Harvest-associated Disturbance in Upland Ozark Forests of the Missouri Ozark Forest Ecosystem Project

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Abstract.—The Missouri Ozark Forest Ecosystem Project (MOFEP) is a long-term, multidisciplinary, landscape-based research program studying effects of even-aged (EAM), uneven-aged (UAM), and no-harvest (NHM) management on forest communities. The first MOFEP timber harvests occurred from May through November 1996. Harvest-related disturbance occurred on 69 of 180 permanent 0.2-ha study plots in which interactions between *Armillaria* populations, forest structure, and forest management are being studied. On each of these 69 plots, we mapped and measured 1) all injured non-harvested trees ≥ 5.0 cm d.b.h. (diameter at breast height) and their injuries, 2) all stumps and girdled trees, and 3) all vehicle paths. Roots ≥ 1.0 cm diameter and their injuries were characterized in 0.2-m deep x 0.25-m^2 excavations beneath skidder tracks that passed through the 69 study plots. Excavations exposed an average of 1.0 m of root, and multiple- and single-haul skid trails averaged 1.3 vs. 0.7 injuries per meter of discovered root, respectively. Skidder tracks disturbed an estimated 3 percent of the forest floor, resulting in > 900 root injuries per hectare harvested. Partial cutting occurred on 56 of our 69 disturbed plots (14 EAM and 42 UAM). In 22 partially cut plots (15 UAM and 7 EAM), all trees ≥ 5.0 cm d.b.h. (both injured and non-injured) were mapped and characterized. Approximately 11 percent of non-harvested saplings and 3 percent of larger stems were broken, shattered, uprooted, or pushed over; an additional 4 percent of saplings and 10 percent of larger stems incurred xylem-exposing injuries; and another approximately 3 percent of non-harvested trees incurred phloem wounds. Average wound size was smaller for saplings than for larger stems, but percentage stem circumference injured was similar (27 vs. 23 percent, respectively). Frequency of buttress root injury increased with tree d.b.h. An average 62 percent of all injured plot trees occurred ≤ 2.0 m from vehicle paths, whereas 54 percent of trees this close to vehicle activity were injured. For the 22 completely mapped plots, we used stepwise logistic regression to explore each tree's probability of injury based on tree characteristics, harvest-related factors, and site factors. Probability of stem injury was positively associated with north- to east-facing slopes, the length of truck haul road passing through the study plot, and the number of stumps ≥ 45 cm diameter created within the study plot. Probability of stem injury was negatively associated with stem quality, distance from vehicle paths, day of year harvested, two specific logging crews, and UAM.

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Silvicultural thinning and single-tree selection operations are planned disturbance events that produce a suite of outcomes influencing long-term forest structure dynamics in a number of ways (e.g., Dey 1994). We categorize the results of harvest operations as intended, collateral, or accidental. The intended result is a prescribed adjustment of stand structure and composition to provide a planned flow of values over time—for example, some combination of commercial wood products, wildlife habitat improvement, and aesthetic values. Collateral products are the inherent results of the harvest that may or may not serve an intended purpose (e.g., stump populations and skidding disturbance). For example, managers may anticipate that stump-sprouting will provide desirable regeneration (see Dey and Jensen, this proceedings), yet stumps and their root systems represent potential food bases for increasing root-infecting fungus inoculum potential over time (e.g., Armillaria root disease, see Termorshuizen 2000, Wargo and Harrington 1991). Similarly, managers may anticipate that forest floor disturbance caused by skidding activity will create valuable seedbeds, yet this form of disturbance also injures roots, thus increasing, to some extent, tree vulnerability to infection (e.g., Popoola and Fox 1996, Weaver 1974). Accidental products of harvest are neither essential to the harvest nor completely avoidable. The most important accidental products are physical injuries to residual live stems and root systems. While large stem injuries directly reduce wood product values over time through discoloration and decay, wound compartmentalization anywhere on a tree reduces the volume of energy storage tissue in the tree (Shigo 1984, 1985; Shigo and Tippett 1981), and root and buttress injuries have been shown to facilitate infection and decline (Benzie *et al.* 1963, Kessler 1992, Popoola and Fox 1996, Weaver 1974).

Levels of individual harvest disturbance components vary both spatially and temporally across the landscape. Factors determining patterns of local disturbance intensity include topography, initial stand structure and composition, the silvicultural system applied, the harvest design and methods employed, the skill level and sense of purpose of harvest crews, the season of harvest, and the weather encountered. Overall, the challenge is twofold. First, we need to understand the incremental relationships between levels of individual harvest disturbance components and consequent levels of tree damage capable of inciting forest decline (Manion and Lachance 1992). This knowledge is needed to guide efforts to set acceptable limits on the components of harvest disturbance.

Because forest decline disease syndromes with similar symptoms can result from various interactions among numerous factors (Manion and Lachance 1992), it is important to know the extent to which declines in a specific region reflect recurrent causal themes (e.g., Armillaria root disease) with implications for forest management. Foresters have attributed a major role in upland Ozark oak decline to Armillaria root disease (Johnson and Law 1989). We have identified *Armillaria gallica* Marxmüller & Romagn., *A. mellea* (Vahl:Fr.) P. Kumm., and *A. tabescens* (Scop.) Emel in these forests and have evaluated their ecological distributions (Bruhn *et al.* 2000). Harvest-related disturbances and Armillaria root disease fit the concepts of "inciting" and "contributory" factors in the decline spiral model (Manion and Lachance 1992).

RESEARCH GOALS AND OBJECTIVES

Our overall goal is to understand the ecological distributions and activities of *Armillaria* species in the Ozark Highlands, with specific respect to each other, to silvicultural and natural disturbances, and to forest structure dynamics.

Clearly, evaluation of harvest disturbances first requires their documentation. Our primary objective in this phase of our studies was to explicitly map and measure all harvest-related disturbance caused by 1996 MOFEP timber harvest activities on the study plots included in Armillaria root disease studies. Spatially explicit disturbance data will permit us to revisit injured trees to evaluate wound response, defect development, growth, decline, and survival. To further study the context within which these disturbances took place, and as a basis for future evaluation of their ramifications with respect to forest structure, we have mapped and measured all trees ≥ 5.0 cm d.b.h. on randomly selected plots within which disturbance was documented. Future evaluations of value losses due to injury-initiated forest product defects, Armillaria root disease, and other forest decline factors will build on our baseline documentation of harvest disturbance factors, summarized here.

METHODS

Plot Selection

The Missouri Ozark Forest Ecosystem Project (MOFEP) comprises nine upland forest sites (266 ha to 527 ha in size) in southeastern Missouri (Shifley and Brookshire 2000, Sheriff, this proceedings). These sites are arranged in three blocks of three sites each, with three silvicultural systems (i.e., even-aged management (EAM), uneven-aged management (UAM), or no-harvest management (NHM) applied to one site each in each block for a time period equivalent to an EAM rotation (100 - 150 years). Upland forest predominates; overstory vegetation is mostly mature second-growth *Quercus*, *Carya*, and *Pinus echinata* Mill. (Shifley *et al.* 2000). Sites 1 through 6 and 9 occur in the Current-Black River Oak-Hickory Forest Breaks Landtype Association (LTA), characterized by extensive bedrock dissection. Sites 7 and 8 occur in the Current-Eleven Point River Hills LTA, with gentler relief. The bedrock stratigraphy, landforms, and soils in these LTAs have been described (Kabrick *et al.* 2000).

In 1993 - 1994, we randomly selected 180 of the total 648 MOFEP 0.2-ha vegetation study plots, stratified by ecological landtype (ELT) over all nine sites, for studies of *Armillaria* species ecology, forest disturbance, and vegetation dynamics (Bruhn *et al.* 2000). The first set of MOFEP harvests (May - November 1996, see Kabrick *et al.*, this proceedings) disturbed 69 of our 180 plots. Harvest activity on these 69 plots took the form of EAM clearcuts on 13 plots and partial cutting on 56 plots (14 EAM intermediate thinning and 42 UAM single- or single- and group-tree selection). We report here on 1) root damage detected by excavations beneath skid trail tracks adjacent to all 69 plots (table 1), and 2) non-harvested stem injury in the 56 partially cut plots (table 2).

Data Collection

Shortly after harvest was completed in a stand, all injured and intentionally girdled stems ≥ 5 cm d.b.h., all stumps ≥ 5 cm diameter, and all vehicle paths in each of the 69 disturbed *Armillaria* study plots were mapped and measured for future spatial analysis. Roads and skid trails were characterized as haul roads or as multiple- or single-haul skid trails. For 22 of the 56 partially cut plots (15 UAM and 7 EAM plots), we have completed total stem maps (i.e., including non-injured trees ≥ 5 cm d.b.h.).

As soon as possible after harvest, we examined belowground woody lateral roots (≥ 1 cm diameter) for injury. For this purpose, we randomly located four small-scale forced-water excavations (0.5 m x 0.5 m x 0.2 m deep) immediately adjoining our plots in the two tracks within each vehicle path that entered each study plot (table 1). Forest floor disturbance was recorded at the site of each excavation as the maximum depth of forest floor displacement and/or compression by the vehicle track. Within each excavation, the diameter, length, depth, and dimensions of any injuries were recorded for each woody root segment encountered. A total of 145 excavations were made in multiple-haul skid trails and 110 were made in single-haul skid trails.

The following data were collected for all mapped stems: species, d.b.h., canopy position, condition (i.e., living, moribund, died post-harvest, or died pre-harvest) and pre-injury suitability (+/-) as a crop tree. The shortest distance to a vehicle path (and whether that path was a road or a multiple- or single-haul skid trail) was recorded for all trees ≤ 2.0 m from a vehicle path. All injuries on residual stems were categorized as: 1) only phloem penetrated, 2) xylem exposed, or 3) stem broken. The position and dimensions of each injury were recorded as height above ground level to wound base, maximum wound length along the stem axis, maximum wound width perpendicular to the stem axis, and maximum depth of xylem penetration. It would have been impractical to graphically determine individual wound surface area. Instead, we expressed wound area as the traditional index calculated by multiplying maximum wound length by maximum circumferential wound width. Ohman (1970) reported that although actual wound area ranged from one-half to two-thirds of the index value, both calculations were good indicators of probability of value loss. Stump-top diameter and identity (at least genus) were recorded for all mapped stumps.

Our study plots are characterized for analysis by MOFEP block, landtype association, and slope position, aspect, and steepness. Harvest disturbance at each plot has been characterized by silvicultural system, 1996 harvest activity class, day of year harvested, length of each class of vehicle trail, diameter distribution of the stump population, and harvest crew identity.

Table 1.—*Distribution of the 255 skid trail excavations[a] used to evaluate root injury associated with 1996 harvest disturbance*

Site[b]	Block	Silvicultural system[c]	1996 activity[d]	ELT[e]	No. of excavations	
					Mult.-haul skid trails	Single-haul skid trails
2	1	UAM	STS	11	12	4
				17	8	4
				18	8	0
			S/GTS	11	4	4
				17	0	0
				18	4	4
3	1	EAM	CC	11	0	0
				17	0	0
				18	4	0
			INT	11	0	4
				17	4	0
				18	9	6
4	2	UAM	STS	11	12	0
				17	4	8
				18	12	8
			S/GTS	11	4	0
				17	4	4
				18	0	0
5	2	EAM	CC	11	0	4
				17	4	4
				18	12	0
			INT	11	4	8
				17	0	0
				18	4	0
7	3	UAM	STS	11	4	4
				17	12	0
				18	4	0
			S/GTS	11	0	8
				17	4	0
				18	0	0
9	3	EAM	CC	11	0	4
				17	0	0
				18	4	4
			INT	11	0	0
				17	0	0
				18	0	0
Total					145	110

[a] Each excavation is 0.25 m^2 square x 0.2 m deep = 0.05 m^3.

[b] See Sheriff (this proceedings, table 1, figures 1 and 3).

[c] Silvicultural systems: UAM, uneven-aged management; EAM, even-aged management.

[d] 1996 harvest activity: STS, single-tree selection; S/GTS, single- and group-tree selection; CC, clearcut; INT, intermediate thinning.

[e] Ecological landtype (ELT) (broad sense): 11, ridgetops; 17, south- to west-facing slopes; 18, north- to east-facing slopes.

Table 2.—*Characteristics of the 56 permanent 0.2-ha vegetation/*Armillaria *study plots that experienced thinning or selection harvest disturbance in 1996*

Site-plot	Mapping[a] complete	Block	Trtmt[b]	1996 activity[c]	ELT[d]	Slope position[e]	Length[f] (m)			Harvest crew	Day of year	No. of stumps[g]	
							Road	Skid1	Skid2			≥ 25 cm	≥ 45 cm
2-16	No	1	U	STS	18	3	0	47	38	1	261	6	6
2-18	No	1	U	STS	11	5	0	41	27	1	262	5	2
2-19	No	1	U	STS	11	5	0	0	57	1	255	3	1
2-25	No	1	U	STS	18	3	0	0	0	2	276	5	0
2-28	No	1	U	S/GTS	18	3	0	0	78	2	235	14	6
2-30	No	1	U	S/GTS	11	5	0	46	18	15	184	13	5
2-31	No	1	U	STS	17	3	0	55	41	15	189	8	3
2-32	Yes	1	U	S/GTS	11	5	0	0	57	15	164	21	6
2-33	No	1	U	STS	18	4	0	37	7	2	213	4	3
2-34	No	1	U	STS	11	5	48	22	20	2	221	6	1
2-67	No	1	U	STS	11	5	46	0	14	2	225	4	1
2-68	No	1	U	STS	11	5	0	25	0	2	228	0	0
2-69	Yes	1	U	STS	17	3	0	49	31	2	248	4	2
2-70	No	1	U	STS	17	4	0	0	24	2	251	0	0
2-72	No	1	U	S/GTS	18	4	0	38	56	2	226	3	2
3-29	Yes	1	E	IH	11	5	47	0	70	1	224	10	2
3-30	Yes	1	E	IH	18	4	0	65	0	1	226	12	5
3-52	Yes	1	E	IH	17	4	0	37	50	4	179	12	4
3-56	No	1	E	IH	18	3	0	0	121	3	290	10	8
3-61	Yes	1	E	IH	18	3	0	0	94	1	241	7	6
3-63	No	1	E	IH	18	4	0	0	81	1	241	7	5
3-70	Yes	1	E	IH	11	5	46	47	14	2	178	8	7
4-15	Yes	2	U	S/GTS	11	5	0	50	26	7	193	11	2
4-16	No	2	U	STS	17	3	0	0	22	7	196	11	4
4-24	No	2	U	STS	11	5	42	65	74	5	197	10	4
4-26	No	2	U	S/GTS	11	5	16	0	0	6	192	20	16
4-28	Yes	2	U	S/GTS	17	3	0	0	66	6	192	17	6
4-30	Yes	2	U	STS	18	3	0	58	17	5	165	10	7
4-31	No	2	U	STS	11	5	50	0	0	6	213	10	3
4-33	Yes	2	U	STS	18	3	0	0	35	5	213	8	3
4-35	No	2	U	STS	18	3	0	0	0	8	274	4	0
4-36	No	2	U	STS	17	3	0	0	45	7	171	16	6
4-37	No	2	U	STS	17	3	0	24	0	7	178	9	3
4-38	Yes	2	U	STS	18	3	0	0	120	7	267	16	6
4-42	Yes	2	U	S/GTS	11	5	0	35	0	7	165	26	8
4-49	No	2	U	STS	18	3	0	32	33	8	242	13	0
4-60	No	2	U	STS	11	5	44	12	0	5	190	21	2
4-70	No	2	U	STS	18	3	0	50	0	5	175	19	3
4-71	Yes	2	U	S/GTS	17	3	0	32	29	5	175	10	5
5-1	Yes	2	E	IH	11	5	47	22	43	8	189	12	6
5-2	Yes	2	E	IH	18	3	0	47	37	8	189	7	4
5-12	No	2	E	IH	11	5	46	0	26	6	182	11	4
5-30	No	2	E	IH	11	5	36	18	28	8	177	14	7
5-33	No	2	E	IH	11	5	0	9	38	5	245	8	5
5-48	No	2	E	IH	11	5	0	0	71	7	207	12	1
7-35	Yes	3	U	STS	17	3	0	56	55	11	171	10	1
7-41	Yes	3	U	STS	11	5	0	51	52	11	127	14	8

(Table 2 continued on next page)

(Table 2 continued)

Site-plot	Mapping[a] complete	Block	Trtmt[b]	1996 activity[c]	ELT[d]	Slope position[e]	Length[f] (m)			Harvest crew	Day of year	No. of stumps[g]	
							Road	Skid1	Skid2			≥ 25 cm	≥ 45 cm
7-43	No	3	U	STS	17	4	0	63	57	11	148	13	7
7-47	Yes	3	U	STS	11	5	33	0	58	10	140	8	3
7-52	No	3	U	S/GTS	11	5	34	0	8	10	140	14	8
7-55	Yes	3	U	STS	18	3	0	89	0	9	177	8	6
7-58	Yes	3	U	S/GTS	11	5	0	41	54	9	177	14	6
7-63	No	3	U	STS	11	5	0	0	0	9	226	5	4
7-65	Yes	3	U	STS	17	4	0	13	42	9	234	6	3
7-66	No	3	U	S/GTS	17	3	0	39	39	9	234	8	7
9-17	No	3	E	IH	18	3	0	58	0	12	135	18	10

[a] Mapping completed: Yes – All non-injured and injured stems ≥ 5.0 cm d.b.h. within the plot were mapped; No – Within the plot, all injured stems ≥ 5.0 cm d.b.h. as well as all non-injured stems ≥ 5.0 cm d.b.h. and ≤ 2.0 m from vehicle trails were mapped.
[b] Experimental treatment: E – even-aged management; U – uneven-aged management.
[c] 1996 harvest activity: STS – single-tree selection; S/GTS – single- and group-tree selection; IH – Intermediate harvest.
[d] Ecological Landtype (broad sense): 11 – ridge-top; 17 – south- to west-facing slope; 18 – north- to east-facing slope.
[e] Slope position: 3 – lower slope; 4 – break from mid-slope to ridge; 5 – ridges.
[f] Length (within plot): Road – truck haul road; Skid1 – multiple-haul skidder trails; Skid2 – single-haul skidder trails.
[g] Number of stumps: The number of stumps on the plot that had a stump-top diameter of ≥ 25 cm or ≥ 45 cm.

Statistical Analyses

To explore hypothesized relationships between site and disturbance factors and the extent of root injury observed in multiple- vs. single-haul vehicle track excavations, root damage in each excavation was characterized both as 1) the number of injuries per (0.25 m^2) excavation, and 2) the number of injuries per meter of root length. Excavations that contained no roots ≥ 1.0 cm diameter did not contribute to our calculations of number of injuries per meter of root length, whereas all 255 excavations contributed to our calculations of number of injuries per excavation. Number of injuries per meter of root length represents the root population beneath skidder tracks in our study plots, whereas number of injuries per excavation can be applied to our estimated proportion of forest floor area under skidder tracks to estimate the extent of root injury throughout harvested stands. These two dependent variables were used to compare root injury occurring beneath multiple- vs. single-haul skid trail tracks. Correlations between these two dependent variables and slope percent, depth of forest floor displacement, and day of year harvested were also examined separately for single- and multiple-haul skid trails.

We selected 37 variables (28 binary classification and 9 continuously distributed) documenting characteristics of location, individual trees, and disturbance (table 3) for use in stepwise logistic regression analysis (SLR; see Sokal and Rohlf 1995) of factors that might explain the different patterns of tree injury encountered on the 22 plots for which we have mapped all stems. The dependent variable was the probability that an observed tree became injured during the harvest operation. All 37 independent variables were selected on the basis of *a priori* hypotheses of relationship to the dependent variable. The stepwise model-selection method (PROC LOGISTIC, $\alpha = 0.05$; SAS/STAT System Release 8.00, SAS Inst., Inc., Cary, NC) was used to eliminate variables that did not help explain the pattern of trees injured.

To evaluate the SLR model, PROC LOGISTIC used the SLR model to assign each tree a probability, p, of injury during harvest. PROC LOGISTIC also calculated the number of different pairs of stems in which injury was observed and not observed for the two members of the pair, as the product (Observed) x (Total - Observed). A measure of each model's predictive strength was then evaluated as its percent concordant, percent discordant, and percent tied (SAS/STAT System Release 8.00, SAS Inst., Inc., Cary, NC). Percent concordance is the percent of all possible pairs of stems for which the larger probability of injury (p) was associated with the injured stem, percent discordance is the percent of pairs of stems for which the larger probability of injury (p) was associated

Table 3.—*Variables included in stepwise logistic regression analyses of harvest disturbance*

Type of variable Variable group	No. of variables
Binary (classification) variables	
Ecological Landtype (broad sense)[a]	3
Landtype Association	2
Logging crew identity[b]	13
Silvicultural system[c]	2
Slope position[d]	3
Statistical block[e]	3
Stem quality[f]	2
Continuously distributed variables	
Day of year harvested	1
Distance to nearest vehicle path (m)	1
Numbers of stumps[g]	2
Slope (percent) at plot center	1
Stem d.b.h. (cm)	1
Vehicle activity[h] (m)	3

[a] Ridgetop, south- to west-facing slope, or north- to east-facing slope.
[b] Each of the 13 logging crews assigned to harvest one or more of our study plots was represented as a binary (classification) variable.
[c] Even- or uneven-aged management.
[d] Ridge, transition from ridge to upper slope, or lower slope position.
[e] Block 1: sites 1–3; block 2: sites 4–6; block 3: sites 7–9.
[f] Stem either of potential crop quality or not.
[g] Number of stumps within each plot of stump-top diameter ≥ 25 cm or ≥ 45 cm.
[h] Total length of trail within each plot, by activity class: truck haul road, or multiple- or single-haul skidder trail.

with the non-injured stem, and percent tied is the percent of pairs of stems for which both were equally likely to be injured (i.e., p equal).

Our SLR model can be field tested in two ways. First, and most straightforward, as we complete the mapping of non-injured trees for additional partially harvested *Armillaria* study plots, we can apply our model to those data sets (which will also represent the 1996 harvest). Alternatively, we can test our model during the next MOFEP harvest, but this approach may be biased if the next harvest proceeds differently.

RESULTS

Vehicle Path Root Injury

Roots ≥ 1.0 cm diameter were found in 92 percent of the 145 multiple-haul and 87 percent of the 110 single-haul skid trail excavations. Root length, diameter, and depth were similar for multiple- vs. single-haul trail excavations, and occurrences of these two trail types were similarly distributed among harvest dates and with respect to slope steepness (table 4). Nevertheless, approximately twice as many injuries were found beneath multiple- vs. single-haul trails on both a per excavation and a per meter root length basis (table 4). Both number of injuries per excavation and number of injuries per meter of root length were skewed distinctly to the right, with 0 injuries found in 41 percent of multiple- and 70 percent of single-haul excavations, and ≥ 9 injuries per excavation and ≥ 10 injuries per meter of root length found in only 1 excavation in each trail class.

Mean lengths of the three types of vehicle path in each of the 56 partially harvested plots were highly variable (table 5). No apparent differences were detected in vehicle path length between EAM and UAM plots for any of the trail types using Student's t-test ($P > 0.05$). However, the overall mean length of single-haul trails averaged 44 percent greater than that of multiple-haul trails (35.2 m vs. 24.5 m, respectively; $t = 2.06$, $P = 0.05$). Presuming approximately 1.0 m vehicle track width in a 3 m wide vehicle path, then plots averaged approximately 24 m^2 and 35 m^2 under vehicle tracks in multiple- and single-haul trails, respectively. These figures extrapolate to approximately 122 m^2 per hectare and 176 m^2 per hectare, respectively, or 1.22 percent and 1.76 percent of the forest floor disturbed by multiple- and single-haul skidder tracks. Extrapolating from 1.13 and 0.55 injuries per 0.25 m^2 excavation under multiple- vs. single-haul skid trail tracks, respectively, we estimate approximately 551 and 387 root injuries per harvested hectare beneath multiple- and single-haul skidder tracks, respectively.

Forest floor disturbance by multiple- and single-haul skidder tracks ranged in depth from 0.4 to 19.0 cm and from 0.6 to 12.0 cm, respectively (see table 4). Disturbance in multiple-haul (but not single-haul) skid trails was positively correlated with slope steepness and day of year harvested (table 6). Neither number of injuries per excavation nor number of injuries per meter

Table 4.—*Mean values for root characteristics, forest floor disturbance, percentage slope, and day of year harvested, for excavations beneath single- and multiple-haul skid trail tracks*

Variable	Single-haul skid trail Mean	N	SD	Multiple-haul skid trail Mean	N	SD
Root diameter[a] (cm)	1.76	266	0.97	1.84	393	0.94
Root depth[a] (cm)	10.84	266	4.82	9.99	393	5.20
Root length[a] (m)	97.64	110	84.73	109.52	145	82.47
Injuries per m root[a]	0.74	96	1.58	1.34	134	2.06
Injuries per excavation[b]	0.55	110	1.25	1.13	145	1.46
Disturbance[c] (cm)	4.38	96	2.19	5.06	145	3.13
Slope percent	20.3	96	12.13	21.1	145	10.44
Day of yr harvested	191.7	96	37.9	206.5	145	36.9

[a] Root diameter, root depth, root length, and number of injuries per meter root length are based on the population of root segments encountered in all excavations.
[b] Number of injuries per excavation is based on all excavations.
[c] Disturbance is the maximum depth of forest floor displacement and/or compression by the vehicle track at each excavation site.

Table 5.—*Lengths of vehicle paths (m) within 0.2-ha plots by treatment*[a]

Vehicle/Activity class	UAM Mean	UAM SD	EAM Mean	EAM SD	All Plots Mean	All Plots SD
Truck haul road	7.4	16.2	15.9	22.3	9.5	18.1
Multiple-haul skid trails	25.4	25.0	21.6	24.3	24.5	24.7
Single-haul skid trails	31.0	27.7	48.1	35.6	35.2	30.5

[a] Based on 42 uneven-aged management plots and 14 even-aged management plots.

of root length was apparently correlated with slope steepness or day of year harvested for either trail type (table 6). Nevertheless, number of injuries per meter of root length in single-haul trails (but not multiple-haul trails) was positively correlated with forest floor disturbance (table 6).

Proportions of Trees Damaged

For summarization, non-harvested stems were classified as saplings (5.0 – 11.0 d.b.h.), poles (11.1 – 29.9 d.b.h.), and sawtimber (≥ 30 d.b.h.), and stem damage was categorized as broken, xylem exposed, or phloem exposed. Proportions of trees in all three size classes experiencing each category of damage were similar for commercial tree species (table 7) vs. all tree species (data not shown). There appears to be very little difference in the patterns of damage occurring in plots partially cut by UAM vs. EAM systems (table 7). Overall, while similar proportions of trees in each size class were damaged, there was a greater tendency for sapling stems to be broken (table 7).

Size and Location of Xylem-exposing Injuries

The size of the largest xylem-exposing wound on damaged trees was highly variable (table 8), with means of 539, 1,040, and 1,877 cm^2, respectively, for saplings, pole-size, and sawtimber-size trees. Corresponding mean percentages

Table 6.—*Correlation coefficients (and corresponding P values) for root injury beneath multiple- vs. single-haul skid trails with forest floor disturbance, percent slope, and day of year harvested*

	Forest floor disturbance	Percent slope	Day of year harvested
		Multiple-haul trails	
Injuries per excavation	0.081 (0.35)	0.070 (0.42)	-0.103 (0.24)
Injuries per meter root	0.068 (0.44)	0.086 (0.32)	0.003 (0.97)
Disturbance		0.248 (0.003)	0.262 (0.002)
		Single-haul trails	
Injuries per excavation	0.171 (0.10)	-0.173 (0.092)	-0.056 (0.59)
Injuries per meter root	0.267 (0.009)	-0.023 (0.82)	-0.034 (0.74)
Disturbance		-0.081 (0.41)	0.101 (0.30)

Table 7.—Categorization of stems (percent) of commercial species by "most severe injury" class, d.b.h. class, and silvicultural system

	D.b.h. class											
	5.0 – 11.0 cm				11.1 – 29.9 cm				≥ 30.0 cm			
System[a]	Broken[b]	Xylem[c]	Phloem[d]	Uninjured	Broken	Xylem	Phloem	Uninjured	Broken	Xylem	Phloem	Uninjured
UAM	9.6	5.1	1.9	83.4	3.1	10.7	2.4	83.8	2.4	10.2	3.3	84.1
EAM	12.8	2.6	6.1	78.6	3.3	10.3	4.0	82.5	4.7	8.2	3.5	83.5
Combined	10.5	4.4	3.2	82.0	3.2	10.5	3.0	83.3	3.0	9.7	3.3	84.0

[a] UAM, uneven-aged management, based on 15 completely mapped plots; EAM, even-aged management, based on 7 completely mapped plots.
[b] This category includes stems uprooted, pushed over, shattered, permanently bowed, and/or broken off at a point precluding future merchantability.
[c] Xylem exposed.
[d] Phloem damaged, without immediately exposing xylem.

of stem circumference damaged by these wounds were more consistent among stem size classes, ranging from 23 percent for pole- and sawtimber-size trees to 27 percent for saplings (table 8). Largest xylem-exposing wounds occurred consistently in the butt log portions of damaged trees, averaging 33 cm, 36 cm, and 25 cm above ground level for saplings, pole- and sawtimber-size trees, respectively.

The largest xylem-exposing wounds on all injured saplings occurred above the root buttress on the bole (table 9). As tree size class increased, the percentage of trees with the largest xylem-exposing wounds involving buttress roots increased (table 9). The proportion of trees with the largest xylem-exposing wounds involving a buttress root was greater for both pole- and sawtimber-size trees in plots under EAM vs. UAM (table 9).

Relationship of Vehicle Activity to Non-harvested Stem Damage

In the 22 completely mapped plots, 67 percent of all injured stems were located ≤ 2.0 m from a vehicle track, with no apparent difference between UAM and EAM plots or among stem size classes (table 10). All 56 of our disturbed plots averaged a total of 69.2 m of vehicle path, including 9.5 m of haul road and 59.7 m of skid trails (table 5). With skid trails averaging 3 m wide, we estimate that 67 percent of all injured stems occurred on approximately 23 percent of the non-road plot area. In all 56 plots, over 50 percent of saplings ≤ 2.0 m from a haul road or skid trail were injured (table 11). The mean percentage of pole stems injured ranged from 35 percent along single-haul skid trails to 51 percent along multiple-haul skid trails. Fifty percent and 19 percent of non-harvested sawtimber stems ≤ 2.0 m from multiple- or single-haul skid trails, respectively, were injured (table

Table 8.—*Dimensions of largest xylem-exposing injury on trees of commercial species, by d.b.h. class and silvicultural system*

Wound feature[a]	D.b.h. class 5.0 – 11.0 cm N	Mean	SD	11.1 – 29.9 cm N	Mean	SD	≥ 30.0 cm N	Mean	SD
Even-aged Management (14 plots)									
Area (cm^2)	18	671	1,226	68	1,025	1,097	7	683	706
% Stem Circumf.	18	26	10	66	22	10	5	12	7
Height (cm)	18	34	31	75	30	46	13	44	138
Uneven-aged Management (42 plots)									
Area (cm^2)	66	504	588	177	1,046	1,178	49	2,047	3,813
% Stem Circumf.	66	27	11	173	23	11	44	24	35
Height (cm)	66	32	36	188	38	97	63	21	55
Combined									
Area (cm^2)	84	539	764	245	1,040	1,154	56	1,877	3,598
% Stem Circumf.	84	27	10	239	23	11	49	23	33
Height (cm)	84	33	35	263	36	86	76	25	75

[a] Wound area index (cm^2) calculated as the product of maximum wound length and width, percent of stem circumference affected at the point of maximum wound width, and height (cm) to wound base.

Table 9.—*Location (percent) of largest xylem-exposing injuries on injured stems of commercial species, by d.b.h. class and silvicultural system*

System[a]	D.b.h. class 5.0 – 11.0 cm Bole[b]	Root[c]	Both	11.1 – 29.9 cm Bole	Root	Both	≥ 30.0 cm Bole	Root	Both
EAM	100.0	0.0	0.0	75.7	13.0	11.4	35.0	60.0	5.0
UAM	100.0	0.0	0.0	89.2	6.2	4.6	63.8	28.7	7.5
Combined	100.0	0.0	0.0	85.5	8.0	6.6	59.2	33.7	7.1

[a] EAM, even-aged management, based on 14 plots; UAM, uneven-aged management, based on 42 plots.
[b] Injuries that do not extend into contact with the forest floor.
[c] Injuries that expose lateral root xylem.

11). A comparable percentage for sawtimber trees ≤ 2.0 m from haul roads could not be determined because all sawtimber trees ≤ 2.0 m from haul roads in our plots had been harvested.

Harvest and Site Characteristics Related to Tree Injury

Our SLR model showed that a tree's likelihood of being injured was greater in 1) plots with northern to eastern slope aspects ($P < 0.001$), and 2) plots where more large stumps were created ($P < 0.001$) (table 12). A tree's likelihood of becoming injured was lower in 1) UAM plots

Table 10.—*Distribution of injured stems with respect to distance from vehicle tracks, potential crop tree designation, and silvicultural system*[a]

D.b.h. class (cm)	All injured trees ≤ 2.0 m	All injured trees > 2.0 m	All injured trees % Injured ≤ 2.0 m	Injured crop trees ≤ 2.0 m	Injured crop trees > 2.0 m	Injured crop trees % Injured ≤ 2.0 m
Uneven-aged Management (15 plots)						
5.0 – 24.9	420	266	61.2	295	151	66.1
25.0 – 44.9	98	35	73.7	92	33	73.6
45.0 – 64.9	3	4	42.9	3	4	42.9
Even-aged Management (7 plots)						
5.0 – 24.9	165	129	56.1	110	63	63.6
25.0 – 44.9	25	7	78.1	25	5	83.3
45.0 – 64.9	4	1	80.0	3	1	75.0

[a] Data from haul roads and multiple- and single-haul skid trails were combined for all plots representing each silvicultural system.

Table 11.—*Frequency of stem injury in close proximity to three classes of vehicle activity, with respect to potential crop tree designation*[a]

D.b.h. class (cm)	All trees within 2.0 m Injured	All trees within 2.0 m Uninjured	All trees within 2.0 m % Injured	Crop[b] trees within 2.0 m Injured	Crop[b] trees within 2.0 m Uninjured	Crop[b] trees within 2.0 m % Injured
Truck haul roads						
5.0 – 24.9	80	64	55.6	62	56	52.5
25.0 – 44.9	22	30	42.3	20	30	40.0
45.0 – 64.9	0	0	—[c]	0	0	—[c]
Multiple-haul skidder trails						
5.0 – 24.9	161	100	61.7	113	87	56.5
25.0 – 44.9	39	37	51.3	36	34	51.4
45.0 – 64.9	3	5	37.5	3	3	50.0
Single-haul skidder trails						
5.0 – 24.9	338	243	58.2	221	200	52.5
25.0 – 44.9	61	112	35.3	58	108	34.9
45.0 – 64.9	4	13	23.5	3	13	18.8

[a] Data from 42 UAM and 14 EAM plots were combined for each vehicle activity class.
[b] Stems of commercial species were classified as crop trees if their condition prior to harvest activity would have permitted them to be considered potential crop trees.
[c] Not applicable, no trees.

(P < 0.001), 2) plots harvested later in the summer and autumn (P < 0.001), and 3) plots harvested by crew number 5 and crew number 8 (P < 0.001) (table 12). Potential crop trees were less likely to be injured than cull trees or non-commercial species (P < 0.001) (table 12). Also, a tree's likelihood of becoming injured decreased with increasing distance from the nearest vehicle track (P < 0.001) and increased with increasing within-plot haul road length (P < 0.001) (table 12). Concordance and discordance values for this SLR model were 82.6 percent and 16.3 percent, respectively (table 12).

DISCUSSION

As a component of the long-term MOFEP program, our study documents the suite of harvest disturbances in a spatially explicit manner, as a contribution toward understanding the ecological relationships between disturbance factors, individual tree and forest health, and consequent forest structure in upland Ozark forests. The 1996 MOFEP harvests occurred in stands that had not been harvested for at least 40 years. Sheriff (this proceedings) has described the silvicultural prescription process. For both the EAM- and (especially) the UAM-designated sites, an important objective of this first set of harvests was to shift stand structure toward the desired silvicultural model. Therefore, the 1996 MOFEP EAM thinning and (especially) the UAM single-tree selection harvests were not yet typical of either EAM or UAM.

Nor does the analysis of a single set of harvests reflect the more frequent stand entries inherent with UAM. More frequent stand entry should involve: 1) shorter time intervals between disturbances; 2) greater cumulative length of both single- and multiple-haul skid trails during the equivalent of an EAM rotation period; 3) a tendency to recognize and re-use the most convenient multiple-haul trails, resulting in a third class of skid trail, repeated multiple-haul; 4) correspondingly greater cumulative levels of root and stem damage during the equivalent of an EAM rotation; and 5) no clear regeneration harvest at a location until it is designated for group-tree selection. More frequent stand entry also presents *Armillaria* species with more stable temporal and spatial distributions of infection courts and woody food base resources.

Table 12.—*Results of stepwise logistic regression analysis to identify factors associated with probability of stem injury during harvest*

		Explanatory variables[a]			Predictive evaluation[b]		
Model	**Intercept**	**Variable name**	**Parameter estimate**	**Pr > Wald Chi-square**	**Percent concord.**	**Percent discord.**	**No. pairs**
Complete plots, All trees	4.0620			< 0.001	82.6	16.3	1,338,805
		Stem quality	-0.8328	< 0.001			
		Distance	-1.9584	< 0.001			
		ELT 18	+1.0381	< 0.001			
		Day of year	-0.0111	< 0.001			
		Crew no. 8	-1.9545	< 0.001			
		Crew no. 5	-0.6858	< 0.001			
		Uneven-aged management	-0.5388	< 0.001			
		Truck haul road length	+0.0151	< 0.001			
		No. stumps ≥ 45 cm dia	+0.1230	< 0.001			

[1] Variable names: Stem quality, +/- potential crop-quality stem pre-harvest; Distance, stem distance from nearest vehicle trail; ELT 18, northern to eastern slope aspect; Day of year, calendar day of year harvested; Crew no., identity of logging crew that harvested the plot. The significance test used by PROC LOGISTIC is based on the Wald statistic (Sokal and Rohlf 1995; SAS/STAT System Release 8.00, SAS Inst., Inc., Cary, NC).

[2] No. Pairs represents the product (Observed) * (Total - Observed), the number of possible pairwise combinations of stems for which the specified scenario (injury) was observed and not observed for the two members of the pair. For each stem in each model, SLR assigned a probability, p, that injury would be observed. "Percent Concordant" is the percentage of pairs for which the larger probability of injury (p) was associated with the stem on which injury was observed. "Percent Discordant" is the percentage of pairs for which the larger probabilit of injury (p) was associated with the stem on which injury was not observed (SAS/STAT System Release 8.00, SAS Inst., Inc., Cary, NC).

EAM involves more dramatic harvest disturbances, but longer intervals between disturbances. While stems injured during thinning may deteriorate further because they remain in the stand longer, regeneration by clearcut eliminates almost all injured stems. And while a clearcut creates the greatest volume and most thorough distribution of potential woody food base resources for *Armillaria*, it is not yet clear how the longer interval between thinning and clearcutting affects the inoculum potential of the three *Armillaria* species in the area and their relative abilities to capture the woody resources made available by a clearcut.

The relationship between physical injury and tree decline is associated with the processes by which trees respond physiologically to injury. Trees do not restore the function of injured tissues or tissues that die in the wound response. Instead, trees expend energy to "compartmentalize" these tissues (Shigo 1984).

Compartmentalization is a variably effective process for containment of microbial colonization, involving both the sacrifice of ray and xylem tissues pre-dating injury and an attempt to overgrow the injury as quickly as possible (Shigo 1984). Because ray parenchyma tissues within compartments die in the process, an injured tree's energy storage capacity is correspondingly reduced, impairing its abilities to respond to subsequent stress or infection (Shigo 1985). The extension of stain and decay slows greatly once a wound is overgrown, as closure seals the injured tissue from further desiccation and aeration (Basham 1978). Thus, smaller wounds generally result in smaller compartments, faster wound closure, and less discoloration and decay.

Trees attempt to compartmentalize root injuries and infections in the same manner as stem injuries (Shigo and Tippett 1981). The success of the compartmentalization process in a tree root depends on the physiological condition of the tree and the nature of any pathogenic challenge. A tree's physiological response to stress or injury diverts energy that might also be needed to compartmentalize root injuries or infections, and in doing so, temporarily increases root concentrations of carbon and nitrogen forms preferred by *Armillaria* species (Wargo 1996).

Skidder tracks covered an estimated 3 percent of the forest floor, resulting in > 900 root injuries per hectare harvested. There were no differences between EAM and UAM plots in the mean length of single- or multiple-haul skid trails. If this pattern remains true for future partial cuts, then a much greater proportion of the forest floor will be skidded over with UAM than with EAM during an EAM rotation-equivalent period of time. We are not aware of any other studies characterizing skid trail damage to subterranean woody roots. Consequently, we have no case studies with which to compare the levels of root damage we observed, and are not presently able to predict the magnitude of their effect(s) on forest health. Comparative evaluation of root disease level relative to distance from skid trails will eventually clarify this issue. Weaver (1974) showed that *A. tabescens* infected and colonized wounded peach roots more readily than non-wounded roots. Popoola and Fox (1996) found that root-pruned black currant plants were more readily infected by both *A. gallica* and *A. mellea* compared with non-injured plants, and that *A. mellea* infection resulted in higher levels of twig and root mortality on both pruned and non-injured plants than *A. gallica*.

The positive correlation between forest floor disturbance in multiple-haul skid trails and slope steepness was anticipated (table 6). However, the positive correlation between forest floor disturbance in multiple-haul skid trails and harvest day of year (table 6) is misleading, because very few of our plots were harvested early in the spring when soil moisture is especially conducive to soil displacement and compaction. Only 5 of our 56 study plots happened to be harvested as early as May, and the last 10 were harvested in September and October (table 2). Earlier harvesting in sites 7 and 9 than in sites 2 through 5 resulted in some very severe rutting (locally ≥ 60 cm deep), which, however, did not occur close to our plots. Forest managers in sites 7 and 9 rationalized correctly that ruts would close with time. Because so few of our plots were harvested early, our correlation analysis apparently detected increasing disturbance associated with the late season rise in soil moisture. The lack of correlation for both root injury indices with slope steepness and day of year harvested (table 6) is also probably misleading. The small correlation coefficients observed are probably associated with the very rocky soils characteristic of the upland Ozarks and with complete displacement of some injured root segments from more disturbed tracks on steeper slopes. "Number of injuries per meter of root length" was positively correlated with forest floor disturbance, but only in single-haul skid trails. We attribute this to more frequent displacement of damaged root material from more heavily used trails. On rocky soils, combined displacement and compaction may not be adequate indicators of either disturbance or root damage. Overall, we consider our extrapolated estimates of root damage at the site level to be conservative.

We expect approximately 15 percent sapling stem mortality in partially cut plots under both EAM and UAM, because of the effects of suppressed forest canopy position on their ability to recover from injury (Nyland 1994). The greater proportion of saplings injured than larger trees is undoubtedly due to their greater density, the fact that they are small enough to safely run over, and the focus of loggers' attention on avoiding damage to larger stems. Sapling destruction is of special concern in UAM because: 1) the greater frequency of stand entries with UAM provides more frequent opportunities to damage residual stems; and 2) UAM depends on a constant supply of appropriately distributed advance regeneration from which to select future crop trees (Daniel *et al.* 1979, Nyland 1994). The extent to which old skid routes are used in future UAM harvests will largely determine how much total sapling destruction occurs.

The largest xylem-exposing wound on each injured tree averaged 539 cm^2 for saplings and 1,877 cm^2 for sawtimber stems, respectively, and covered approximately 25 percent of stem circumference for both size classes (table 8). Because the barrier zone produced by the vascular cambium during compartmentalization extends substantially beyond the wound margins (Shigo 1984, 1985), the percent stem circumference actually affected by an injury is much greater than wound dimensions suggest. Several relatively long-term studies have addressed the prognosis for wounds on various tree species in different climatic zones. For example, Benzie *et al.* (1963) found that yellow birch injuries increased in size during the year after wounding, whereas sugar maple injuries did not. Smith *et al.* (1994) found that injuries > 322 cm^2 on Appalachian hardwoods often require over 15 years to close. Basham (1978) observed that sugar maple injuries inflicted during the spring closed faster than autumn injuries of the same size, leading to greater defect development from autumn *vs.* spring injuries. Basham (1978) also found that wounds that penetrated the xylem resulted in substantially greater defect than wounds that exposed but did not penetrate the xylem. Lamson and Smith (1988) found no d.b.h. growth loss associated with injuries > 645 cm^2 during the 5 years following thinning in Appalachian hardwoods.

The greater frequency of buttress root damage on larger trees (table 9) is doubtless due to the increase in buttress size and exposure as trees grow. The frequency of buttress injury is also expected to increase with the total length, degree of curvature and number of turns in skid trails, and with increasing length of skidded logs. In addition, loggers may presume that buttress root injuries are less important than stem injuries because trees with buttress root injuries can often be harvested before the associated defect extends into the valuable butt log. In fact, Benzie *et al.* (1963) found that decay in yellow birch and sugar maple was much more commonly associated with 4-year-old buttress root injuries than with stem injuries, although decay generally had not yet progressed into the butt log. Kessler (1992) found an association between buttress root injuries and branch dieback in black oak.

Non-harvested stem damage was heavily concentrated ≤ 2.0 m from vehicle paths (tables 10 and 11). Two-thirds of all injured stems occurred in the approximate 23 percent of plot area (excluding permanent haul roads) that was ≤ 2.0 m from a vehicle path. Skid trails were not predesignated for this harvest, and merchantable tree-length logs were skidded to decks alongside haul roads. Fifty and eighteen percent, respectively, of the non-harvested sawtimber trees ≤ 2.0 m from a multiple- or single-haul skid trail were injured. We need to emphasize that stem damage incurred during harvest constrains the professional forester's subsequent freedom to implement silvicultural guidelines, subjugating considerations of stand structure to the removal of damaged stems (e.g., Ohman 1970). In this light, a study of residual stem damage resulting from whole-tree harvest thinning of northern hardwoods found that predesignation of skid trails greatly reduced the level of damage to residual stems (Ostrofsky *et* *al.* 1986). The potential benefits to be derived from logger education and careful harvest layout are clear (Bruhn 1986, Dey 1994, McNeel and Copstead 1994, Nyland 1994, Ostrofsky *et al.* 1986). While it is not possible to completely avoid residual stem damage, it is important to realize that we will live with the effects of harvest disturbance for a long time.

While relationships detected by stepwise logistic regression (SLR) are not necessarily causal, SLR is a valuable tool for exploring potential relationships in a data set. Our SLR analysis of the probability of tree injury during the first MOFEP harvest included only factors of MOFEP experimental design (i.e., silviculture system and statistical block) or of direct hypothetical interest (table 3). As such, the results are instructive in designing future planned comparisons. A few of the detected associations merit emphasis. Two of the 13 logging crews involved with our 56 plots were associated with less damage than the other crews. Crew 5 harvested seven plots, and crew 8 harvested five plots (table 2). It would be difficult to determine whether these two crews were assigned easier plots to harvest, harvested the plots they were assigned more carefully, or both. All skidding was accomplished with rubber-tired tractors hauling merchantable tree-length logs. Meyer *et al.* (1966) found that rubber-tired tractors skidding tree-length logs caused excessive damage compared with log-length skidding. The generally lower probability of injury under UAM in this first MOFEP harvest may be partly due to the skidding of fewer and smaller stems out of or through plots under this system than under EAM. Probability of stem injury was also associated with the number of large stumps created within plots. Stump size is directly related to merchantable tree length. The greater probability of injury in stands with northern to northeastern slope aspects is likely due to higher soil moisture levels and higher site index values in these more productive stands (J. M. Kabrick, personal communication). The declining probability of stem injury as the growing season progressed is explained by the progressive tightening of bark with the advancing growing season. Overall, the 82.6 percent concordance of our SLR model suggests that important variables determining probability of stem injury were included (tables 3 and 12).

Loss of commercial tree value due to direct stem injury depends heavily on the tree species, its initial condition, and the desired product mix (e.g., veneer, lumber, or charcoal). We have deliberately refrained at this time from predicting the economic consequences of 1) different types and sizes of stem injury, 2) different frequencies of stem injuries, and 3) levels of structural root damage associated with skidder tracks. We have also refrained from predicting the economic costs of reducing disturbance levels. Nevertheless, the documentation approach we have taken provides the baseline data necessary for followup studies of dynamics of wood products quality (e.g., mortality, rates of wound closure and defect development) as well as dynamics of forest health and structure. Results of this and related studies will facilitate evaluation and enhancement of forest operation guidelines to maintain or improve overall forest health.

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