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Productivity and Cost of Post-Tornado Salvage Logging in Upper Coastal Plain of South Carolina, USA

Joseph L. Conrad IV

Abstract

*Salvage harvesting is common in the US South following natural disasters such as tornadoes and hurricanes; nevertheless, few studies have evaluated the productivity and costs of these harvests because of their geographic dispersion and the short interval between natural disasters and salvage harvesting. An Enhanced Fujita Scale 3 (EF3) tornado with winds in excess of 250 km per hour struck Aiken County, South Carolina in April of 2020, uprooting trees and severing other stems above breast height. The goal of this study was to estimate the productivity and cost of salvage harvesting in loblolly pine (*Pinus taeda *L.) stands following severe tornado damage. Salvage harvests were conducted with a rubber-tired drive-to-tree feller-buncher, grapple skidder, tracked loader, and chipper. All stems were chipped and used to produce energy; no roundwood was produced from the harvests. Elemental time-and-motion studies were conducted in three pulpwood-sized stands (<30 cm large-end diameter) and three sawtimber-sized stands (≥30 cm large-end diameter). Hourly harvesting costs were estimated using the machine rate method and per-ton costs were estimated using a modified version of the Auburn Harvesting Analyzer. Skidding productivity was low in each harvest unit, but especially so in the three pulpwood-sized stands because of stem breakage and low weight per stem. Harvesting costs averaged \$29.78 and \$19.97 (USD) per tonne (onboard truck) in the pulpwood- and sawtimber-sized stands, respectively. High salvage harvesting costs mean that landowners can expect significantly reduced stumpage prices from these harvests; nonetheless, landowners do benefit from reduced reforestation costs. Harvesting promptly after a tornado can reduce harvesting costs and increase timber value recovery.*

Keywords: timber harvesting, forest restoration, bioenergy, chipping

1. Introduction

Salvage logging is common in the US South because of disturbances such as wildfires, tornadoes, hurricanes, and insect and disease infestations. Many studies have evaluated the ecological, water quality, and landowner financial returns from salvage logging (Haight et al. 1995, Elliott et al. 2002, Nelson et al. 2008, Brooks and Stouffer 2010, James and Krumland 2018). Because of the South's warm and humid climate, wood quality declines rapidly after a disturbance. State forestry agencies recommend that salvage harvesting operations be completed within 3–8 months of a natural disaster (Bradley et al. 2018, Dickens et al. 2018).

The short interval for conducting salvage operations and the geographic dispersion of salvage logging opportunities mean that loggers in the southern US must use conventional logging equipment to conduct salvage operations. More than 95% of logging businesses in the Coastal Plain and Piedmont of the US South use feller-bunchers, grapple skidders, and knuckleboom loaders to harvest timber (Barrett et al. 2017, Conrad et al. 2018). Information is lacking on harvesting productivity and costs of salvage logging in the US South, probably because the short window of opportunity between a natural disaster and salvage operations makes it difficult for researchers to conduct studies of these operations. The lack of information on salvage harvesting productivity and cost can make it difficult for timber buyers to make reasonable bids for salvage timber sales and expose loggers to significant risk of loss if harvesting costs exceed estimates.

Research in other US regions and internationally suggests salvage logging productivity is lower and costs higher than harvesting undamaged stands. Productivity falls and costs rise when merchantable trees develop lean or fall to the ground, both of which increase handling time by felling equipment. Leaning and down trees are most common after wind events. Down trees can also be a concern after insect infestations in the West because harvesting may occur years after tree mortality (Kim et al. 2017, Han et al. 2018) but is less of a concern in the South because of the short interval between infestation and salvage harvesting.

In the midwestern states of Minnesota and Wisconsin, salvage harvesting accounts for 10% of the volume harvested on state and county lands (Russell et al. 2017). Approximately 40% of logging businesses reported conducting salvage operations in 2015 or 2016 (Russell and Blinn 2018). Loggers' primary concerns associated with salvage harvesting included reduced productivity and reduced wood quality. Reductions in wood quality can be particularly important in the South because of higher decomposition and staining rates associated with high temperatures. Almost all (98%) of respondents in the Russell and Blinn (2018) study stated that harvesting windthrow would reduce productivity compared to harvesting undamaged stands. However, fewer loggers suggested productivity would be reduced when harvesting insect/disease and fire damaged stands.

In Colorado, whole-tree harvesting in beetle-killed stands produced approximately 69 t per productive machine hour (pmh; excluding delays) at an average cost of \$11.94 (USD) green t^{-1} onboard truck (i.e., excluding hauling costs) (Han et al. 2018). The presence of downed trees increased feller-buncher cycle time by up to 56% relative to felling and bunching only standing trees. Harvesting costs were estimated to increase linearly as the percentage of downed trees increased.

In western Montana, whole-tree harvesting in beetle-killed stands produced 64 t pmh^{-1} at an average cost of \$18.02 green t^{-1} onboard truck (Kim et al. 2017). The authors estimated that an alternative configuration, operating one skidder instead of two, could reduce costs to \$17.16 green t^{-1}. Feller-buncher cycle time increased by 89% when downed trees were handled relative to handling standing trees only.

In Finland, harvesting productivity ranged from 7.2–9.6 t pmh^{-1}, 19–33% lower than when harvesting undamaged stems (Kärhä et al. 2018). Harvester cycle time increased by 23–49% when harvesting windfall relative to undamaged stems. Average logging costs ranged from \$15.07–\$25.09 t^{-1} when harvesting windthrow, 10–30% higher than when harvesting undamaged stems. Differences in harvesting productivity and costs between harvesting windfall and undamaged stems were inversely related to average stem volume. Similarly, Dvorak (2010) found that windfall and broken trees required additional time for the harvester to process relative to undamaged trees in the Czech Republic.

Forwarder productivity ranged from 13.0 to 20.6 t pmh^{-1} on three salvage harvest sites in the Italian Alps (Cadei et al. 2020). Load volume and extraction distance were the primary determinants of forwarder productivity, as would be expected.

In British Columbia, a feller-buncher/grapple skidder harvesting system averaged 23.8 t pmh^{-1} conducting a partial harvest of mountain pine beetle-killed stands (Han and Renzie 2005). The harvest cost an average of \$27.42 t^{-1} onboard truck, which was much more expensive than typical operations in the area at the time. Harvesting productivity and cost were very sensitive to average tree volume, with small trees costing much more to harvest than larger ones. At an average tree size of 0.4 t, harvesting costs were \$19.54 t^{-1}; however, if tree size was reduced to 0.2 t, harvesting costs would rise to \$31.66 t^{-1}.

In central Italy, roadside chipping produced 100 t pmh^{-1} at a cost of \$14.28 green t^{-1} during pine salvage operations (Marchi et al. 2011). Chipping costs were approximately 50% higher for terrain chipping. In Iran, salvage logging with chainsaws and a cable skidder produced 1.4 t pmh^{-1} during salvage harvesting, which was 6–15 times lower than during non-salvage harvests (Bodaghi et al. 2018). Salvage harvesting costs with that system averaged \$79.22 t^{-1} (Bodaghi et al. 2018). A case study of windthrow salvage in Romania found that cable skidding produced between 4.5 and 6.2 t pmh^{-1} (Borz et al. 2013).

In April of 2020 an Enhanced Fujita Scale 3 (EF3) tornado struck Aiken County, South Carolina USA. An EF3 tornado has wind speeds of 254–332 km per hour, sufficient to tear roofs and walls from well-constructed buildings and uproot most trees in an area (NWS 2022). The tornado did extensive damage to forest stands on the Savannah River Site (SRS), which is a National Environmental Research Park owned by the US Department of Energy with forestland managed by the USDA Forest Service (USDA Forest Service-Savannah River 2022). Salvage timber harvests began in July 2021 and concluded in January 2022, over one year after the tornado occurred. The long interval between the tornado and salvage harvesting resulted from a delay in advertising the timber sale and the purchaser's decision to begin harvesting at the end of the contract period.

Salvage harvesting following natural disasters is common in the US South. However, because of the short interval between the natural disaster and harvesting, very few studies have evaluated the harvesting operations. Therefore, the goal of this study was to estimate the productivity and cost of salvage harvesting in loblolly pine (*Pinus taeda* L.) stands following severe tornado damage.

2. Materials and Methods

Time-and-motion studies were conducted on six salvage timber harvest units on SRS between August and December 2021. Three of the harvest units were pulpwood-sized stands (PPW), which were defined as stands with a majority of harvested stems with large-end diameters smaller than 30 cm. The other three harvest units were sawtimber-sized stands (ST), which were defined as stands with a majority of harvested stems with large-end diameters ≥30 cm. Extensive tornado damage was evident in each unit. The majority of the merchantable trees were uprooted, while other trees were snapped above breast height (1.4 m) (Fig. 1). Fallen trees overlapped each other, and in some cases, broken tops of trees hung dangerously overhead, making a timber inventory unsafe and impractical.

The goal of the harvests was to remove fallen and damaged timber to facilitate reforestation. Because of extensive damage from the tornado and the interval between the tornado and the harvest, no attempt was made to merchandize sawtimber and pulpwood. Instead, all material was chipped and delivered to Ameresco's biomass cogeneration facility within SRS (Ameresco 2017).

The harvests were conducted using three harvesting machines, and one chip van. A Tigercat 720G rubber-tired drive-to-tree feller-buncher was used sporadically to sever fallen trees from the stump and roots, fell standing tree boles whose tops had been removed by the tornado, and fell standing trees that impeded removal of damaged timber. A John Deere 748L-II grapple skidder transported timber to the landing. A Tigercat T234 tracked loader was used to feed the chipper and occasionally perform pre-processing with a slasher saw (e.g., removing roots from stem, removing forked top, etc.) prior to feeding a stem through the chipper. Chipping was performed by a Morbark 40/36 drum chipper. There were three employees on site, including a truck driver. One employee split time between the loader and feller-buncher, one operated the skidder, and the other drove the truck and sometimes operated the loader.

Elemental time studies were conducted on each harvesting machine to estimate harvesting productivity. Time per cycle, stems per cycle, and delay time were recorded for the feller-buncher, skidder, and loader/chipper. These data were combined with

Fig. 1 A formerly fully stocked stand on Savannah River Site in Aiken County, SC USA where a tornado uprooted most trees and severed other stems above breast height

weight per stem to calculate productivity per productive machine hour. Average stem weight was estimated for each harvesting unit based on the number of stems per van load and average observed payload from scale tickets.

A feller-buncher cycle began when a bunch was placed on the ground and ended when the next bunch was placed on the ground. Cycle time, number of stems by damage class, and delay time were recorded for each feller-buncher cycle. Tree damage classes were based on the categories used by Kärhä et al. (2018):

⇒ standing, undamaged trees ≥15 cm DBH
⇒ standing, undamaged trees <15 cm DBH
⇒ whole tree hung up in an adjacent standing tree
⇒ leaning tree (>45°)
⇒ uprooted tree lying on the ground
⇒ broken top above 1.4 m.

A skidder cycle began when the skidder dropped a turn of logs at the landing and ended when the next turn was dropped at the landing. Skidding distance, number of stems, cycle time, and delay time were recorded for each cycle. Skidding distance was measured using a TruPulse 200L laser rangefinder (Laser Technology Inc. 2017). A chipper cycle began when the first chips entered the chip van and ended when the last chips settled in the chip van and no more material was being fed into the chipper. Stem count, cycle time, and delay time were recorded for each chipping cycle. Cycle times for each machine were measured using stopwatches.

Hourly costs of owning and operating the in-woods equipment were estimated using the machine rate method (Miyata 1980, Brinker et al. 2002, Dodson et al. 2015 (Table 1)). Off-road diesel prices were obtained from EIA (2022). Operator wages of $20.98 per scheduled machine hour (smh) including delays)) (BLS 2022) plus 40% overhead and fringe benefits were assumed. One employee operated both the loader and the feller-buncher and so half of this employee's wages were assigned to each machine. Initial movement of equipment to each harvest unit was assumed to require one hour at a distance of 8 km. The crew was assumed to travel 64 km one-way to the harvest site each day at a cost of $0.35 km^{-1} (IRS 2020). A monthly overhead cost of $3000 per month was assumed. Machine life was assumed to be five years for all machines except for the chipper, which was assumed to have an economic life of 10 years (Garren et al. 2021). Chippers tend to have low utilization rates, and failure to extend the useful life to account for a low number of operating hours per year can lead to an overestimation of harvesting costs (Sessions et al. 2021).

Transportation costs were estimated in two ways. The first approach assumed the logging company owned and operated one chip van and truck, and trucking could limit production. Owning and operating a tractor and chip van was assumed to cost $52.86 per hour (Leslie and Murray 2021) plus fuel costs, which were calculated assuming a cost of $0.90 l^{-1}, fuel economy of 2.1 km l^{-1}, and a one-way haul distance of 16 km. The second approach assumed the logger used contract hauling and trucking capacity did not limit in-woods production. Contract hauling costs were

Table 1 Machine rate assumptions

Variable	Machine			
	Feller-buncher	Grapple skidder	Tracked loader	Chipper
Purchase price, USD	265,000	310,000	335,000	700,000
Salvage value, % of purchase price	20	20	20	20
Economic life, yr	5	5	5	10
Interest, insurance, and taxes, % of average value invested	10	10	10	10
Fuel consumption, l pmh^{-1}	20.8	28.0	14.0	94.6
Fuel price, $ l^{-1}	0.77	0.77	0.77	0.77
Lubrication, % of fuel cost	36.8	36.8	36.8	36.8
Maintenance and repair, % of depreciation	100	90	90	100
Mechanical availability	90	90	90	90
Utilization, %	50	85	65	31
Scheduled machine hours per year	2000	2000	2000	2000

l pmh^{-1} – liters per productive machine hour (excluding delays) calculated assuming a hauling cost of \$0.11 t^{-1} loaded km^{-1} with a minimum haul distance of 64 km (TimberMart-South 2021). The minimum haul distance is the minimum distance for which the truck owner is paid even if the actual distance travelled is shorter. The minimum haul distance is designed to compensate the truck owner for the disproportionate time spent loading and unloading on short hauls.

Trucking productivity was estimated assuming that trucks travelled an average of 3 km on woods roads at an average speed of 8 km h^{-1} and 13 km on gravel and paved roads at an average speed of 48 km h^{-1} to and from the energy plant. Unloading was assumed to take 30 minutes. Average chipping time was calculated using observations from the elemental time study.

Hourly productivity and cost estimates were combined in a modified version of the Auburn Harvesting Analyzer (Tufts et al. 1985) to estimate cut-and-load (i.e., onboard truck) and cut-and-haul (i.e., delivered) costs per tonne. Harvesting costs were compared to the market value of in-woods whole-tree pine chips to evaluate the financial viability of the harvests. TimberMart-South (2021) reported prices in three categories: low, high, and average. The low value is the average of the lower half of the price distribution, the high value is the average of the upper half of the price distribution, and the average is the average of the high and low values. This reporting system was designed to guarantee the anonymity of companies reporting prices to TimberMart-South. As the timber in this study had been on the ground for more than a year and may have deteriorated, the low price category was used for comparison purposes. TimberMart-South prices do not include hauling costs.

3. Results

3.1 Harvesting Productivity

Feller-buncher cycle time averaged 1.22 and 1.71 minutes per cycle in the PPW and ST units, respectively (Table 2). The feller-buncher handled approximately three stems per cycle in both types of units. In the PPW units, the most commonly handled stems were those with broken tops (46%), standing non-merchantable stems (23%), and uprooted stems (17%). In the ST units, 60% of the felled stems were standing non-merchantable, 22% had broken tops, and 11% were uprooted. Broken-top stems were sheared by wind 3–6 m above the ground. The non-merchantable stems were generally hardwoods <15 cm DBH that were felled to allow access to storm-damaged trees and/or to facilitate regeneration. Non-merchantable stems did not include brush that had grown since the tornado or stems too small to be skidded and chipped. Uprooted stems were stems that were laying on the ground with the root ball attached. The feller-buncher used the sawhead to sever the root ball from the stem to facilitate skidding. As most of the trees were blown over by the tornado, feller-buncher work was sporadic and this is the reason for the small sample size in some units. The majority of salvaged trees were skidded to the landing without any action by the feller-buncher.

Skidder productivity was low in all harvest units, but especially in the PPW stands (Table 3). Average productivity was 55% higher in the ST units. Productivity was below 15 tonnes per productive machine hour in every PPW unit, whereas productivity exceeded 25 tonnes per productive machine hour in two of

Table 2 Feller-buncher cycle times and stems per cycle

Harvest unit	n	Delay-free cycle time, min		Stems per cycle					
		Mean	Standard deviation	Standing merchantable	Standing non-merchantable	Lean (> 45°)	Uprooted	Broken top	Total
PPW 1	92	1.40	0.98	0.14	0.46	0.03	0.79	1.58	3.00
PPW 2	21	1.13	0.65	1.10	0.71	0.05	0.62	0.71	3.19
PPW 3	78	1.12	0.57	0.01	0.95	0.00	0.18	2.05	3.15
ST 1	50	1.21	0.77	0.22	0.44	0.04	0.12	0.58	1.40
ST 2	19	2.90	3.01	0.16	4.32	0.00	0.84	0.42	5.74
ST 3	83	1.03	0.67	0.16	0.69	0.00	0.08	1.00	1.93
PPW average[1]	3	1.22	0.73	0.42	0.71	0.03	0.53	1.45	3.13
ST average[1]	3	1.71	1.48	0.18	1.82	0.01	0.35	0.67	3.02

[1] Average of three sites

Table 3 Descriptive statistics for skidder cycles

Harvest unit	n	Delay-free cycle time, min		Stems per cycle		Skidding distance, m		Average payload green tonnes	Productivity green tonnes pmh^{-1}
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
PPW 1	109	6.93	3.59	6.38	2.02	114	55	1.69	14.6
PPW 2	26	7.06	6.39	5.88	4.01	185	140	1.24	10.6
PPW 3	82	6.08	4.18	6.67	3.32	98	66	1.49	14.7
ST 1	22	8.27	4.17	4.63	1.95	115	38	4.46	32.4
ST 2	60	7.71	4.03	2.92	1.83	194	128	1.66	13.0
ST 3	43	6.79	4.23	2.84	2.20	88	51	3.02	26.8
PPW average[1]		6.69	4.72	6.31	3.12	132	87	1.48	13.3
ST average[1]		7.59	4.33	3.46	1.99	132	72	3.05	24.0

[1] Average of three sites
pmh – productive machine hours (i.e., excluding delays)

the three ST units. Time per cycle and average skidding distance were similar between PPW and ST units. The differentiating factor was average skidder payload, which was 79% higher in the ST units.

Sawtimber-sized stems obviously weigh more than pulpwood-sized stems. Even after accounting for the additional number of stems per turn in the PPW units, average skidder payload was substantially lower in the PPW units. Part of the reason for low skidder payload in the PPW was the delay in harvesting the material after the tornado. In the ST units, there was minimal stem breakage during skidding, except for small branches. In contrast, pulpwood-sized stems often broke into two pieces when picked up by the skidder.

Table 4 Chipper cycle time and productivity

Harvest unit	n	Delay-free cycle time, min		Productivity green tonnes pmh^{-1}
		Mean	Standard deviation	
PPW 1	10	27.6	9.62	50.8
PPW 2	3	24.0	2.38	63.9
PPW 3	8	20.1	2.25	70.2
ST 1	7	26.1	6.46	64.0
ST 2	6	22.5	4.31	71.7
ST 3	5	26.3	6.72	64.4
PPW average[1]	3	23.9	4.75	61.6
ST average[1]	3	25.0	5.83	66.7
PPW 1	10	27.6	9.62	50.8

[1]Average of three sites
pmh – productive machine hours (i.e., excluding delays)

This breakage increased skidder cycle time as skidders had to collect broken portions of stems, and also reduced skidder payload when portions of trees were left in the woods.

The chipping function was very productive with delay-free cycle times averaging between twenty and thirty minutes in all units (Table 4). Productivity ranged from 51–72 tonnes per productive machine hour. The chipper high productivity relative to skidding and trucking led to significant idle time. Limited trucking capacity allowed sufficient time for the skidder to stockpile material on the landing so that most chipping cycles were conducted without delays.

3.2 Harvesting Costs

Assuming that trucking did not constrain in-woods production, onboard truck (i.e., excluding hauling) costs averaged an estimated \$29.78 and \$19.97 t^{-1} in the PPW and ST units, respectively (Table 5). These estimates do not include a profit for the logger. The market price for in-woods whole-tree pine chips was \$31.72 t^{-1} at the time of the study (TimberMart-South 2021). At recent chip prices and estimated harvesting costs, a logger could pay the landowner stumpage prices of approximately \$12 t^{-1} and still break even or make a small profit on the ST units (Table 5). In contrast, the break-even stumpage price on the PPW harvests was less than \$2 t^{-1} and harvesting costs exceeded the market value of the chips on PPW unit 2.

When trucking was allowed to constrain in-woods production, estimated onboard truck costs averaged \$30.72 and \$24.69 t^{-1} in the PPW and ST units, respectively (Table 6). Under this scenario, the logger could pay break-even stumpage prices of approximately

$7 t^{-1} in the ST units and $1 t^{-1} in the PPW units. Onboard truck costs were slightly higher under this scenario compared with the contract hauling scenario because trucking limited production on two-thirds of the PPW and ST units.

Hauling costs were an average of $2.02 t^{-1} and $2.82 t^{-1} lower in the PPW and ST units, respectively, when logger-owned trucking was used (Tables 5 and 6). Given the short haul distances in this study, the minimum haul distance (i.e., 64 km) paid to contract haulers made this option much more expensive.

Payload averaged 24.1 tonnes per load on the PPW units and 27.7 tonnes per load on the ST units, which resulted in lower hauling costs in the ST units when logger-owned trucking was used (Table 6). Contract haulers are compensated per tonne-km, and so payload does not affect hauling costs from the perspective of the logging business owner (i.e., the contract hauler bears the cost of low payloads rather than the logging business owner).

3.3 System Balancing

Cut-and-haul costs were lower with logger-owned trucking on the PPW units and lower with contract hauling on the ST units. On the ST units, in-woods production losses were sufficient to offset hauling cost savings associated with logger-owned trucking. In the PPW units, production losses were minimal due to limited trucking capacity and thus had a small impact on cut-and-haul costs. Adding a second logger-owned truck on the ST units would have reduced onboard truck and cut-and-haul costs on the two units where trucking limited production; however, a second truck would have increased cut-and-haul costs on all of the PPW units.

Table 5 Harvesting system productivity and cost assuming unlimited contract trucking

Harvest Unit	Function Cost, $ t^{-1}				Onboard Truck $ t^{-1}	Cut-and-haul $ t^{-1}	System rate t smh^{-1}	Limiting factor
	Felling	Skidding	Chipping	Trucking				
PPW 1	5.60	8.72	12.68	7.05	27.69	34.75	13.2	Skidding
PPW 2	7.74	12.05	14.68	7.05	35.37	42.43	9.5	Skidding
PPW 3	5.58	8.69	11.31	7.05	26.27	33.33	13.2	Skidding
ST 1	2.54	3.95	7.39	7.05	14.27	21.32	29.1	Skidding
ST 2	6.33	9.85	12.29	7.05	29.24	36.30	11.7	Skidding
ST 3	3.07	4.77	8.10	7.05	16.39	23.45	24.1	Skidding
PPW average[1]	6.31	9.82	12.89	7.05	29.78	36.83	12.0	–
ST average[1]	3.98	6.19	9.26	7.05	19.97	27.02	21.6	–

[1] Average of three sites
smh – scheduled machine hours (i.e., including delays)

Table 6 Harvesting system productivity and cost with limited logging business-owned trucking

Harvest Unit	Function Cost, $ t^{-1}				Onboard Truck $ t^{-1}	Cut-and-haul $ t^{-1}	System rate t smh^{-1}	Limiting factor
	Felling	Skidding	Chipping	Trucking				
PPW 1	6.03	9.33	13.66	4.81	29.79	34.60	11.7	Hauling
PPW 2	7.74	12.05	14.68	5.81	35.37	41.18	9.5	Skidding
PPW 3	5.73	8.90	11.65	4.46	27.00	31.46	12.7	Hauling
ST 1	4.17	6.29	11.14	3.98	22.25	26.23	14.2	Hauling
ST 2	6.33	9.85	12.29	4.79	29.24	34.03	11.7	Skidding
ST 3	4.33	6.59	11.01	3.92	22.58	26.51	14.4	Hauling
PPW average[1]	6.50	10.09	13.33	5.03	30.72	35.74	11.3	--
ST average[1]	4.94	7.58	11.48	4.23	24.69	28.92	13.4	--

[1] Average of three sites
smh – scheduled machine hours (i.e., including delays)

On the PPW units, with existing in-woods capacity, an average of 1.0 trucks were needed to match in-woods productivity. Trucking needs in the PPW units ranged from 0.7 trucks in PPW2 to 1.1 trucks in PPW1. On the ST units, an average of 1.5 trucks were needed to match in-woods productivity with trucking needs ranging from 0.8 trucks in ST2 to 2.1 trucks in ST1.

Adding a second skidder would have reduced chipping costs by an average of 34% and 30% in the PPW and ST units, respectively, assuming trucking does not constrain productivity. Adding a second skidder reduced onboard truck costs by an average of 22% in the PPW units compared to 11% in the ST units when trucking did not constrain productivity. Of course, adding a second skidder would necessitate additional trucking capacity. If the logging business used its own trucks, it would have to devote considerable additional resources to improve system balance and reduce cut-and-haul costs.

4. Discussion

Landowners and land management agencies in the US South can expect minimal compensation for tornado-damaged timber given the high and variable harvesting costs associated with harvesting this material, especially when there is a long interval between the tornado and the harvest. Given the variability in harvesting productivity and costs, challenges associated with system balancing, and uncertainty regarding product quality, logging businesses and timber buyers should bid conservatively on salvage timber sales. Nonetheless, removing the damaged timber will enable reforestation, meaning the landowner receives significant benefit from salvage harvests. Fortunately, the value of the salvaged timber was sufficient to cover the cost of chipping and delivering the material, meaning the landowner or land management agency did not have to pay for the material to be removed as is often the case for hazardous fuels reduction treatments in the US West (Calkin and Gebert 2006, Bennett and Fitzgerald 2008, Hartsough et al. 2008, CBO 2022).

The long interval between the tornado and the salvage operation reduced the value of the damaged timber and increased harvesting costs. The delay in harvesting meant that all stems were chipped, whereas harvesting immediately following the tornado may have allowed some of the stems to be delivered as roundwood pulpwood, chip-n-saw, and sawtimber. Large sawtimber-sized trees that had been uprooted suffered the largest value losses from the delayed salvage operations. In addition, harvesting productivity was reduced and harvesting costs increased in the PPW stands because of stem breakage during skidding. This study supports existing recommendations by state forestry agency that salvage harvesting be conducted within 3–8 months of a natural disaster (Bradley et al. 2018, Dickens et al. 2018).

Productivity trends during salvage harvesting were consistent with observations in the midwestern and western US (Kim et al. 2017, Han et al. 2018, Russell and Blinn 2018), Canada (Han and Renzie 2005), and elsewhere (Dvorak 2010, Bodaghi et al. 2018, Kärhä et al. 2018). Skidding productivity in this study was 62% and 31% lower in the PPW and ST units, respectively, compared to non-salvage conventional harvesting in pine stands in the upper Coastal Plain of Georgia, USA (Conrad and Dahlen 2019). Skidding productivity in the PPW units was 41% lower than roundwood skidding productivity on energy chipping harvests in the Coastal Plain of South Carolina and Virginia (Garren et al. 2021). In contrast, skidding productivity in the ST units was slightly higher (6%) than in the study by Garren et al. (2021).

Onboard truck costs in the ST units were comparable to previous estimates for producing energy chips on non-salvage harvests in the Coastal Plain of the US South, whereas onboard truck costs were much higher in the PPW units (Conrad et al. 2013, Jernigan et al. 2013, Garren et al. 2021). Similarly, felling and skidding costs per tonne in the ST units were comparable to previous estimates from non-salvage harvests producing energy chips, whereas felling and skidding costs were higher in the PPW units (Conrad et al. 2013, Hanzelka et al. 2016, Garren et al. 2021). However, chipping costs in the salvage harvests were higher than estimates from these same studies despite comparable or higher chipper productivity in the salvage harvests. High ownership and operating costs coupled with low chipper utilization were the culprits in high chipping costs.

Logging business owners face difficult tradeoffs in balancing the capacity of their in-woods equipment, their own truck fleets, and contract hauling. Salvage harvesting introduces reduced productivity and higher variability, making system balancing even more challenging. Given the infrequency of salvage harvesting, a logger will typically be forced to use his existing number of in-woods machines. The logger must determine whether his equipment mix is sufficiently well-suited for salvage harvesting before deciding to engage in salvage logging.

Trucking constrained in-woods production on two-thirds of the harvest units in this study (Table 6). Adding a second truck would have reduced cut-and-haul costs on two of the three ST units but would have increased cut-and-haul costs on all three PPW units. Trucking needs vary considerably from harvest site to harvest site based on distance to markets and in-woods productivity. A logging business using company-owned trucks must make a long-term decision about fleet size. Inevitably, this leads to overcapacity on some sites and insufficient capacity on others. Logging businesses often strive to maintain a baseline level of capacity from company-owned trucks and hire contract trucks on sites when company-owned trucking capacity is insufficient. However, contract hauling capacity has declined in some areas in recent years because of rising insurance premiums and competition from other sectors (Conrad 2018, Conrad 2022).

5. Conclusion

This study demonstrated that salvage logging is economically viable following severe tornado damage, even after a long delay, when energy chip markets are available. The Savannah River Site had the advantage of an on-site energy facility; however, the harvest would have been economically viable at typical transportation distances (i.e., 60–100 km) (TimberMart-South 2021). The harvest is unlikely to have been economically viable without a market for energy chips, especially with the long interval between the tornado and the harvest.

Harvesting productivity was reduced by more than half compared to typical non-salvage harvests in the US South. Consequently, harvesting costs were considerably higher than in non-salvage operations (TimberMart-South 2021). Therefore, timber buyers must bid conservatively on salvage timber sales and landowners can expect minimal compensation from these sales. Nevertheless, it is in landowners' best interests to conduct salvage sales in exchange for negligible cash compensation because of significantly reduced costs for reforestation.

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Author's address:

Assoc. prof. Joseph Conrad IV, PhD
e-mail: jlconrad@uga.edu
University of Georgia
Harley Langdale Jr. Center for Forest Business
Warnell School of Forestry & Natural Resources
180 E Green Street
Athens, Ga 30602-2152
USA