Small Mammal Responses to Fine Woody Debris and Forest Fuel Reduction in Southwest Oregon

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ABSTRACT Despite its importance for wildlife, most forests in the Pacific Northwest contain low volumes of large downed wood compared to fine woody debris (FWD). We used a replicated experiment to compare short-term responses of deer mice (*Peromyscus maniculatus*) and western red-backed voles (*Clethrionomys californicus*) among 3 arrangements of FWD: piled, lopped and scattered, and pile burning, a commonly used method of fuel reduction in commercial Douglas fir (*Pseudotsuga menziesii*) forests in southwest Oregon, USA. We assessed habitat use, density, and survival of mice and voles during 2 consecutive summers (Jun–Aug 1999 and 2000). Both mice and voles used FWD cover disproportionately from its availability, and they differed in their responses to specific FWD arrangements. Mice used piled FWD (proportional use = 37.0%, 90% CI = 33.0–44.0) 43% more than expected (26.0). Number of mice captured ($\bar{x} = 1.9$ mice, 90% CI = 1.5–2.5) and index of home range size ($\bar{x} = 4.8$ m, 90% CI = 0.7–8.9) at individual FWD piles decreased up to 16% and increased up to 50%, respectively, for each 1-m increase in distance from piles. Voles used all FWD cover classes in proportion to availability, but number of voles captured increased slightly ($\bar{x} = 0.016$ voles/m, 90% CI = 0.001–0.031) for each 1-m increase in distance from piles. Piled FWD had no discernable effect on population density and apparent survival of mice, but analyses had low power (0.25, 0.67). Our results suggest that piling FWD would benefit deer mice, whereas lopped and scattered FWD might benefit voles. Thus, a combination of methods to reduce fire risk should be considered to accommodate multiple small mammal species. (JOURNAL OF WILDLIFE MANAGEMENT 72(3):625–632; 2008)

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Downed wood is important for wildlife in old-growth and managed forests of the Pacific Northwest (Maser and Trappe 1984, Harmon et al. 1986, Tallmon and Mills 1994). Compared to old-growth forests, however, managed forests in this region contain low volumes of large woody debris (pieces >10 cm in diam and >1.5 m in length; Harmon and Sexton 1996). In managed forests, the primary source of woody detritus is fine woody debris (FWD; pieces <10 cm in diam; Harmon and Sexton 1996, Pyne et al. 1996), a forest component that has received little attention in wildlife literature.

Fine woody debris accumulates in managed forests during silvicultural activities such as tree thinning and is commonly removed to reduce risk of wildfire (Walstad et al. 1990, Wickman 1992, Mutch et al. 1993, Harmon and Sexton 1996, Brown et al. 2004). Consequently, efforts to reduce FWD in managed forests increased as federal land managers implemented the Northwest Forest Plan, Federal Wildland Fire Management Policy, and Healthy Forest Initiative (U.S. Forest Service and U.S. Bureau of Land Management 1994*a*, U.S. Department of the Interior and U.S. Department of Agriculture 2001, U.S. Forest Service 2003).

Fine woody debris is removed by prescribed burning, pile burning, or mechanical methods (Mutch 1994, Brown et al. 2004). Selection of a method for fuel reduction on a specific site is based on risk of wildfire and volume of FWD remaining after trees are removed (e.g., pile burning is used when fire risk and volume are high; Brown et al. 2004). Because fuel reduction may affect soils, vegetation, and wildlife (DellaSala and Frost 2001), Carey and Johnson (1995) and Tiedemann et al. (2000) proposed leaving FWD where it fell in a lopped and scattered condition to conserve organic material. Lopped and scattered FWD does not ameliorate short-term fire risk, but piled FWD that is not burned might achieve the combined goals of reducing fire risk and conserving organic material.

Downed wood is an important habitat component for several species in old-growth forests, including small mammals (Maser and Trappe 1984, Harmon et al. 1986, Hayes and Cross 1987, Gibbons 1988); therefore, it is plausible that the amount of FWD could affect habitat for small mammals in managed forests. We used a replicated field experiment to compare habitat use, density, and survival of deer mice (*Peromyscus maniculatus*) and western red-backed voles (*Clethrionomys californicus*) among 3 arrangements of FWD in commercially thinned Douglas fir (*Pseudotsuga menziesii*) forests in southwest Oregon.

STUDY AREA

We conducted our study in the Applegate Adaptive Management Area (AAMA) on the eastern escarpment of the Siskiyou Mountains within the Klamath Mountains Geological Province of southwest Oregon, USA (Franklin and Dyrness 1973). The province is recognized as a center of endemism, speciation, and biodiversity for the Pacific states (Whittaker 1961, Stebbins and Major 1965, DellaSala et al. 1999). We focused our research in mixed-evergreen vegetation (Franklin and Dyrness 1973), characterized by Douglas fir, tanoak (*Lithocarpus densiflorus*), canyon live oak (*Quercus chrysolepis*), madrone (*Arbutus menziesii*), sugar pine (*Pinus lambertiana*), and Jeffrey pine (*P. jeffreyi*).

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Forest management in the AAMA included thinning and fuel reduction (U.S. Forest Service and Bureau of Land Management 1994*a*, *b*). Tree densities were thinned 37–43%, resulting in 3 density levels, the most prevalent being 124 trees/ha (Bureau of Land Management 1996). Thinned forest stands were typically dominated by Douglas fir, madrone, snowberry (*Symphoricarpos albus*), trailing snowberry (*S. mollis*), ocean spray (*Holodiscus discolor*), and poison oak (*Toxicodendron diversilobum*). Understory vegetation varied within stands due to scarring, uprooting, and clearing during thinning activities.

Fuel reduction typically involved hand-piling and pile burning when volumes were high (>12,548 kg/ha). At low volumes (<12,548 kg/ha), FWD was typically broadcast burned, whereas, at still lower volumes, it was lopped and scattered to decompose (G. Chandler, Bureau of Land Management, personal communication).

METHODS

Experimental Design

We used a randomized complete block design to compare responses of deer mice and western red-backed voles to 3 arrangements of FWD after tree thinning. Treatments were lopped and scattered FWD (Carey and Johnson 1995, Tiedemann et al. 2000), piled FWD, and pile burning, which we considered a baseline treatment level. We randomly selected 3 forest stands that we classified as blocks from a population of 27 stands (each ≥5.1 ha) along an elevation-climatic gradient from cool and moist low-elevation to warm and dry high-elevation forests. Blocks contained >12,548 kg/ha of FWD and were ≥130 m wide to ensure that each could support our study plots.

We randomly positioned 3 0.8-ha plots in each block, each separated by ≥100 m, and established a 9 × 11 trapping grid with 10-m intervals between traps in each plot. Plots were ≥20 m from streams, roads, adjacent treatment areas, and forest-stand boundaries, minimizing effects of habitat edges (Murcia 1995, Kremsater and Bunnell 1999). We assumed a 20-m buffer width was adequate because Mills (1995) showed that edge effects were less in interior forest areas compared to forest edges along clearcuts.

Blocks were thinned to 124 trees/ha using chainsaws, draglines, and skip loaders in April 1999, which represented the dominant tree density after thinning in the AAMA. We randomly allocated the 2 FWD arrangements and baseline treatment level to each study plot without replacement within a block. Fine woody debris was hand-piled in October and burned in November 1999; we sampled animals and vegetation before and after treatments. Average density of piles in the piled treatment was 54 piles/ha (SE = 5.4).

Animal Sampling

We used mark–recapture methods to estimate density and survival before and after treatment. We sampled animals during summer (Jun–Aug) to evaluate population responses during a period when we expected high rates of population growth following low, intra-annual late winter and spring densities (Petticrew and Sadleir 1974, Sullivan 1979). We began pretreatment sampling, which consisted of 5 4-day (occasion) trapping sessions separated by 4 10-day time intervals, 2 months after trees were thinned and 2 months before treatment. We assumed the 4 time intervals between sessions supported open population conditions suitable for estimating apparent survival. We prebaited traps equally across all plots during each 10-day survival interval. Posttreatment sampling followed the same regime and began 7 months after treatment. We assumed that 7 months was adequate for short-term responses by these species because small mammals respond rapidly to habitat perturbations (Tevis 1956, Sullivan 1979).

Each trap site contained one Sherman live-trap (7.6 × 8.9 × 22.9 cm; H. B. Sherman Traps, Tallahassee, FL) with polyester batting, rolled oats, and sunflower seeds. We marked new captures with individually numbered Monel fingerling tags (National Band and Tag Co., Newport, KY) and identified them to species, sex, and reproductive condition (i.e., scrotal, nonscrotal, pregnant, nonpregnant). Capture methods complied with American Society of Mammalogists (1998) guidelines approved under the Oregon State University, Institutional Animal Care and Use Committee (protocol 2316).

Habitat Sampling

We collected habitat data across each plot and at each trap. At the plot level, we established point intercepts at 3-m intervals along 3 evenly spaced 100-m line transects, from which we calculated percentage of herb–grass and shrub cover (Bonham 1989). We sampled FWD along 15 evenly spaced 12-m line-intercepts that extended in random directions from the vegetation transects (Brown 1974). We calculated volume (m^3/ha) of FWD at the plot-level. Because understory vegetation and FWD varied after plots were thinned (Thysell and Carey 2000), we sampled FWD volumes before treatments and herb–grass and woody shrub cover before and after treatments.

We recorded percent cover of lopped and scattered FWD and presence of piles within a 100-m^2 area centered on each trap site in the 3 plots where FWD was piled. We divided the 100-m^2 area into 4 quadrants and used percent cover classes to visually estimate FWD cover: Class 1 (0%), Class 2 (1–25%), Class 3 (26–50%), Class 4 (51–75%), and Class 5 (76–100%; Daubenmire 1959). We assigned trap sites with piles within the 100-m^2 area to Class 6. We averaged cover-class estimates for each trap site and measured distance (m) from each trap site to the nearest pile as a continuous variable.

We sampled ambient air temperature (°C) under piles and 3 additional levels of FWD cover, 1–75%, 76–100%, and on barren ground, to examine differences in abiotic conditions that may influence patterns of use. From mid- to late-July 2000, we used a digital thermometer to simultaneously measure temperatures under each type of cover at 4 randomly located sites in each plot. We cooled thermometers on ice for 30 minutes before placing them in the center of piles, and out of direct sunlight in remaining cover types, during randomly selected times of day; and thermometers remained under each cover type for 30 minutes prior to temperature readings.

Analysis of Habitat Use

We assessed differences in observed versus expected use of the 6 classes of FWD cover by deer mice and western red-backed voles from the 3 plots where FWD was piled with a goodness-of-fit chi-square test (χ^2; Siegel 1956), followed by a use-availability test (Neu et al. 1974). We used trap stations as the sampling unit. Expected values within each plot were number of stations in each category of FWD cover and observed values were total number of individuals captured at stations within each of the 6 categories (Alldredge and Ratti 1986). We calculated 90% Bailey's confidence intervals to determine which cover classes contributed to the overall chi-square statistic (Cherry 1996). We assessed influences of environmental conditions on habitat use by deer mice by performing these tests with all blocks combined and separately for each block because conditions varied among blocks. Small samples of voles prevented an analysis of habitat use in each block. We used ambient air temperatures (° C) measured under different cover categories to relate habitat use to types of FWD cover at trap sites.

We used Akaike's Information Criterion (AIC; Akaike 1973, Burnham and Anderson 1998) to examine relationships between distance from piles (explanatory variable) and average number of individuals captured in traps within each 1-m increase in distance from piles. We compared the relative fit of linear and logarithmic ($\log_e$) regression models (PROC REG; SAS Institute 2000) to the number of animals captured using the small-sample corrected AIC (AIC_c; Akaike 1973, Burnham and Anderson 1998). Log_e of number of animals captured represented the hypothesis that numbers of animals would become asymptotic with distance from piles. Similarly, we examined the relationship between distance from piles and home-range size at each 1-m increase in distance from piles, indexed by average distance between successive captures for animals captured $\geq$2 times (Otis et al. 1978).

Density and Survival

We followed a 2-step process to analyze effects of FWD treatments on populations. First, we estimated density and survival before and after treatments in each study plot. Second, we used these estimates in mixed-effects models to test hypotheses about effects of FWD arrangements.

We estimated abundance for each biweekly trapping session using the first-order jackknife estimator in program CAPTURE (Burnham and Overton 1978, 1979; Rexstad and Burnham 1992). We estimated densities from abundance in effective trapping areas using half the mean maximum distance moved as the boundary-strip width (Dice 1938, Otis et al. 1978, White et al. 1982, Wilson and Anderson 1985, Rexstad and Burnham 1992). We transformed estimated densities of western red-backed vole using $\log_{10}(x + 1)$.

Table 1. Apparent survival (Φ) of deer mice before and after 2 arrangements of fine woody debris (FWD) and an experimental control (pile burning) in thinned Douglas fir forests on the Applegate Adaptive Management Area, Jackson County, Oregon, USA, June–August 1999–2000. Results are shown for models with highest likelihood.[a]

FWD arrangement (before and after replicate [rep] no.)	AIC_c wt (w_i)[b]	Φ	SE
Lop and scatter (before, rep 1)	0.858	0.839	0.066
Lop and scatter (before, rep 2)	0.916	0.667	0.086
Lop and scatter (before, rep 3)	1.000	1.000	0.000
Lop and scatter (after, rep 1)	0.974	0.591	0.105
Lop and scatter (after, rep 2)	0.453	0.834	0.069
Lop and scatter (after, rep 3)	0.993	0.946	0.067
Pile (before, rep 1)	0.951	0.759	0.085
Pile (before, rep 2)	0.957	0.808	0.077
Pile (before, rep 3)	0.442	0.700	0.145
Pile (after, rep 1)	0.529	0.745	0.090
Pile (after, rep 2)	0.919	0.793	0.095
Pile (after, rep 3)	0.760	0.945	0.149
Pile burning (before, rep 1)	0.939	0.857	0.076
Pile burning (before, rep 2)	0.935	0.760	0.085
Pile burning (before, rep 3)	0.881	0.827	0.091
Pile burning (after, rep 1)	0.919	0.705	0.089
Pile burning (after, rep 2)	0.842	0.833	0.068
Pile burning (after, rep 3)	0.958	0.810	0.087

[a] Based on comparing 4 mark–recapture models using Akaike weights (Burnham and Anderson 1998): 1) Φ(.), P(.) with 2 parameters, survival and recapture probability constant among individuals, 2) Φ(t), P(.) with 5 parameters, survival varied with time and common recapture probability, 3) Φ(.), P(t) with 5 parameters, survival constant and recapture probability varied with time, and 4) Φ(t), P(t) with 8 parameters, survival and recapture probability varied with time.

[b] Akaike weights (w_i), an estimate of the likelihood of the model within the set of models considered (Burnham and Anderson 1998), based on the small-sample size corrected Akaike's Information Criterion (AIC_c).

We estimated survival using Cormack–Jolly–Seber models in program MARK (Cormack 1964, Jolly 1965, Seber 1965, White and Burnham 1999). We considered animals captured $\geq$1 times in a study plot during a biweekly trapping session as present. Small sample sizes required pooling of age classes, reproductive conditions, and sex for each species. Western red-backed voles were present in low numbers ($\leq$4 individuals) in one plot of each treatment, and therefore we were unable to estimate apparent survival in these 3 plots. We tested for time effects in survival in each plot separately using 4 a priori models (Table 1) and assessed goodness-of-fit for the global model using 1,000 bootstrap simulations. We based model selection on Akaike weights, derived from AIC_c.

We tested for population responses with mixed effects models (Littell et al. 1996), where we considered change in survival and density as response variables, treatments and treatment periods as main effects, plots as replicates, and biweekly trapping sessions as repeated measures through time in each plot.

To adjust for baseline variation among plots, our response was the difference between population estimates from before and after treatments. However, the magnitude of change in a plot could have been affected by inherent differences in vegetation among plots; therefore, we also incorporated possible effects of preexisting variation among plots in our models by using initial estimates of density, shrub cover, herb–grass cover, and volume of FWD as covariates. We used orthogonal contrasts to assess differences between pile burning and 2 arrangements of FWD (Steel et al. 1997). We removed nonsignificant ($P < 0.1$) variables iteratively.

We based mixed effects models of survival only on process variance. We used central difference approximations to second partial derivatives to estimate the process variance–covariance matrix for survival estimates (White and Burnham 1999). We then forced this matrix structure on our mixed effects survival models.

We conducted retrospective power analyses to evaluate the potential of making Type II errors (Steidl et al. 1997). All power analyses were 2-tailed and we calculated them with $\alpha = 0.1$, $n = 3$, and estimated standard deviations from our samples. We chose an effect size of 50% change in a population parameter relative to that parameter associated with pile burning, which we believe reflects a biologically meaningful effect because deer mice and vole populations have been shown to rapidly change following forest management practices (Tevis 1956; Sullivan 1979, 1980).

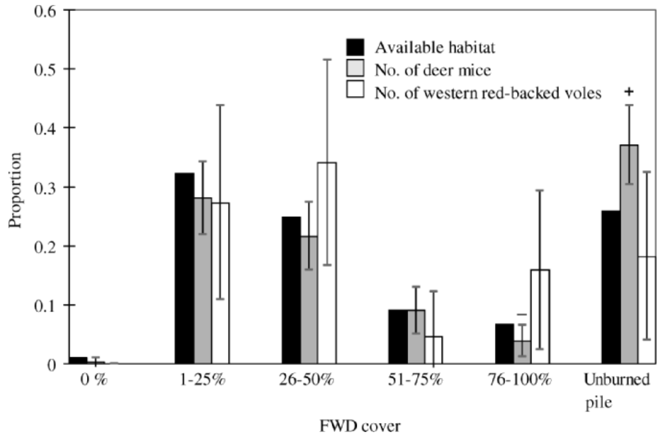

Figure 1. Proportions of available habitat and total individuals of deer mice ($n = 310$) and western red-backed voles ($n = 44$) in 6 classes of fine woody debris (FWD) cover in the Applegate Adaptive Management Area, Jackson County, Oregon, USA, June–August 2000. Vertical bars represent 90% Bailey's confidence intervals for individual cover categories (Cherry 1996). Categories are percent cover by lopped and scattered fine woody debris (%) and piles. Pluses (+) indicate a species used fine woody debris cover ($P \leq 0.1$) more than expected and minuses (–) indicate use less than expected, based on a use-availability test (Neu et al. 1974).

RESULTS

We recorded 1,538 captures of 536 deer mice and 1,057 captures of 248 western red-backed voles. Deer mice and western red-backed voles had the highest numbers of captures out of 15 small mammal species captured in our study area. Recapture probabilities were high (>0.84 for mice and >0.74 for voles), and we detected no movements among plots.

FWD Treatments

Average herb–grass cover among treatment areas increased from 49.8% (SE = 3.2) before to 56.4% (SE = 2.4) after FWD was rearranged, whereas average shrub cover changed little ($\bar{x} = 42.6\%$, SE = 4.6 before and $\bar{x} = 43.3\%$, SE = 4.9 after). Understory vegetation cover increased ≤35% in plots 8 months after FWD was rearranged, although patches of forest floor where FWD piles were burned remained barren.

Average volume of FWD among treatment areas before FWD was rearranged was 244.68 m^3/ha (SE = 18.9). Pile burning reduced average FWD volumes from 287 m^3/ha (SE = 43) before to 61 m^3/ha (SE = 11) after treatments. Piling ($\bar{x}$ = 54 piles/ha, SE = 5.4) produced clumped distributions without altering FWD volumes.

Ambient temperatures in open areas (0% cover; $\bar{x} = 33.8°$ C, SE = 1.5) were 20% higher than under piles ($\bar{x} = 26.9°$ C, SE = 3.4), about 9% higher than beneath 76–100% FWD cover ($\bar{x} = 30.9°$ C, SE = 3.2), and 3% higher than under 1–75% FWD cover ($\bar{x} = 32.6°$, SE = 1.6). Although temperatures were lowest under piles, temperatures in large areas between piles were relatively high (≤20% higher) due to low amounts of FWD cover.

Habitat Use

Deer mice in all 3 blocks used FWD cover disproportionately to its availability ($\chi^2 = 23.24$, df = 5, $P < 0.001$). Mice used FWD piles ($n = 115$, proportional use = 37.0%, 90% CI = 33.0–44.0) 43% more than expected (0.26), trap sites with 76–100% FWD cover ($n = 12$, proportional use = 4.0%, 90% CI = 1.0–7.0) 43% less than expected (7.0), and remaining FWD cover classes in proportion to availability (Fig. 1). Although evidence of differential selection for FWD cover classes by voles was weak ($\chi^2 = 9.79$, df = 5, $P = 0.081$), use-availability analysis did not provide evidence of selection for any cover class (Fig. 1).

Deer mice used FWD cover disproportionately less from its availability in warm and dry high-elevation forest ($\chi^2 = 23.16$, df = 5, $P = 0.000$). Use did not differ from availability in lower elevation forests ($\chi^2 = 2.77$, df = 5, $P = 0.59$).

Numbers of deer mice captured decreased logarithmically with increased distance from FWD piles (lowest AIC_c; $r^2 = 0.60$, $n = 16$, $P = 0.001$; Fig. 2A). Numbers captured declined by 46% at 7 m (90% CI = 0.28–0.80) from piles and declined at a lesser rate at greater distances (Fig. 2A). Size of deer mice home ranges increased linearly with distance from piles ($r^2 = 0.24$, $n = 16$, $P = 0.05$; Fig. 3).

Numbers of western red-backed voles captured increased slightly (0.016 voles/m, 90% CI = 0.001–0.031) for each 1-m increase in distance from piles (lowest AIC_c; $r^2 = 0.23$, $n = 13$, $P = 0.02$; Fig. 2B). Size of vole home ranges did not vary with distance from piles ($r^2 = 0.01$, $n = 13$, $P = 0.84$).

Population Responses

Neither arrangement of FWD nor any other factors ($P > 0.1$) affected densities of deer mice ($F_{2,4} = 0.60$, $P = 0.58$) or voles ($F_{2,4} = 2.28$, $P = 0.22$; Table 2). Power to detect a 50% change in density of deer mice was moderate ($\alpha = 0.1$, $n = 3$, SE = 1.67, power = 0.67), although power was low for detecting such a change in voles ($\alpha = 0.1$, $n = 3$, SE = 4.13, power = 0.25).

We found no evidence that arrangement of FWD or any other factors ($P > 0.1$) affected apparent survival of deer

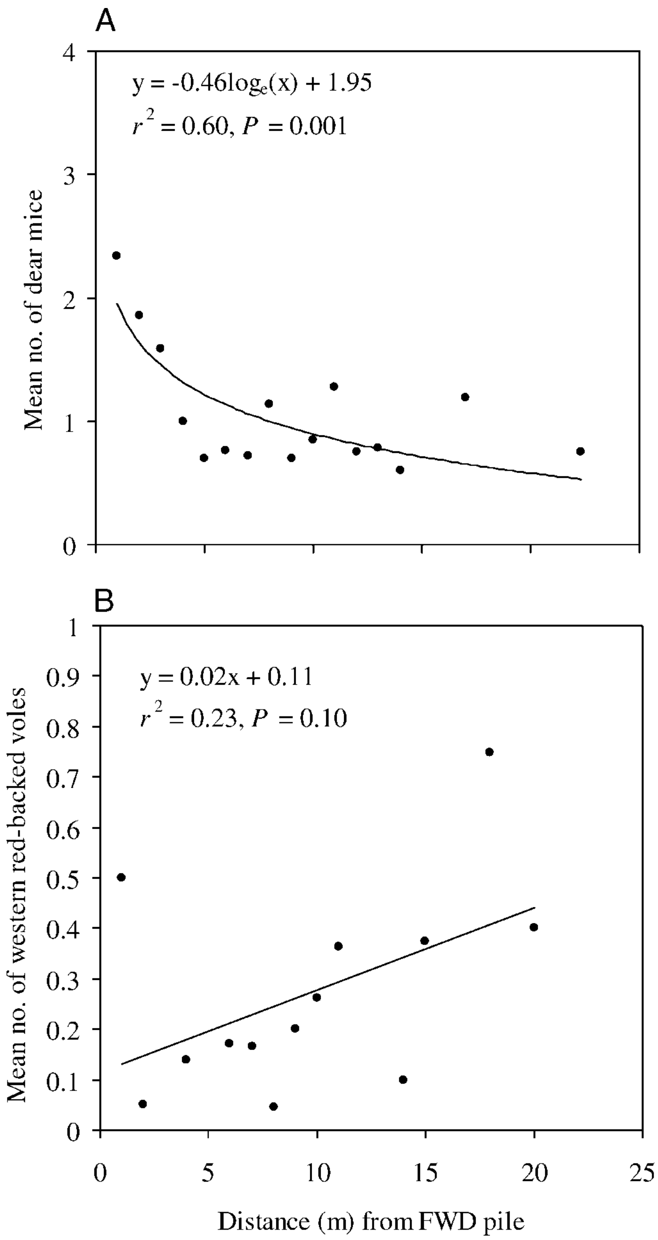

Figure 2. Average number of individual deer mice (A) and western red-backed voles (B) as a function of distance from piled fine woody debris (FWD) in the Applegate Valley Adaptive Management Area, Jackson County, Oregon, USA, June–August 2000, averaged from samples of 310 deer mice and 44 voles.

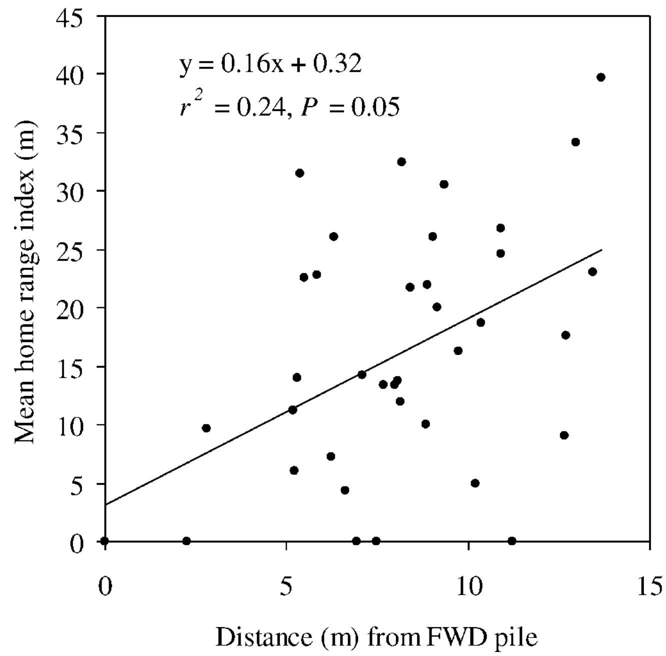

Figure 3. Average home range size of deer mice as a function of distance from piles of fine woody debris (FWD) in the Applegate Valley Adaptive Management Area, Jackson County, Oregon, USA, June–August 2000. Average distance moved (m) is considered an index of average home range diameter (Otis et al. 1978) based on all individuals that occupied trap stations at the corresponding nearest distance from a FWD pile.

mice ($F_{2,4} = 0.24$, $P = 0.79$; Table 2); however, power to detect a 50% change in survival was moderate ($\alpha = 0.1$, $n = 3$, SE = 0.05, power = 0.5). Although low numbers of voles prevented reliable testing, apparent survival of voles in lopped and scattered FWD increased by an estimated 36% (90% CI = –0.06 to 0.66; Table 2). Arrangement of FWD also did not affect juvenile:adult ratios of either species ($F_{2,4} = 0.46$, $P = 0.76$).

DISCUSSION

Deer mice and western red-backed voles differed in their responses to specific FWD arrangements. Fine woody debris piles represent an important habitat component for deer mice in managed forests, demonstrated by their use of piles and increased numbers and decreased home range sizes in close proximity to piles. A similar pattern involving voles and deer mice has been reported for large downed wood and naturally deposited woody debris piles along barren cobble bars in riparian drainages (Hayes and Cross 1987, Rosenberg et al. 1994, Steel et al. 1999). Our results suggest that FWD piles in managed forests provide functions such as thermal cover (20% lower temp) for deer mice compared to surrounding bare ground. Piles also may function as communal nest sites (Wolff 1989, Verts and Carraway 1998) and provide protective cover, because we frequently observed mice escaping under piles after being released at capture sites.

Higher numbers of mice near FWD piles did not translate to differences in population densities or apparent survival among treatments potentially because the 7-month period between arranging FWD and sampling may have been too short to allow population responses. However, we do not believe this to be the case because small mammals respond rapidly to habitat perturbations (Tevis 1956, Sullivan 1979), and our posttreatment sampling encompassed the season of peak abundance for deer mice (Petticrew and Sadleir 1974, Sullivan 1979). Additionally, total volume of FWD, rather than its distribution (e.g., piles) may be a better indicator of habitat quality at the population level. However, initial volumes of FWD did not explain population responses after FWD was rearranged. Our results also may reflect a wide range of tolerance to habitat change and forest management, microhabitat associations in mice that do not translate to a

Table 2. Average change in biweekly densities (N) and apparent survival (Φ) of deer mice and western red-backed voles in response to 2 arrangements of fine woody debris (FWD) and an experimental control (pile burning) in thinned Douglas fir forests on the Applegate Adaptive Management Area, Jackson County, Oregon, USA, June–August 1999–2000.

Population parameter[a]	FWD arrangement	Deer mice		Western red-backed voles	
		$\bar{x}$	90% CI	$\bar{x}$	90% CI
ΔN	Lop and scatter	−0.53	−4.54 to 3.48	3.00	−8.12 to 14.12
	Pile	−1.07	−0.40 to −1.74	−2.47	−13.06 to 8.12
	Pile burning	0.53	−2.23 to 3.29	−0.8	−7.59 to 5.99
$\Delta\Phi$	Lop and scatter	−0.05	−0.37 to 0.28	0.30	−0.06 to 0.66
	Pile	0.03	−0.30 to 0.35	−0.03	−0.39 to 0.33
	Pile burning	−0.04	−0.36 to 0.28	−0.06	−0.42 to 0.30

[a] Based on mark–recapture models (Cormack 1964, Jolly 1965, Seber 1965, Otis et al. 1978).

population response, or a lack of power necessary to detect effects of our FWD arrangements (Wiens et al. 1986, Bowman et al. 2000).

Increased numbers of voles with increased distance from piles suggests that voles avoided piles. However, greater numbers of voles further from piles did not translate to greater numbers in plots where FWD was piled and may in part be attributed to lack of sufficient power to detect an effect. However, there was some evidence that lopped and scattered FWD may have increased apparent survival of voles, suggesting that the method proposed by Carey and Johnson (1995) and Tiedemann et al. (2000) to conserve organic material on the floor of managed forests may be important for voles. We suspect that the increase in apparent survival of voles in plots that contained the baseline treatment level may be due to an interaction between conditions on the forest floor that were created by thinning trees and the high amount of cover provided by the lopped and scattered FWD. Voles are most abundant in old-growth forests that provide large downed wood, cool temperatures, and shaded forest floors (Tevis 1956, Doyle 1987, Rosenberg et al. 1994), but these habitat components were not prevalent in the thinned forests we studied. Selective removal of trees opened the canopy and increased solar radiation to the forest floor environment, which may have degraded conditions preferred by voles and desiccated the vole's primary food source: belowground sporocarps of microrrhizal fungi (Gashwiler 1970, Maser et al. 1981, Ure and Maser 1982, Hayes et al. 1986, Mills 1995). We speculate that extent and depth of cover provided by lopped and scattered FWD were comparatively greater than what remained after FWD was piled or pile burned. Lopped and scattered FWD likely minimized desiccation of fungal sporocarps, thereby maintaining higher amounts of voles' primary food that could have sustained higher rates of apparent survival. Thus, further studies are needed to investigate small mammal responses to interactive effects of fuel reduction and thinning across a broad range of environmental conditions.

There are many ways FWD can be arranged beyond what we investigated, and future research should explore small mammal responses to alternative arrangements that meet the combined goals of reducing fire risk and conserving forest floor communities. Furthermore, size and decay class also may be important in linking small mammals with FWD, as it is with large downed wood (e.g., Thomas 1979, Doyle 1987, Tallmon and Mills 1994), and should be considered in future research.

MANAGEMENT IMPLICATIONS

Because mice and voles differed in their responses to specific FWD arrangements and pile burning, one method of reducing fire risk (e.g., pile burning) may not provide habitat conditions that are necessary to support the entire community of small mammal species. Deer mice numbers and habitat use can be predicted to some extent from presence and distribution of FWD piles, whereas apparent survival of western red-backed voles may be improved with lopped and scattered FWD relative to the other 2 arrangements. Thus, forest managers should consider applying a combination of these treatments, and other methods of reducing fire risk within forest stands to conserve biodiversity and maintain the prey base of sensitive species, such as the northern pygmy owl (*Glaucidium gnoma*; Holt and Petersen 2000) and northern spotted owl (*Strix occidentalis caurina*; Thomas et al. 1990, Lujan et al. 1992, Carey and Johnson 1995).

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