An economic assessment of implementing streamside management zones in central Appalachian hardwood forests

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Abstract

The effects of variable width of streamside management zones (25, 50, 75, and 100 ft) (SMZs) and removal level of trees (10%, 30%, and 50% of basal area) on production and cost of implementing SMZs in central Appalachian hardwood forests were simulated by using a computer model. Harvesting operations were performed on an 80-year-old generated natural hardwood stand with a manual harvesting system of chainsaw felling and cable skidder extraction. Two skidding patterns using one landing with a stream crossing and two landings without a stream crossing were examined in the study. The hourly felling production with SMZs was 3.21 cunit (100 ft^3) with an average unit cost of $9.04 per cunit. The productivity of conventional cable skidding with SMZs was 2.59 cunit per productive machine hour (PMH) and the unit cost averaged $31.12/cunit. Results indicated that felling with SMZs was 13 percent less productive and 15 percent more expensive than the felling operations without SMZs, while the skidder's productivity with SMZs was 8 percent lower and its unit cost was 9 percent higher than without SMZs. SMZ width and removal level did significantly affect the felling and skidding operations. The opportunity cost was indicated as a major cost component for implementing SMZs in central hardwood forests, which accounted for 27 percent of the total on-board cost.

Forestry best management practices (BMPs) are perhaps the most critical methods to influence the environmental impacts of forest operations. One of the key components of BMPs is streamside management zones (SMZs) where special attention is required during forest operations to protect the land adjacent to perennial, intermittent, and ephemeral streams, and ponds or lakes (WVDOF 2002). SMZs are of great importance in maintaining water quality and reducing soil erosion during forest operations. SMZs can effectively trap and filter out suspended sediments, maintain stream temperatures, and then preserve the aquatic habitat (WVDOF 2002, Carroll et al. 2004). The guidelines for locating haul roads, skid trails, landings, stream crossings, and especially SMZs are fairly consistent among states (Wang et al. 2004). For example, the recommended minimum widths are from 25 to 100 feet in most BMPs guidelines (Phillips et al. 2000).

SMZ implementation cost accounted for 3 percent of the BMP cost for forest industry and 10 percent for nonindustrial private forest (NIPF) landowners (Cubbage 2004). Loggers are the major bearers of the BMP implementing cost, while sometimes landowners or forest industry may also take some share of the cost (Shaffer et al. 1998). Therefore, for landowners, forest industries, and especially loggers, there are real cost concerns associated with implementation of BMPs and SMZs (Phillips et al. 2000). Their concerns include whether some operations should be conducted in SMZs, at what level the operation should be conducted, and what the production and cost will be in association with such operations.

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This study evaluated the productivity and cost of implementing SMZs and their relationship to SMZ width, removal level, harvesting method, and skidding pattern factors in central Appalachian hardwood forests. Specifically, the objectives of this study were to: 1) perform harvesting operations with consideration of SMZs by using a computer simulation model under generated central Appalachian hardwood stand conditions; 2) analyze the relationships among the width of SMZs, removal level, harvesting method, and skidding pattern factors; and 3) quantify the felling and skidding costs, SMZ-related cost, total on-board cost, and productivity of harvesting with SMZs under different scenarios of SMZ width, removal level, harvesting method, and skidding pattern.

Several studies have investigated the economic effects of implementation of SMZs on harvesting activities. Kluender et al. (2000) summarized two major costs of implementing SMZs, including the cost of one-time loss in tree-growing area because land is taken out of the normal productive base and the stream-locked land that may be lost to production. They reported that about 6 percent of the forestland was taken out of production due to the implementation of SMZs (ranging from 3% to 10%), and the benefit/cost ratio of harvestable timber value to harvesting cost also decreased with the implementation of SMZs. Ellefson and Weible (1980) examined the cost associated with variable width of SMZs and found that leaving buffer strips of 30, 60, and 100 feet increased total costs by \$80, \$160, and \$266, respectively, for harvesting a 104-acre tract or \$0.77, \$1.54, and \$2.56 per acre, respectively, in southeastern Minnesota.

Flagging an SMZ and the operational cost according to BMP recommendations within SMZs could reach \$76 per SMZ (Shaffer et al. 1998), which accounted for about 0.38 percent of gross harvest revenue (Lickwar et al. 1992) or 10 percent of SMZ implementation cost (Cubbage 2004). The opportunity cost incurred by not harvesting and selling the timber in SMZs was reported as the most expensive BMP cost (Ellefson and Miles 1985). It increased by \$75 per acre for small timber (average diameter at breast height [DBH] of 18 in) and by \$168 per acre for large timber (average DBH of 28 in) when SMZ width changed from 35 to 50 feet (Olsen et al. 1987).

Materials and methods

Harvesting simulations were performed on an 80-year-old hardwood stand that was generated by using a stand generator (Wang et al. 2002) based on the stand conditions of the West Virginia University research forest, which was assumed to be representative in the region. The generated stand was 1.0 acre in size and with a random spatial pattern. Tree DBH averaged 12.2 inches with average total height of 71 feet. Basal area per acre was 233 ft^2 and volume per acre was 43.5 cunit. Yellow-poplar (*Liriodendron tulipifera*) (38%), black cherry (*Prunus serotina*) (17%), and northern red oak (*Quercus rubra*) (16%) were the major species and accounted for 71 percent of the total number of trees in the generated stand.

Felling

Directional felling was used during the felling operations. We assumed that trees were felled in a herringbone pattern with tops falling away from the stream. Chain saw felling was simulated on two blocks, i.e., with SMZ and without SMZ (No-SMZ). Each felling block was a 1.0-acre plot of the generated hardwood stand. The logger started from one corner at one side of the plot and always cut the next nearest tree selected to be cut. Diameter-limit cut is the most common practice in central Appalachia, which accounted for 51 percent of the total harvesting operations in West Virginia while clearcut only accounted for 7 percent (Milauskas and Wang 2006). Diameter-limit cut was applied to both SMZ and No-SMZ blocks with clearcut as the basis for comparison. All trees greater than 16 inches of DBH were selected for diameter-limit cut. The stand was cut to the edge of the stream bank without consideration of the SMZ guidelines for the No-SMZ block, while four SMZ widths of 25, 50, 75, and 100 feet were employed for the SMZ block (**Fig. 1a**). Trees within the SMZ were removed throughout the SMZ at three levels of 10, 30, and 50 percent of basal area (4.32, 12.98, and 20.66 cunit/acre), with no harvesting of trees in the streams or on the immediate stream banks. No-cut in SMZ was also considered as a control examined for comparisons with the treatments. Trees outside of the SMZ were removed by using either the diameter-limit cut or clearcut method, whichever was employed in the corresponding No-SMZ block. Only one SMZ was assumed on a harvesting tract. It was also assumed that there were no stream-locked trees. All trees marked could be felled and removed.

There were 32 (4 × 2 × 4) felling combinations for SMZ block involving three experimental factors of four SMZ widths (25, 50, 75, 100 ft), two harvesting methods (clearcut and diameter-limit cut), four removal levels within SMZ (0%, 10%, 30%, 50% of basal area). Additionally, two felling combinations of clearcut and diameter-limit cut were also applied for the No-SMZ block. It yielded a total of 34 felling treatment combinations. Each combination was replicated 3 times for a total of 102 felling simulation experiments. A random number was generated to order the sequence for all the experiments.

Extraction

Extraction with a cable skidder was simulated on a 36-acre tract, which was the result of replicating a felling plot 36 times. Specifically, the site for skidding operations with SMZ was created by 6 replications of a SMZ felling plot in the middle of the tract and 30 replications of a No-SMZ felling plot for the rest (**Fig. 1b** and **1c**). Two skidding patterns were examined: one landing with a stream crossing perpendicular to the stream (**Fig. 1b**) vs. two landings that were located on each side of the stream without a stream crossing (**Fig. 1c**). Two major skid trails parallel to the stream were laid out on each side of the stream for both No-SMZ and SMZ blocks. The skidder stayed on the skid trails and cables were pulled out to the felled trees within SMZs, which were then winched back to the trails. In the No-SMZ block, a skidder was allowed to reach to the stream bank if necessary without crossing the stream for two landings without a stream crossing pattern or crossing the stream through a bridge for one landing with a stream crossing pattern. However, a skidder can only run adjacent to the SMZ boundaries but was not allowed in the SMZs for the SMZ block. A total of 204 extraction combinations were simulated for both skidding patterns based on 102 felling plots.

Data analysis

The general linear model (GLM) for analyzing felling operations is as follows:

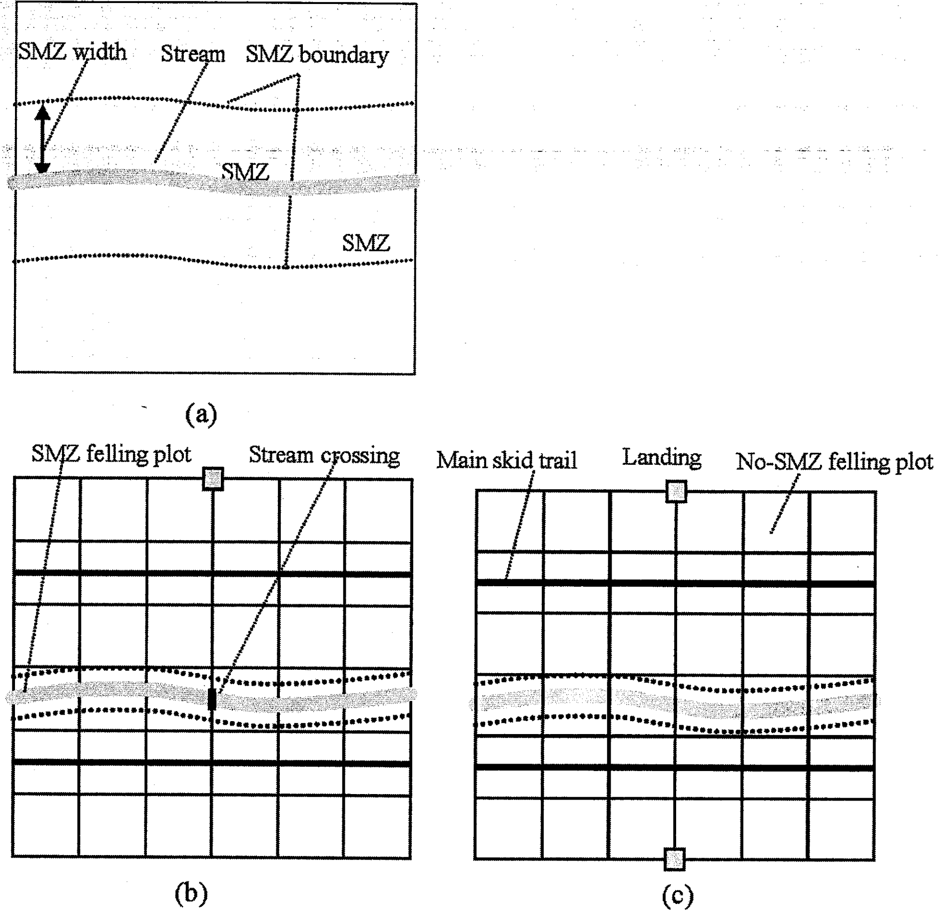

Figure 1. — Block layouts for felling and skidding operations.

$$Y_{ijkl} = \mu + W_i + R_j + H_k + W_i^* R_j + W_i^* H_k + \varepsilon_{ijkl}$$

where i = set of SMZ widths {1, 2, 3, 4, 5} (1 represents No-SMZ or 0 width of SMZ); j = set of removal levels {1, 2, 3, 4} (1 stands for No-cut or 0 removal level); k = set of harvesting methods {1, 2}; l = number of replications {1, 2, 3}; Y_{ijkl} = the response variable of cycle time or productivity; W_i, R_j, H_k = the effects of SMZ width, removal level, and harvesting method, respectively; μ = overall mean of the response variable; and ε_{ijkl} = an error component that represents all uncontrolled variability.

The GLM for analyzing skidding operations can be stated as:

$$Y_{ijklm} = \mu + W_i + R_j + H_k + SP_l + W_i^* R_k + SP_l^* W_i + \varepsilon_{ijklm}$$

where i = set of SMZ widths {1, 2, 3, 4, 5}; j = set of removal levels {1, 2, 3, 4}; k = set of harvesting methods {1, 2}; l = set of skidding patterns {1, 2}; m = number of replications {1, 2, 3}; Y_{ijklm} = the response variable of cycle time, productivity, or average skidding distance; W_i, R_j, H_k, SP_l = the effects of SMZ width, removal level, harvesting method, and skidding pattern, respectively; μ = the overall mean of the response variable; and ε_{ijklm} = an error component that represents all uncontrolled variability. Cost estimates of the chain saw and cable skidder were calculated by using the machine rate method (Miyata 1980). Machine unit costs were calculated by dividing machine hourly costs with average hourly production rates.

Results

The DBH of felled trees averaged 16.35 inches, ranging from 13.64 to 19.06 inches (**Table 1**). Implementation of an SMZ reduced 7 percent of the volume harvested per acre on average from 42.34 cunit to an average of 39.31 cunit. The area of SMZs with a width of 25, 50, 75, and 100 feet accounted for 24, 48, 72, and 96 percent of total felling area on a per-acre basis and therefore lowered harvested volume by 3, 6, 9, and 11 percent per acre, respectively, in comparison to the No-SMZ block. Compared to No-cut in SMZ, removing 50 percent of basal area in SMZ could increase 5 percent of the volume harvested on a per-acre basis. Volume per felled tree varied from 0.23 to 0.43 cunit while distance traveled between harvested trees was between 11.19 and 18.91 feet.

Felling cycle time ranged from 3.30 to 7.95 minutes and differed significantly among removal levels (F = 83.29; df = 90; p = 0.0001) and between harvesting methods (F = 796.87; df = 90; p = 0.0001). However, it was not significantly different among SMZ widths (F = 0.56; df = 90; p = 0.64). The hourly felling production rate differed significantly among SMZ widths (F = 112.16; df = 90; p = 0.0001) and among removal levels (F = 44.27; df = 90; p = 0.0001). It decreased 12 percent from 3.36 to 3.01 cunit/PMH when the SMZ width changed from 25 to 100 feet, while it was lowered 14 percent from 3.69 to 3.21 cunit/PMH from the No-SMZ to SMZ scenario. The felling operation was 9, 10, 15, and 18 percent less productive with SMZ widths of 25, 50, 75, and 100 feet, respectively, compared to the No-SMZ block.

Table 1. — Means and significance levels of felling simulation variables by SMZ width, removal level, and harvest type (n = 102)[a].

	Average DBH removed	Volume harvested	Volume per felled tree	Distance traveled per harvested tree	Cycle time	Productivity
	(in)	(cunit/acre)	(cunit)	(ft)	(min)	(cunit/PMH)
SMZ width (ft.)						
0 (No-SMZ)	18.33 A	42.34 A	0.34 A	12.18	5.10 A	3.69 A
25	16.95 B	40.92 B	0.35 A	12.20 C	5.38 A	3.36 B
50	16.47 B	39.98 C	0.34 A	12.71 C	5.45 A	3.31 B
75	15.98 C	38.59 D	0.32 B	14.51 B	5.56 A	3.14 C
100	15.34 C	37.74 E	0.29 C	18.91 A	5.75 A	3.01 D
Removal level within SMZ (% of basal area)						
0 (No-Cut)	14.24 B	38.14 D	30.43 B	12.12 D	4.19 D	3.44 A
10	15.74 A	38.48 C	32.41 A	16.21 A	6.34 A	3.21 C
30	15.98 A	39.26 B	32.36 A	14.64 B	5.50 B	3.28 C
50	15.83 A	40.16 A	32.97 A	12.90 C	4.87 C	3.34 B
Harvesting method outside of SMZ						
Clearcut	13.64 A	39.94 A	22.88 B	11.19 B	3.30 B	3.37 A
Diameter-limit cut	19.06 A	39.64 B	42.64 A	17.60 A	7.95 A	3.26 B

[a]Values with the same capital letter in a column within a group are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

Table 2. — Means and significance levels of skidding simulation variables by SMZ width, removal level, harvest type, and skidding pattern (n = 204).[a]

		ASD	Cycle time	Productivity
		(ft)	(min)	(cunit/PMH)
SMZ width (ft.)	0 (No-SMZ)	652 C	16.38 C	2.81 A
	25	718 B	17.14 D	2.69 B
	50	734 B	17.65 C	2.61 C
	75	751 A	18.08 B	2.57 D
	100	770 A	18.45 A	2.51 E
Removal level within SMZs (% of basal area)	0 (No-Cut)	635 B	17.06 B	2.64 A
	10	763 A	17.72 A	2.54 B
	30	761 A	17.70 A	2.59 B
	50	760 A	17.69 A	2.63 B
Harvesting method	Clearcut	629 B	17.03 B	2.65 A
	Diameter-limit cut	879 A	18.05 A	2.55 B
Skidding pattern	One landing with a stream crossing	570 B	14.81 B	2.73 A
	Two landings without a stream crossing	904 A	20.27 A	2.48 B

[a]Values with the same capital letter in a column within a group are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

Average skidding distances (ASD) ranged from 570 to 904 feet (**Table 2**). It differed significantly among SMZ widths (F = 27.04; df = 180; $p = 0.0001$) but not among removal levels of 10, 30, and 50 percent (F = 0.13; df = 180; $p = 0.61$). The ASD increased 14 percent from 652 to 743 feet from the No-SMZ tract to SMZ tract. Skidding cycle time ranged from 14.81 to 20.27 minutes with an average of 17.54 minutes, which was mainly impacted by average skidding distance (**Table 2**). The skidding cycle time was significantly different among SMZ widths (F = 1176.37; df = 180; $p = 0.0001$), but not among removal levels of 10, 30, and 50 percent (F = 0.07; df = 180; $p = 0.92$). From the No-SMZ to SMZ tract, the skidding productivity was reduced 8 percent from 2.81 to 2.59 cunit/PMH. Increasing the removal level from 10 to 50 percent of basal area only increased the skidding productivity by 3 percent. The hourly skidding productivity differed significantly among SMZ widths (F = 1198.14; df = 180; $p = 0.0001$), but not among three removal levels (F = 0.41; df = 180; $p = 0.67$). Additionally, all the variables examined including ASD, cycle time, and extraction productivity differed significantly between harvesting methods and between skidding patterns. The skidding production rate slightly decreased by 4 percent from the clearcut site to the diameter-limit cut site, while it decreased 9 percent from one landing with a stream crossing pattern to two landings without a stream crossing pattern.

Hourly cost of a representative chain saw was $29.0/PMH in the region with a mechanical availability of 50 percent (Long 2003). The purchase price of a cable skidder was assumed at $130,000 with an economic life of 5 years and salvage value of $26,000 (20% of purchase price). Fuel and lubricant consumption rates were at 2.5 gal/PMH and 0.2 gal/PMH with unit price of $2.31/gal and $30.13/gal, respectively. Maintenance and repair was assumed at 90 percent of the machine depreciation. The cable skidder was assumed to have a mechanical availability of 65 percent and 2,000 scheduled machine hours per year. Interest, insurance, and tax were assumed at 20 percent of purchase price. Labor cost was $12 per hour plus 35 percent fringe benefits. Hourly cost for the cable skidder was then estimated at $80.7/PMH. By dividing machine hourly cost with average hourly production rates of 3.21 and 2.59 cunit/PMH, the unit cost was calculated as $9.04 and $31.12 per cunit for the chain saw and the cable skidder, respectively. All other unit costs were calculated in the same way.

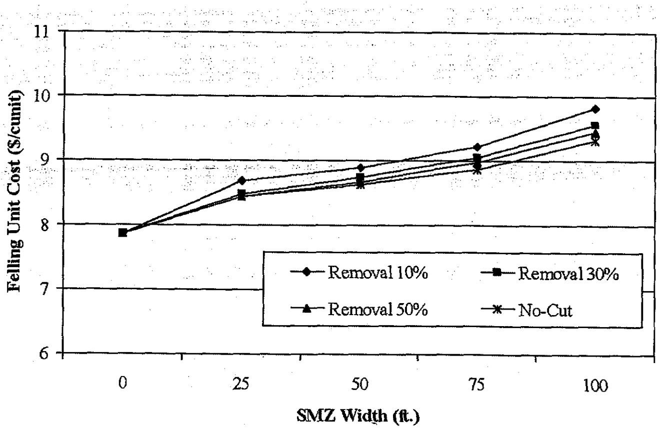

Figure 2. — Felling unit cost vs. SMZ width with variable removal levels.

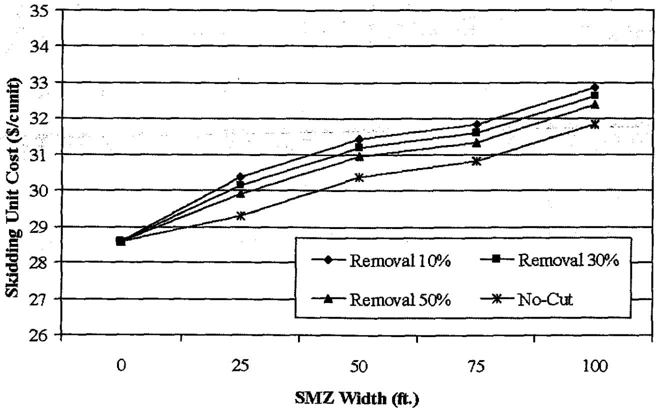

Figure 3. — Skidding unit cost vs. SMZ width with variable removal levels.

Table 3. — Costs estimation for implementing SMZs without a stream crossing by SMZ width and removal level.[a]

SMZ width	Removal level	Felling		Skidding		SMZ flagging		Opportunity cost		Stream crossing		Total on-board cost	
(ft)	(% of basal area)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)
25	0	8.44	321.83	29.31	1,176.30	0.02	0.69	8.40	276.08	--	--	46.17	1,775
	10	8.69	320.28	30.39	1,179.82	0.02	0.69	8.59	260.69	--	--	47.69	1,761
	30	8.49	323.19	30.14	1,191.21	0.02	0.69	6.18	207.82	--	--	44.83	1,723
	50	8.45	325.64	29.90	1,206.48	0.02	0.69	3.58	129.94	--	--	41.95	1,663
50	0	8.64	307.81	30.37	1,139.99	0.03	0.71	21.32	504.83	--	--	60.36	1,953
	10	8.90	309.18	31.45	1,136.92	0.03	0.71	19.62	480.54	--	--	60.00	1,927
	30	8.74	316.24	31.20	1,164.24	0.03	0.71	13.42	375.84	--	--	53.39	1,857
	50	8.66	321.33	30.96	1,174.88	0.02	0.71	7.80	251.02	--	--	47.44	1,748
75	0	8.87	291.28	30.83	1,056.01	0.07	0.73	85.77	898.55	--	--	125.54	2,247
	10	9.24	294.69	31.85	1,071.22	0.05	0.73	59.69	807.52	--	--	100.83	2,174
	30	9.06	305.19	31.60	1,104.70	0.04	0.73	31.43	621.37	--	--	72.13	2,032
	50	8.98	315.22	31.33	1,133.31	0.03	0.73	16.63	433.55	--	--	56.97	1,883
100	0	9.33	277.94	31.85	1,019.41	0.27	0.76	400.07	1,126.98	--	--	441.52	2,425
	10	9.84	285.63	32.87	1,041.70	0.10	0.76	135.15	992.07	--	--	177.96	2,320
	30	9.58	299.93	32.63	1,075.68	0.05	0.76	55.48	787.63	--	--	97.74	2,164
	50	9.45	311.35	32.40	1,120.11	0.03	0.76	23.52	533.92	--	--	65.40	1,966
Average		8.96	307.92	31.19	1,124.50	0.05	0.72	56.04	543.02	--	--	96.24	1,976

[a] The $/acre cost was derived by multiplying the $/cunit cost by volume harvested per acre for a tract of 36 acres.

The cost variation is due primarily to hourly production rate changes. Both felling and skidding costs increased steadily with the implementation of SMZs of different widths (**Figs. 2** and **3**). The implementation of SMZs could add 15 and 9 percent more to the felling and skidding costs of $7.86/cunit and $28.58/cunit without SMZ, respectively. The harvesting unit cost varied increasingly with SMZ width, while it decreased with removal level. The felling cost increased 12 percent from $8.62 to $9.63 per cunit and skidding cost increased 7 percent from $29.88 to $31.98 per cunit when the SMZ width increased from 25 to 100 feet (**Fig. 2**). The harvesting unit costs, however, were less affected by removal level than SMZ width. A reduction of 5 and 3 percent were reported for felling and skidding unit costs, respectively, as the removal level changed from 10 to 50 percent of basal area (**Figs. 2** and **3**).

Total on-board cost, usually referred to as harvesting cost before loading, including felling, skidding, and SMZ-related costs, was examined by SMZ width (**Table 3**). Felling and skidding costs were calculated based on the simulated unit costs. SMZ-related cost contains SMZ flagging cost, opportunity cost, and stream crossing cost if applicable. The SMZ-related cost was assumed to be zero for No-SMZ blocks. The cost of flagging SMZs was $0.72/acre based on the hourly rates of $20 per hour and 0.25 mile of perimeter per hour (Lickwar et al. 1992). The value of timber tied up in the SMZ during harvesting was counted as the opportunity cost. The opportunity cost for SMZ blocks was estimated as $543/acre by multiplying the volume loss per acre due to SMZ implementation by stumpage price. The stumpage price was derived from the Pennsylvania Woodlands' Timber Market Report (2005). A portable timber bridge with a longitudinal glulam deck designed for wheeled log skidders used in extraction was assumed for the stream crossing and the average cost was $325 per site under the assumption that the bridge was installed at 50 different sites during its service life (Taylor et al. 1999). Harvesting a tract with SMZ presented higher felling and skidding cost per cunit than harvesting without considering SMZ. For a 36-acre harvesting tract in this study, the total on-board cost increased 29 percent from $1,537/acre to

Table 4. — Costs estimation for implementing SMZs with a stream crossing by SMZ width and removal level.[a]

SMZ width	Removal level	Felling		Skidding		SMZ flagging		Opportunity cost		Stream crossing		Total on-board cost	
(ft)	(% of basal area)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)	($/cunit)	($/acre)
25	0	8.44	321.83	30.75	1,174.63	0.02	0.69	8.40	276.08	0.29	9.03	47.90	1,782
	10	8.69	320.28	31.88	1,179.12	0.02	0.69	8.59	260.69	0.29	9.03	49.47	1,770
	30	8.49	323.19	31.81	1,191.60	0.02	0.69	6.18	207.82	0.27	9.03	46.76	1,732
	50	8.45	325.64	31.62	1,204.14	0.02	0.69	3.58	129.94	0.25	9.03	43.92	1,669
50	0	8.64	307.81	33.06	1,155.21	0.03	0.71	21.32	504.83	0.38	9.03	63.43	1,978
	10	8.90	309.18	36.99	1,152.74	0.03	0.71	19.62	480.54	0.37	9.03	65.91	1,952
	30	8.74	316.24	34.80	1,179.53	0.03	0.71	13.42	375.84	0.32	9.03	57.31	1,881
	50	8.66	321.33	33.55	1,185.95	0.02	0.71	7.80	251.02	0.28	9.03	50.31	1,768
75	0	8.87	291.28	33.39	1,084.65	0.07	0.73	85.77	898.55	0.86	9.03	128.96	2,284
	10	9.24	294.69	34.57	1,100.06	0.05	0.73	59.69	807.52	0.67	9.03	104.22	2,212
	30	9.06	305.19	33.64	1,133.89	0.04	0.73	31.43	621.37	0.46	9.03	74.63	2,070
	50	8.98	315.22	33.57	1,161.98	0.03	0.73	16.63	433.55	0.35	9.03	59.56	1,921
100	0	9.33	277.94	35.32	1,053.74	0.27	0.76	400.07	1,126.98	3.21	9.03	448.20	2,468
	10	9.84	285.63	35.97	1,075.96	0.10	0.76	135.15	992.07	1.23	9.03	182.29	2,363
	30	9.58	299.93	35.41	1,110.32	0.05	0.76	55.48	787.63	0.64	9.03	101.16	2,208
	50	9.45	311.35	35.39	1,152.76	0.03	0.76	23.52	533.92	0.40	9.03	68.79	2,008
Average		8.96	307.92	33.86	1,143.52	0.05	0.72	56.04	543.02	0.64	9.03	99.55	2,004

[a] The $/acre cost was derived by multiplying the $/cunit cost by volume harvested per acre for a tract of 36 acres.

$1,976/acre due to implementation of SMZs, while the utilization of a portable timber bridge for a stream crossing added only 1 percent more to the total on-board cost with SMZ. The opportunity cost was $218, $403, $690, and $860 per acre with a SMZ width of 25, 50, 75, and 100 feet, respectively. It increased drastically with the SMZ width and accounted for 27 percent of the total on-board cost. Removal level also impacted the opportunity cost significantly, which varied from $561, to $510, to $404, and to $280 per acre as the removal level within SMZ increased from no cut, to 10 percent, to 30 percent, and to 50 percent of basal area.

This study did not address the amount of sediment reaching streams and the costs associated with that. Usually, the sediment is expensive to dredge and store, and adds maintenance costs to water treatment (Cangelosi 2002). According to the estimation of the U.S. Policy Committee, there is around 75 million yd^3 sediment needed to be cleaned up with an associated cost range of $1.4 to 4.4 billion (Great Lakes National Program Office 2002). The study could be extended by examining the revenues and potential benefits associated with implementation of the SMZs with stream sedimentation prediction to further justify the cost effectiveness of implementation of BMPs or SMZs. Topography condition and stream type are of great importance in defining SMZ widths. Future research could consider incorporating these two factors into the simulation study to improve the layout of landing and skid trails, and make the decision for suitable SMZ width. The actual tract map, together with a digital elevation model (DEM), could be used by introducing geographic information system (GIS) technology into the simulation model.

Conclusions

The productivity of felling operations was significantly affected by SMZ width, removal level, and harvesting method. Felling operations were 4 percent more productive as the removal level increased from 10 to 50 percent of basal area. However, the felling unit cost could increase 12 percent when the SMZ width changed from 25 to 100 feet. In comparison with the felling operations without SMZs, felling with SMZs was 13 percent less productive and 15 percent more expensive.

Average skidding distance, a major factor affecting skidding productivity, varied with SMZ widths but was not significantly different among the removal levels. However, skidding productivity differed significantly among SMZ widths, between harvesting methods, and between skidding patterns but not among the removal levels. Applying a clearcut outside of SMZs was 4 percent more productive than a diameter-limit cut. The hourly production rate using one landing with a stream crossing pattern was 25 percent higher than two landings without a stream crossing pattern due to the longer skidding distance. The implementation of SMZs resulted in the skidding operation being 8 percent less productive and 9 percent more expensive in comparison with the skidding operations without SMZ. This is attributed to the longer average skidding distance and relatively longer cycle time for skidding within SMZs, since no skidder traffic was allowed in SMZs. Implementing SMZs in central Appalachian hardwood forests could make the total on-board cost 29 percent more expensive, which might be a major concern to landowners or loggers during the operations. The opportunity cost could increase by $185, $287, and $170 per harvested acre when SMZ width changed from 25 to 50, 50 to 75, and 75 to 100, respectively. Although the opportunity cost of implementing SMZs accounted for 27 percent of the total on-board cost, SMZ flagging cost was negligible, with a contribution to the total on-board cost of 1 percent. The results indicated that opportunity cost was a major component of the on-board cost for implementing SMZs in central Appalachian hardwood forests. The results could be used as a decision tool and guidance for implementing BMP guidelines in the region. The application of this simulation study could further improve the cost assessment of timber harvesting associated with implementation of SMZs.

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