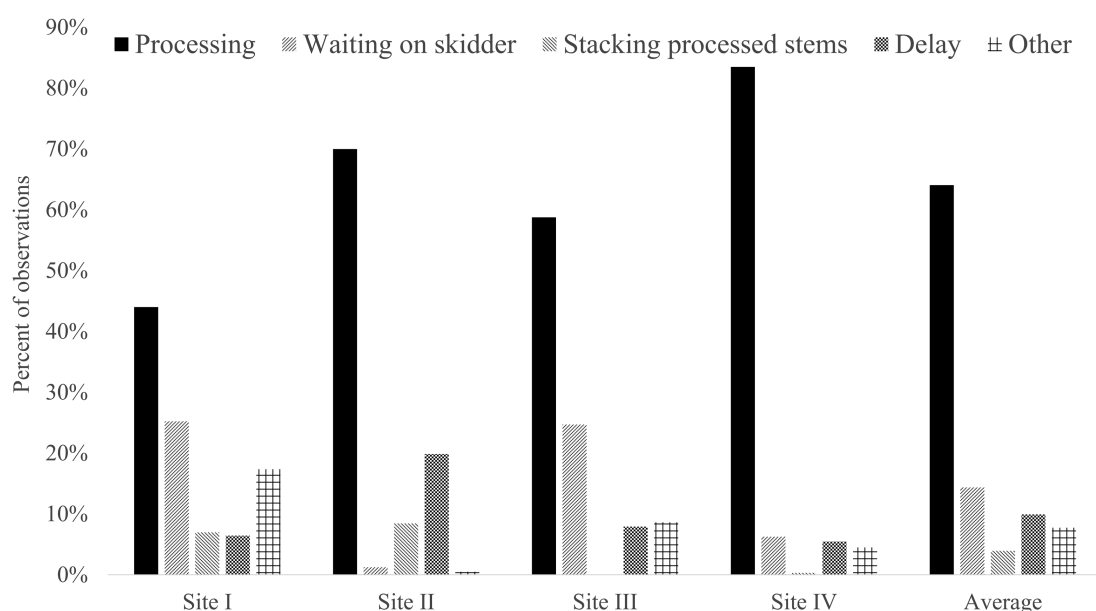

Figure 1. Processor time allocation on the four harvest sites measured by activity sampling.

II to 34 percent on Site I. The average deduction was 0.31 tons on conventional loads and 0.26 tons on processor loads ($P < .01$). The ability of processors to quickly make multiple bucking cuts allows processors to remove defects that a conventional system may not attempt to remove. Receiving standard log lengths rather than random tree-lengths and receiving logs with fewer defects likely improves mill efficiency. Most mills in the South receive random tree-length logs; consequently, additional bucking cuts are required in the mill, and more residual material is produced that must be marketed or disposed. In some cases, residual material handling can create a bottleneck in the mill. Mills began receiving tree-length material decades ago before precise mechanized bucking could be conducted in the woods and when integrated forest products companies used residual material in their pulp mills. In 2019, processors are available to precisely measure stem lengths and diameters in the woods, and sawmills are no longer owned by pulp and paper companies, making residuals from tree-length log processing a potential liability.

Conclusion

Whole-tree harvesting systems delivering tree-length material have dominated southern timber harvesting for approximately three decades (Greene et al. 1988, Barrett et al. 2017, Conrad et al. 2018a). Consequently, precise length and diameter measuring technology has not been deployed on southern timber harvests. Previous research suggests processors and cut-to-length harvesters can increase value recovery compared to conventional equipment (Gingras 1996, Gingras and Soucy 1999, Hamsley et al. 2009, Lang et al. 2010). The present study found that processors can be added to southern whole-tree systems at costs competitive with conventional whole-tree systems (Table 5). However, given increased processing and loading costs (Table 7) and susceptibility to restrictive quotas (Table 8), loggers are likely to demand a US$1–2 per ton logging rate premium. Given the potential for increased volume and value recovery and increases in mill efficiency resulting from receiving logs of standard length, some mills and/or large landowners may be willing to pay loggers a premium for adding a processor. Given the large capital expenditure (≥US$500,000), most logging business owners are unlikely to add processors without a financial incentive as long as most timber markets accept tree-length logs.

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