SMALL MAMMALS AND FOREST MANAGEMENT IN NORTHERN CALIFORNIA

By

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ABSTRACT

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Limited information exists on small mammals in industrial forests of northern California, USA. My thesis focuses on patch-level and fine-scale habitat elements that influence small mammal communities in industrial forests of northern California. I trapped 11 small mammal species during the summers of 2011-2013 and collected count data on a subset of those species. In Chapter 1, I analyzed small mammal populations in 4 forest types (recent clearcuts (3-5 years old), 10-20 year-old plantations, rotation-aged stands (60-80 years old), and Watercourse and Lake Protection Zones) commonly found in industrial forests. I used generalized linear mixed models (GLMM) to assess patch-level (~6.35 ha) relationships between small mammal counts and commonly found forest types, and downed wood volume. Land cover composition of areas surrounding trapping webs was more influential on small mammal counts than was the forest type that contained the trapping array. Downed wood volume was positively correlated to small mammal abundance. In Chapter 2, I examined small mammal counts in relation to fine-scale (64 m^2) habitat elements surrounding trap locations. I used GLMMs and found that shrub and downed wood cover were positively correlated with the number of individual small mammals captured; this relationship held across multiple taxon and trap types. This study is one of the first to be conducted on the small mammal community in industrial forests of northern California. Results of this research provide insight on small mammal populations in industrial forests and can inform timber management practices.

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INTRODUCTION

The Klamath Mountain region of southern Oregon and northern California is considered a biodiversity hot spot (Whitaker 1960; Wagner 1997; DellaSala et al. 1999). Currently, a majority of land cover change in this region is attributed to timber harvest (Parks et al. 2005); ~25% of timberlands in California are owned by the timber industry (Laaksonen-Craig et al. 2003). Given the substantial presence of industrial forest management in California and growing public demand for ecologically sound forest management, conservation of wildlife has increasingly influenced forest practices. Some members of the forest products industry have taken a proactive approach in conducting research and adapting forest management to balance economic viability with conservation goals. This is exceedingly important in California where the timber industry is a polarizing entity, however, incorporating conservation goals and adapting forest management can improve public standing and relationships with stakeholders.

Small mammals are commonly studied in the Pacific Northwest (PNW), however, targeted habitat management for small mammals on industrial forests primarily occurs when a small mammal species is legislatively protected, a predator is protected that preys on small mammals, or to mitigate small mammal impacts on forest regeneration. Small mammals are considered important components of forest ecosystems by serving as prey and thereby influencing the distribution and habitat use of predatory species (Carey et al. 1992). In the Klamath Mountains, several protected predators of small mammals occur on industrial forests, including northern spotted owl (*Strix occidentalis*) and Pacific fisher (*Martes pennant pacifica*). In addition, small mammals provide benefits to forest ecosystems. For instance, small mammals can regulate invertebrate populations (Buckner 1966; Carey and Johnson 1995; Elkinton et al.

1996; Carey and Harrington 2001), disperse fungal spores (Maser et al. 1978), and serve as indicators of habitat suitability in managed forests (Carey and Harrington 2001; Pearce and Venier 2005). Although research on small mammals and forest management is abundant, small mammal response to timber harvest often varies by species and geographic region. Currently, small mammal research in the northern California portion of the Klamath Mountains is limited.

Given the importance of small mammals to forested ecosystems and the prevalence of industrial forests in the PNW, understanding small mammal relationships in common forest types and habitat features in industrial forests can aid management. Data on small mammal response to timber harvest are variable and species-specific (Zwolak 2009) and often depend on specific timber harvest techniques, geographic location, and climate. Some studies suggest that small mammals respond positively to clearcutting (Kirkland 1990), while others propose that clearcutting negatively impacts biodiversity (Peterken 1996; Lust et al. 1998; Lindenmayer and Franklin 2002; Betts et al. 2005). In addition, research on small mammals has indicated the importance of retained habitat features, such as retention patches, downed wood, and riparian buffers (Cross 1985; Sullivan and Sullivan 2001; Lee 2012; Cockle and Richardson 2003; Smith and Maguire 2004).

The topic of this thesis is how small mammal communities are influenced by timber management practices in northern California. In Chapter 1, I explored patch-level (~6.35ha) relationships between small mammals and common forest types found on industrial forestlands. I also assessed stand-level responses of small mammals to downed wood volume. I used generalized linear mixed models (GLMM) to determine species-specific associations with surrounding forest types and downed wood volume. In Chapter 2, I used GLMMs to assess the influence of localized ($64m^2$) land cover designation and habitat features at trap locations on small mammals. Results of this study can inform future forest management and can facilitate the incorporation of forest practices that benefit small mammal communities.

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CHAPTER 1

LOCALIZED FACTORS CORRELATED WITH SMALL MAMMAL ABUNDANCES IN INDUSTRIAL FORESTS OF NORTHERN CALIFORNIA, USA

Abstract

Limited information exists on small mammal communities in industrial forests of northern California, USA. Small mammals are functionally important to ecosystems, so research on small mammals is needed to inform timber management. I documented small mammals that were susceptible to live-trapping in 4 forest classes commonly found throughout industrial forests of northern California. I evaluated how forest class, downed wood volume, and proximate forest classes influenced localized (~6.35 ha) abundances for the most commonly captured species. I trapped from May to August of 2011-2013 in 69 stands that represented: 1) recent clearcuts (3-5 years post-harvest), 2) 10-20 year-old conifer plantations, 3) rotation-aged conifer stands, and 4) Watercourse and Lake Protection Zones (WLPZs). I captured 11 small mammal species; 4 were captured in sufficient numbers from 2011-13 ($\geq$ 10 individuals) for regression modeling (*Peromyscus* spp., *Neotoma* spp., California ground squirrel (*Spermophilus beecheyi*), and Allen's chipmunk (*Tamias senex*)). Average abundance estimates across all forest classes were 4.66 (SE = 0.42), 0.28 (SE = 0.11), 1.13 (SE = 0.33), and 0.24 (SE = 0.10) individuals per web location (~0.75 ha) for *Peromyscus* spp., *Neotoma* spp., California ground squirrels, and Allen's chipmunks, respectively. The forest class containing the trap array was not an important variable for describing small mammal abundance. Rather, downed wood volume and the composition of proximate areas were more influential. My results indicate that retaining forest elements like downed wood and providing a small-scale mosaic of diverse forest types and age classes are

factors positively influencing small mammal abundances in industrial forests of northern California.

1.1. Introduction

In the Pacific Northwest of the United States (PNW) small mammals are known to influence the distribution and habitat use of predatory species (Carey et al. 1992), regulate invertebrate populations (Buckner 1966; Carey and Johnson 1995; Elkinton et al. 1996; Carey and Harrington 2001), disperse fungal spores (Maser et al. 1978), and serve as indicators of habitat suitability (Carey and Harrington 2001; Pearce and Venier 2005). Industrial forests are common throughout the PNW. For instance, corporate owners manage 14% of forestlands in California (Christensen et al. 2008). Although industrial forests are common in the PNW, they are rarely managed for small mammals unless the areas contain a protected small mammal species, protected predators that depend on small mammals, or small mammals that damage forest regeneration. For example, in the Klamath-Siskiyou Mountains of southern Oregon and northern California, several protected predators of small mammals occupy industrial forests including northern spotted owl (*Strix occidentalis caurina*), Pacific fisher (*Martes pennanti pacifica*), and Humboldt marten (*M. americana humboldtensis*). Given that land uses in the Klamath-Siskiyou Mountain region include timber harvest (Smith et al. 2004; Parks et al. 2005), management of industrial timberlands often occurs in conjunction with protected species conservation. Understanding the relationships between small mammal communities and vegetation characteristics provided by industrial forests can aid managers in providing the habitat conditions needed to support small mammals and their associated predators (Maser et al. 1978; Aubry et al. 1991; Carey and Johnson 1995; Williams et al. 2014).

Small mammal habitat is generally described based on food, cover, nesting (or denning), and microclimate requirements (Hallet et al. 2003). These vary among forest types, seral stages, soils, and management regimes (Hallet et al. 2003). Although some researchers have demonstrated that clearcutting (even-aged forest management) negatively impacts biodiversity by reducing horizontal and vertical structural diversity (Peterken 1996; Lust et al. 1998; Lindenmayer and Franklin 2002; Betts et al. 2005), Kirkland (1990) found a positive initial (≤ 6 years post clearcut) response by small mammals to clearcutting in temperate coniferous forests. Furthermore, varying species-specific responses were observed among small mammals between conventional clearcuts and unmanaged forests, with generalist species colonizing shortly after clearcutting (Sullivan et al. 2012). Species richness was found to be higher in young pine (17 yrs) and seed-tree (17-18 yrs) age classes than in older growth (70-133 yrs; Sullivan et al. 2000). As forests mature these differences may be lost. For example, in the Washington and Oregon Cascades and Coast Ranges few differences in small mammal community structure and composition were detected between young (35-79 yrs), mature (80-195 yrs), and old growth forests (200-730 yrs; Aubry et al. 1991).

In industrial forests, managers can manipulate several fine-scale features known to benefit small mammals. Downed wood is an important habitat component for several small mammals because it is used for reproduction, foraging, resting, and thermal cover (Maser et al. 1978; Amaranthus et al. 1994; Carey and Johnson 1995; McComb 2003). Downed wood, also called coarse woody debris, is defined as fallen trees or branches (Keddy and Drummond 1996). In western Washington State, Lee (2004) found that sites with higher amounts of downed wood resulted in significantly higher populations and greater population stability in deer mice (*Peromyscus maniculatus*) than sites with lower amounts of downed wood. In the central Oregon

Coast Range, small mammal survival was positively linked to the downed wood volume at the individual home range (Manning and Edge 2004). Differences in small mammal community composition, structure, and abundances between young (44-67 yrs) and old-growth (300-400 yrs) stands in the Olympic Peninsula of Washington were attributed to the reduced amount of localized downed wood found in young, managed stands (Carey and Johnson 1995). Management of downed wood can potentially mitigate the impacts of timber harvest on small mammals.

Riparian zones also influence small mammal communities in managed forest landscapes. Small mammal species richness and abundance are generally greater in riparian zones than in upland areas (southwest Oregon, Cross 1985; Cascade Range of Oregon, Doyle 1990). Alternatively, a study in the boreal mixed wood of Alberta, Canada found that small mammal assemblages did not respond to timber harvest and riparian buffer width (Hannon et al. 2002). The influence of riparian buffer zones on small mammal communities likely relates to the aridity of the larger landscape and the habitat matrix, which potentially explains these conflicting results among studies.

Although extensive research has been conducted on small mammal communities of the PNW, limited information exists on small mammals within the northern California portion of the Klamath Mountains. I used a combination of live trapping and modeling to explore relationships between small mammal communities and forest conditions that result from intensive management at the local-level (~6.35 ha). Specifically, I: 1) documented the small mammal communities that were susceptible to live-trapping in 4 forest classes that commonly occur in industrial forests, and 2) evaluated how downed wood and proximate forest classes influenced localized abundances for the most commonly captured species. Results of this study provide insight into the factors that influence small mammal occurrence and abundance in industrial forests.

1.2. Methods

1.2.1. *Study Area*

This study was conducted in the Klamath Mountain ecoregion of northern California (Trinity County, 8,309 km^2), USA. This landscape features heterogeneous and intricate vegetation patterns partially resulting from diverse climate, topography, and parent materials (Sawyer et al. 1977). Soil moisture regimes are xeric with soil temperatures varying from mesic to frigid and some cryic at higher elevations (Miles and Goudey 1997). The climate is considered Mediterranean, with hot and dry summers (Skinner et al. 2006). Average maximum daily temperatures from May through August range from 25 to 34°C and average precipitation ranges from 3.4 to 0.5 cm. The coolest and wettest month is May and the hottest (August) and driest (July) months occur toward the end of summer (Weaverville Ranger Station, US Forest Service, Trinity County).

Land use is predominately forestry, agriculture, tourism, and mining, with 83% of the land within the ecoregion (47,791 km^2) federally owned (Sleeter and Calzia 2008). Historically, fire was the primary disturbance in this region that shaped current forest structure (Mohr et al. 2000). Vegetation in this region is broadly classified as Douglas-fir (*Pseudotsuga menziesii)* – Ponderosa pine (*Pinus ponderosa*; Miles and Goudey 1997), with the industrial forests managed for Douglas-fir, incense cedar (*Calocedrus decurrens*), ponderosa pine, and secondarily supporting diverse hardwoods including canyon live oak (*Quercus chrysolepis*), black oak (*Q. kelloggii*), and madrone (*Arbutus menziesii*).

I conducted this project on timberlands owned and managed by Sierra Pacific Industries

(SPI). My replicates were stands, where a stand refers to a relatively homogeneous forest patch harvested at approximately the same time. The dominant silviculture regime is small-scale (<8 ha) clearcutting followed by site preparation that includes various combinations of chemical, mechanical, and fire treatments. Stands in this study were clearcut but contained a diversity of retained structures including riparian buffers (which are called Watercourse and Lake Protection Zones (WLPZ) in California regulatory parlance), retention patches, and occasional single, isolated leave trees. Harvested stands were later replanted (within 1 year of harvest) and monitored periodically for regeneration success. Stands used for trapping averaged approximately 7-8 ha and were located north and south of Weaverville, CA on elevations ranging from 679 to 1,467 m.

1.2.2. *Experimental Design*

I trapped from May to August of 2011-2013 in 69 stands that represented four common forest classes (Figure 1.1.): 1) recent clearcuts (3-5 years old; 17 stands), 2) 10-20 year-old plantations (16 stands), 3) rotation-aged stands (60-80 years old; 19 stands), and 4) Watercourse and Lake Protection Zones (WLPZ; 17 stands). I used a web-based trapping design with a combination of Sherman (Model LFA, 7.6 x 8.9 x 22.9 cm; H.B. Sherman Traps, Inc., Tallahassee, Florida) and Tomahawk (Model 202, 48.3 x 15.2 x 15.2 cm; Tomahawk Live Trap Co., Tomahawk, Wisconsin) live traps (Parmenter and McMahon 1989; Figure 1.2.). The web-based design was first described by Anderson et al. (1983) and has become a favorite design among small-mammal researchers (Bagne and Finch 2010) because it requires fewer assumptions and is more robust to smaller sample sizes (Parmenter and McMahon 1989, Parmenter et al. 2003).

During sampling, I placed a single trapping array in a stand. I trapped each array for 3 (2011) to 5 (2012-2013) nights, which constituted a trapping period. After each trapping period I moved the trapping arrays to the next set of replicate stands. When feasible, one stand of each forest class was trapped during a sampling period to account for population fluctuations. Each individual stand was trapped only once over the course of this study. A trapping array consisted of 5 spokes containing 7 nodes with nodes separated by 7 m. I placed a Sherman live trap at each node, resulting in 35 Sherman traps per web. At the web center and the 3rd and 7th nodes I also placed a Tomahawk live trap, resulting in 11 Tomahawk traps per web. I baited traps with a mixture of whole oats, raisins, creamy peanut butter, and molasses. Traps were set under or beside ground cover such as logs or heavy foliage and those at risk of exposure to direct sunlight were shaded. I also applied cotton batting to all traps. During the 2012-13 field season I also placed two remote sensing cameras in control and WLPZ stands to document other small mammal species potentially not susceptible to ground-based box or cage traps (e.g., northern flying squirrels (*Glaucomys sabrinus*)). Cameras were aimed at a bait mixture that was placed on tree stumps or downed logs within the limits of the array. I also attached several Tomahawk traps to trees at breast height to improve the likelihood of capturing flying squirrels (Risch and Brady 1996).

For stands containing riparian zones or leave patches, I placed arrays so that one or more spokes intersected the retention elements. Due to the limited size of many WLPZs, I centered the webs on the stream channel yet some spokes extended beyond the WLPZ and into adjacent areas. Generally, the vegetation characteristics found within a WLPZ extended beyond the regulatory boundaries of the WLPZ area.

Traps were checked daily between daybreak and noon. I individually marked small mammals to document movements within a trapping array and to ensure that individuals were not captured in more than a single array. Captured animals were marked with a 9-mm passive integrated transponder (PIT) tag injected via a 12-gauge needle subcutaneously in the flank. I used PIT tags instead of ear tags so that individuals could be identified during subsequent captures with minimal handling, to increase accuracy of individual identification, and to shorten animal handling time (Schooley et al. 1993; Morley 2002). Schooley et al. (1993) found no evidence that PIT tagging increased small mammal mortality.

During the 2013 field season I removed a small patch of hair from the back or flank of PIT-tagged *Peromyscus* spp. to document the rate of PIT tag loss in my study. If an animal was captured with a hair clip and without a PIT tag, I recorded the absence of the tag and re-marked the individual. After marking, animals were released on site for potential recapture. Animals that I seldom captured or those that were not conducive to tagging (e.g., shrews) were released without administering a PIT tag. Capture and handling of animals followed American Society of Mammalogists guidelines (Sikes et al. 2011), guidelines recommended by the California Department of Fish and Wildlife under scientific collection permit SC-11913, and was considered exempt via Michigan State University Institutional Animal Care and Use Committee.

1.2.3. *Vegetation Sampling*

In this study, I considered downed wood to be any piece of fallen wood that had a large end diameter that was >11.4 cm. I conducted line intercept (Canfield 1941) sampling for downed wood along the length of each web spoke. For each piece of wood (with a large-end diameter ≥11.4 cm) that intersected the line, I measured length, and large and small-end diameters. The location of the debris along the line was also noted in meters. I calculated the volume of downed wood per web area (~0.75 ha) based on the diameter and length measurements.

1.2.4. *Proximate Forest Classes*

Spatial data were analyzed using ArcGIS 10.1 (Environmental Systems Research Institute, Redlands, CA). Spatial layers including land ownership and forest class were obtained from SPI. Forest classes that occurred in areas surrounding trapping webs that were not part of SPI ownership were acquired through the continuously updated Classification and Assessment with Landsat of Visible Ecological Groupings (Calveg) layer (USDA Forest Service 1981). I used ArcGIS to delineate a circular 142.2 m buffer (~6.35 ha) around the center of each trapping array. I calculated the radius of the buffer based on the maximum straight-line distance moved (93.2 m) by any individual small mammal I recaptured in a web. This distance was then added to the length of a single web spoke (49 m) to represent the potential area used by small mammals during trapping. These buffers were intended to encompass the maximum distance that an animal could have traveled and still be captured within an array. In addition, the buffer area exceeded the estimated home ranges for small mammal species I captured (i.e., yellow-pine chipmunk (*Tamias amoenus*; a similar species to Allen's chipmunk) ~1.6 ha (Broadbooks 1970); dusky-footed woodrat (*Neotoma fuscipes*) ~0.23 ha (Cranford 1977); California ground squirrel (*Spermophilus beecheyi*) ~0.09 ha (Boellstorff and Owings 1995); and brush mouse (*Peromyscus boylii*) ~0.12 ha (Gottesman et al. 2004)). Within each 6.35 ha buffer, I calculated the proportional area of each forest class and used these as explanatory variables in our small mammal abundance models.

1.2.5. *Data Analysis*

I calculated summary statistics for downed wood volume and the proportions of different forest types within a 6.35 ha buffer of the trapping web by forest class. I used the maximum count of small mammals captured on any trap night for the 4 most commonly captured species by forest class to index abundance. I used generalized linear mixed models (GLMM) and a Poisson distribution in program *R* 3.0.2 to estimate the effects of independent covariates on small mammal abundance by species (R Development Core Team 2013). Independent covariates included the forest class containing the trapping grid, downed wood volume, the size of the stand that contained the trapping grid that was within the 6.35 ha buffer, and the proportions of forest classes surrounding the trapping web in the 6.35 ha area. I first conducted a Kruskal-Wallis rank sum test to determine if the forest class containing the trapping grid influenced small mammal counts (by species); a non-significant finding would indicate that this factor could be excluded from the GLMM. Using a Kendall tau rank correlation coefficient, I then generated a correlation matrix and identified those variable combinations that were correlated ($P < 0.05$). I included year as a random effect in species-specific abundance models to account for annual differences in small mammal populations or catchability. I used AICc to rank candidate models and deemed model parameters significant if the 95% confidence intervals did not overlap 0 (Burnham and Anderson 2002).

1.3. Results

1.3.1. *Vegetation and Proximate Forest Classes*

Within a trapping web in 2012 and 2013, I found that average volume of downed wood was highest in rotation-aged and WLPZ stands (Figure 1.3.). In 2011, the average volume of downed wood was highest in 10-20 yr stands (Figure 1.3.). More recently harvested stands (i.e., 3-5 and 10-20 years old) consistently had average downed wood volumes $\leq 0.5 m^3/0.75$ ha (Figure 1.3.). Generally, downed wood volumes were most variable in the older stands (i.e., rotation-aged and WLPZ) and in most instances, wood volumes were 3-15 times higher in the older compared to younger stands (Figure 1.3.).

The non-forest class around trapping webs was rare and hence was not included in my analyses (Figure 1.4.). Trapping webs located in 3-5 yr forest class were closer to more rotation-aged forest (average >40% of the 6.35 ha buffer) and, to a lesser extent, WLPZs (~>10%) compared to the other forest classes (Figure 1.4.a). The proportion of different forest classes around the 10-20 yr trapping webs was highly variable, with all forest classes represented (Figure 1.4.b). Rotation-aged trapping webs were generally surrounded by rotation-aged, and to a lesser extent (<30%) the other forest classes (Figure 1.4.c). Forest classes surrounding our WLPZ webs were highly variable, with all forest classes represented (Figure 1.4.d). Collectively these results indicate that the younger forest classes tended to occur in a matrix of rotation-aged forests, and that WLPZs were equally represented among my trapping webs.

1.3.2. *Small Mammals*

Over the 3 field seasons, 12,411 trap nights were accumulated (~86% of the maximum trap nights that could have occurred). Bears (*Ursus americanus*) and gray foxes (*Urocyon cinereoargenteus*) were most frequently responsible for disabling traps, as indicated by my remote cameras. I caught 11 species: white-footed deer mouse, brush mouse, California ground squirrel, Allen's chipmunk, dusky-footed woodrat, bushy-tailed woodrat (*N. cinerea*), Trowbridge's shrew (*Sorex trowbridgii*), Douglas squirrel (*Tamiasciurus douglasii*), striped skunk (*Mephitis mephitis*), western harvest mouse (*Reithrodontomys megalotis*), and California vole (*Microtus californicus*). The *Peromyscus* spp. were pooled for modeling because field crews could not reliably differentiate the species, particularly juveniles. I also pooled dusky-footed and bushy-tailed woodrats into *Neotoma* spp. because they are found in similar habitat (i.e., areas with abundant shrub cover; Carey 1991) and I only caught 5 bushy-tailed woodrats (~26% of *Neotoma* captures) during this study. Of the 11 captured species, 415 unique individuals were marked with a PIT tag, with *Peromyscus* spp. being the most frequently captured species (78% of all captures). My data on PIT tag retention during the 2013 field season indicated that 5 out of

113 (4.4%) individual *Peromyscus* spp. lost their tag.

Average maximum captures of *Peromyscus* spp. per stand were highest in the WLPZ class ($\bar{x}$ = 5.82, SE = 0.75), followed by 3-5 yr ($\bar{x}$ = 4.88, SE = 0.84), rotation-aged ($\bar{x}$ = 4.16, SE = 0.67), and 10-20 yr ($\bar{x}$ = 3.81, SE = 1.07), but none of these counts were significantly different among forest classes (χ^2 = 5.674, P = 0.129). The number of individual *Peromyscus* spp. among forest classes ranged from 0 (10-20 yr class in 2012) to 17 (10-20 yr class in 2013; Figure 1.5.a).

Generally, most California ground squirrels were captured in younger forest classes, although I also caught a low number in WLPZs (Figure 1.5.b). I marked 61 individual California ground squirrels in 2012 and 2013 and found an average of 2.42 (SE = 1.01) and 1.85 (SE = 1.15) individuals in 3-5 and 10-20 yr forest classes, respectively (Figure 1.5.b). This species was not marked in 2011. Counts did not differ among forest classes (χ^2 = 7.616, P = 0.055).

I marked 19 individual *Neotoma* spp. during the 2012 and 2013 field seasons (Figure 1.5.c) but none during 2011. *Neotoma* spp. were only captured in rotation-aged and WLPZ classes, with the exception of 1 individual that was caught in the 10-20 class (Figure 1.5.c). Wood rats were generally rare; on average 0.88 (SE = 0.40) per WLPZ stand. Counts did not differ among forest classes (χ^2 = 7.749, P = 0.051).

Allen's chipmunks were also rare with most caught in rotation-aged forests (Figure 1.5.d), but counts did not differ among forest classes (χ^2 = 2.594, P = 0.459). I caught 13 individual Allen's chipmunks during 2012 and 2013 (the only years I marked this species); this was the least frequently captured species that we analyzed. The number of individual Allen's chipmunks per forest class ranged from 0 to 5 (WLPZ; Figure 1.5.d).

High variability of counts for all commonly captured species within a forest type likely contributed to my finding that the forest type containing the trapping grid was not an important determinant of small mammal counts (Figure 1.5.). This result suggests that small mammal abundances were more likely influenced by within stand structures, the mosaic of forest classes found in proximity to my trapping webs, or some unmeasured environmental factor(s).

I tested 21 candidate GLMMs for the 4 commonly captured species (Table 1.1.). The top-ranking model for *Peromyscus* spp. included average downed wood volume per 0.75 ha ($ß_1$) and proportional area of the WLPZ forest class ($ß_2$; Table 1.2.). This model accounted for 57% of the evidence weight (Table 1.2.). Both parameters in the top-ranking model were significant ($ß_1$ = 0.20, 95% CI = 0.05, 0.34; $ß_2$ = 0.68, 95% CI = 0.05, 1.30). Counts of *Peromyscus* spp. increased nonlinearly as average downed wood volume and proportional WLPZ area increased (Figure 1.6.a,b).

I found a single, top-ranking model for California ground squirrel that accounted for 64% of the evidence weight (Table 1.2.). The top-ranking model included the proportion of 3-5 yr class within the 6.35 ha buffer ($ß_1$) and average downed wood volume ($ß_2$; Table 1.2.). Both parameters were significant ($ß_1$ = -2.60, 95% CI = -4.37, -1.15; $ß_2$ = -0.54, 95% CI = -1.08, -0.11), and indicated a slight decline in California ground squirrel counts as the proportion of 3-5 yr class and volume of downed wood increased, but the effect size for the 3-5 yr class parameter was negligible (Figures 1.7.a,b).

The top-ranking model for *Neotoma* spp. consisted of the proportion of WLPZ in the 6.35 ha area surrounding my trapping webs (Table 1.2.). The WLPZ parameter was significant ($ß_1$ = 4.21, 95% CI = 1.89, 6.74) and indicated that *Neotoma* counts increase as the amount of WLPZ increased (Figure 1.8.). I also identified a competing *Neotoma* spp. model (i.e., ΔAICc < 2.00) that included the proportional area of rotation-aged ($ß_1$) and WLPZ ($ß_2$) forest classes (Table 1.2.). The rotation-aged class parameter was not significant ($ß_1$ = 1.60, 95% CI = -0.55, 4.09) but the WLPZ parameter was significant ($ß_2 = 4.91$, 95% CI = 2.31, 7.95).

The top-ranking model for Allen's chipmunk included the proportional area of rotation-aged forest ($ß_1$), average downed wood volume ($ß_2$), and proportion of WLPZ ($ß_3$; Table 1.2.). All model parameters were significant ($ß_1 = -1.66$, 95% CI = -3.60, -0.35; $ß_2 = 6.52$, 95% CI = 2.79, 11.82; $ß_3 = 8.63$, 95% CI = 4.43, 14.50). Significant parameters in a competing model also included the proportion of rotation-aged forest class ($ß_1 = 7.06$, 95% CI = 3.35, 11.83), average downed wood volume ($ß_3 = -1.69$, 95% CI = -3.56, -0.44), and the proportional WLPZ area ($ß_4 = 7.17$, 95% CI = 2.94, 13.06). My data suggest that Allen's chipmunk counts are maximized when rotation-aged forests make up 50-75% of the 6.35 ha buffer surrounding a trap web (Figure 1.9.a), when wood volume is low (but this effect size is negligible, Figure 1.9.b), and when the amount of WLPZ in the 6.35 ha buffer increases (Figure 1.9.c).

1.4. Discussion

I captured 11 species of small mammals in industrial forests of northern California using Sherman and Tomahawk live traps. Small mammal species richness in this study was relatively low in comparison to other studies conducted in the PNW, although I am not aware of similar published studies from the Klamath Mountains of northern California. For example, Carey and Harrington (2001) found 18 species (using Sherman live traps) and Carey and Johnson (1995) found 13 species (using pitfall and snap traps) in the Olympic Peninsula, WA. Carey and Wilson (2001) documented 17 species in the Puget Trough, WA, and Wilk et al. (2010) documented 19 species in the Washington Coast Range using Sherman traps. Suzuki and Hayes (2003) documented 18 species in the Oregon Coast Range using pitfall and snap traps. Although comparison to other studies provides context for my results, I caution that species richness is a complex expression of historic and current land use, vegetation structure and composition, site productivity (Heaney 2001), climate, elevation (Rahbek 1995; but see Brown 2001), the regional species pool, and trapping techniques (Stephens and Anderson 2014). For example, other small mammal studies in the PNW have occurred in highly productive areas (e.g., Puget Trough, WA; Olympic Peninsula, WA) relative to the arid Klamath Mountains of northern California.

I found that the composition of localized areas surrounding trapping webs was more influential on small mammal counts than the forest type that contained the trapping array. *Peromyscus* spp. and *Neotoma* spp. were more often captured in areas with higher proportions of rotation-aged and WLPZ forests near the trapping webs. I captured *Neotoma* spp. primarily in riparian areas, consistent with other studies, likely due to higher amounts of understory cover (Sakai and Noon 1993; Innes et al. 2007; Hamm and Diller 2009). My findings for *Peromyscus* spp. contradict other research from the PNW. In general, *Peromyscus* spp. are positively associated with recently harvested forests (Tevis 1956; Gashwiler 1970; Sullivan 1979; Kirkland 1990; Fantz and Renken 2005; but see Anthony et al. (1987); Carey and Johnson (1995). I found *Peromyscus* spp. to more closely associate with downed wood and proximity to WLPZs. Similar to other studies conducted in the PNW, we most frequently captured *Peromyscus* spp. in our trapping webs (Anthony et al. 1987; Coppeto et al. 2006; Manning and Edge 2008; Sullivan et al. 2000, 2009).

Consistent with other studies from the PNW (Carey and Johnson 1995; Carey and Harrington 2001; Lee 2004), I found that downed wood volume was a significant habitat component that positively influenced captures of *Peromyscus* spp. Downed wood benefits small mammals by providing resting and thermal cover, and serves as a substrate for reproduction and foraging (Maser et al. 1978; Amaranthus et al. 1994; Carey and Johnson 1995; McComb 2003). Currently, California Forest Practice Rules (CAL FIRE 2014) in this region primarily focus on the reduction of fuel loads and pests in preparation for reforestation; therefore, retention of downed wood is not required. *Peromyscus* spp. in my study positively responded to downed wood when it exceeded 2 m^3 per 0.75 ha (or 2.7 m^3/ha), therefore, I recommend the retention of ≥9 logs with a length of 4.9 m, and 30 cm in diameter (0.3 m^3 of downed wood) per ha to be randomly distributed post-harvest. Retaining multiple logs of these dimensions is likely a more conducive downed wood treatment than the retention of a single large log or many smaller logs equivalent to 2.7 m^3. My results suggest that this volume of downed wood will result in more *Peromyscus* spp. in managed forests. Although *Peromyscus* spp. is a minor prey item for northern spotted owls in terms of biomass (Rosenberg et al. 2003; Forsman et al. 2004), it may serve as an important supplemental food source for northern spotted owls during the breeding season (Rosenberg et al. 2003). It is unknown how other protected predators like Pacific fisher use *Peromyscus* spp. in this region.

In contrast to the relationship I observed between downed wood and *Peromyscus* spp., captures of California ground squirrels and Allen's chipmunks slightly decreased as downed wood volume increased, but I caution that the effect sizes were minimal (Figures 1.5.b, 1.7.b). Ground squirrels tend to create burrows in open areas where there is minimal tree canopy and ground cover (Owings and Borchert 1975; Ordeñana et al. 2012), presumably to allow improved visibility for predator detection (Grinnell and Dixon 1918; Schooley et al. 1996). Hence, the negative relationship I found between California ground squirrel abundance and downed wood is consistent with their life history. In contrast, Tevis (1956) suggested that Townsend's chipmunks (*Neotamias townsendii*), a similar species to Allen's chipmunk, respond positively to downed logs and timber harvest, although specific data on this relationship are lacking. My findings on the influence of downed wood on California ground squirrels and Allen's chipmunks are based on low captures and effect sizes and thus require further evaluation.

Relative to other variables I measured, my results indicate that small mammal captures are not strongly influenced by the type of forest containing trapping webs in northern California. Rather, small mammal captures in this study were more likely influenced by structures within stands and the proximate forest classes. These results likely relate to the relatively small size of clearcuts in northern California, the practices of retaining habitat elements like downed wood and patches of live and dead trees within harvest units, and the protection of riparian zones consistent with California Forest Practice Rules. *Peromyscus* spp., *Neotoma* spp., and Allen's chipmunks responded positively to higher amounts of WLPZ in the localized buffer surrounding trapping webs. My results indicate that riparian corridors in industrial forest landscapes provide important habitat elements that encourage the persistence of *Peromyscus* spp., *Neotoma* spp. and Allen's chipmunks. In northern California and other drier portions of the PNW, *Neotoma* spp. and to a lesser extent *Peromyscus* spp. are recognized as prey for northern spotted owls (Ward et al. 1998; Forsman et al. 2004). Hence, in addition to protecting water quality in managed forest landscapes WLPZs also have a positive effect on prey for protected predator species. Other studies have similarly shown that riparian zones increase small mammal diversity (Cross 1985; Anthony et al. 1987).

Ground squirrels were frequently observed using burrows within 3-5 yr stands during my study. Gashwiler (1970) also observed California ground squirrels moving into and establishing a local population in a clearcut shortly after harvesting was complete. My modeling results suggesting that California ground squirrel counts are negatively related to the amount of 3-5 yr forest class in the surrounding area are surprising considering that the 3-5 yr forest class satisfied several habitat criteria that are thought to positively influence California ground squirrels (e.g., open area, good visibility; Grinnell and Dixon 1918; Schooley et al. 1996). Although the effect sizes were minimal, 3-5 yr stands generally had a sparse understory and hence may have provided minimal food for California ground squirrels causing them to locate burrows closer to older forest types. McGrann et al. (2013) found that California ground squirrel abundance was highest in areas adjacent to fruit and nut crops, suggesting that lands adjacent to burrows influenced space use. In addition, ground squirrels as a group generally benefit from human disturbance (Grinnell and Dixon 1918), potentially making industrial forests suitable for colonization.

Small mammals are essential components to forested ecosystems. Understanding how small mammals influence forest function and biodiversity are significant ecological issues that impact conservation (Hallet et al. 2003). For predators that prey on small mammals, conservation of food sources is critical to the maintenance and recovery of threatened populations. Industrial forests can support a diverse small mammal community if forest elements such as downed wood and riparian zones are retained (Gomez and Anthony 1998; Carey and Harrington 2001; Cockle and Richardson 2003; Manning and Edge 2004; Lee 2012). Small mammals are generally adaptable to landscape perturbations at smaller scales (Middleton and Merriam 1983; VanDruff and Rowse 1986), indicating that both habitat patches and the surrounding matrix are important to the movement and stability of small mammal populations in a heterogeneous landscape (Szacki and Liro 1991). It is likely that the diverse habitat mosaic commonly associated with forest practices in northern California creates a variety of habitats and corridors conducive to the small mammal species that I commonly captured.

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APPENDIX

Table 1. 1.

Candidate generalized linear mixed models used to estimate the number of individual *Peromyscus* spp., California ground squirrels, *Neotoma* spp., and Allen's chipmunks in industrial forests of northern California, USA, May-August of 2011-2013.

Candidate Models[a]	
1. Rotation + Stand Size + Volume +WLPZ	12. Volume + WLPZ
2. 10-20 + Stand Size + Volume	13. Rotation + Stand Size
3. Rotation + Stand Size + Volume	14. Rotation + WLPZ
4. Rotation + Stand Size + WLPZ	15. Rotation + Volume
5. Rotation + Volume + WLPZ	16. Stand Size
6. 3-5 + Volume + WLPZ	17. 3-5
7. 10-20 + Rotation	18. 10-20
8. Stand Size + Volume	19. Rotation
9. 10-20 + Volume	20. WLPZ
10. 3-5 + WLPZ	21. Volume
11. 3-5 + Volume	

[a] Proportions of forest class in 6.35 ha buffer around the trapping web where 3-5 = 3-5 yr class; 10-20 = 10-20 yr class; Rotation = rotation-aged class; and WLPZ= Watercourse and Lake Protection Zones. Stand Size= stand area (ha); Volume = average volume (m^3) of downed wood.

Table 1.2.

Five top-ranking generalized linear mixed models used to estimate maximum nightly captures for *Peromyscus* spp., California ground squirrel, *Neotoma* spp., and Allen's chipmunk in industrial forests of northern California, USA, May-August of 2011-2013. K[b] = the number of estimated model parameters, AICc = Akaike Information Criteria adjusted for small sample sizes, ΔAICc = difference in AIC from top-ranking model, and *w* = weight of evidence.

Species	Model[a]	K	AICc	ΔAICc	*w*
Peromyscus spp.	Volume + WLPZ	4	384.59	0.00	0.57
	Rotation + Volume + WLPZ	5	386.73	2.14	0.11
	Volume	3	386.84	2.24	0.10
	Rotation + Stand Size + Volume + WLPZ	6	386.85	2.26	0.10
	3-5 + Volume + WLPZ	5	386.86	2.27	0.10
California ground squirrel	3-5 + Volume	4	236.18	0.00	0.64
	3-5 + Volume + WLPZ	5	238.36	2.17	0.22
	3-5	3	240.22	4.04	0.08
	3-5 + WLPZ	4	241.41	5.22	0.05
	10-20	3	247.45	11.26	0.00
Neotoma spp.	WLPZ	3	93.28	0.00	0.29
	Rotation + WLPZ	4	93.53	0.26	0.26
	3-5 + WLPZ	4	95.32	2.04	0.11
	Volume + WLPZ	4	95.56	2.28	0.09
	Stand Size + Rotation + WLPZ	5	95.93	2.65	0.08

Table 1.2. (cont'd)

Species	Model[a]	K	AICc	ΔAICc	*w*
Allen's chipmunk	Rotation + Volume + WLPZ	5	57.99	0.00	0.47
	Rotation + Stand Size + Volume+ WLPZ	6	58.86	0.87	0.31
	3-5 + Volume + WLPZ	5	60.35	2.36	0.15
	Rotation + WLPZ	4	62.84	4.85	0.04
	Rotation + Stand Size + WLPZ	5	64.54	6.55	0.02

[a] Proportions of forest class in 6.35 ha buffer around the trapping web where 3-5 = 3-5 yr class; 10-20 = 10-20 yr class; Rotation = rotation-aged class; and WLPZ= Watercourse and Lake Protection Zones. Stand Size= stand area (ha); Volume= average volume (m^3) of downed wood.

[b] Intercept and random effect (year) included in all models.

Figure 1.1.

Four common forest classes in industrial forests of northern California, USA. Top left = recent clearcuts (3-5 years old), top right = 10-20 year-old plantations, bottom left = rotation-aged stands, bottom right = Watercourse and Lake Protections Zones (WLPZs).

Figure 1.2.

Small mammal trapping web design, northern California, USA, 2011-13.

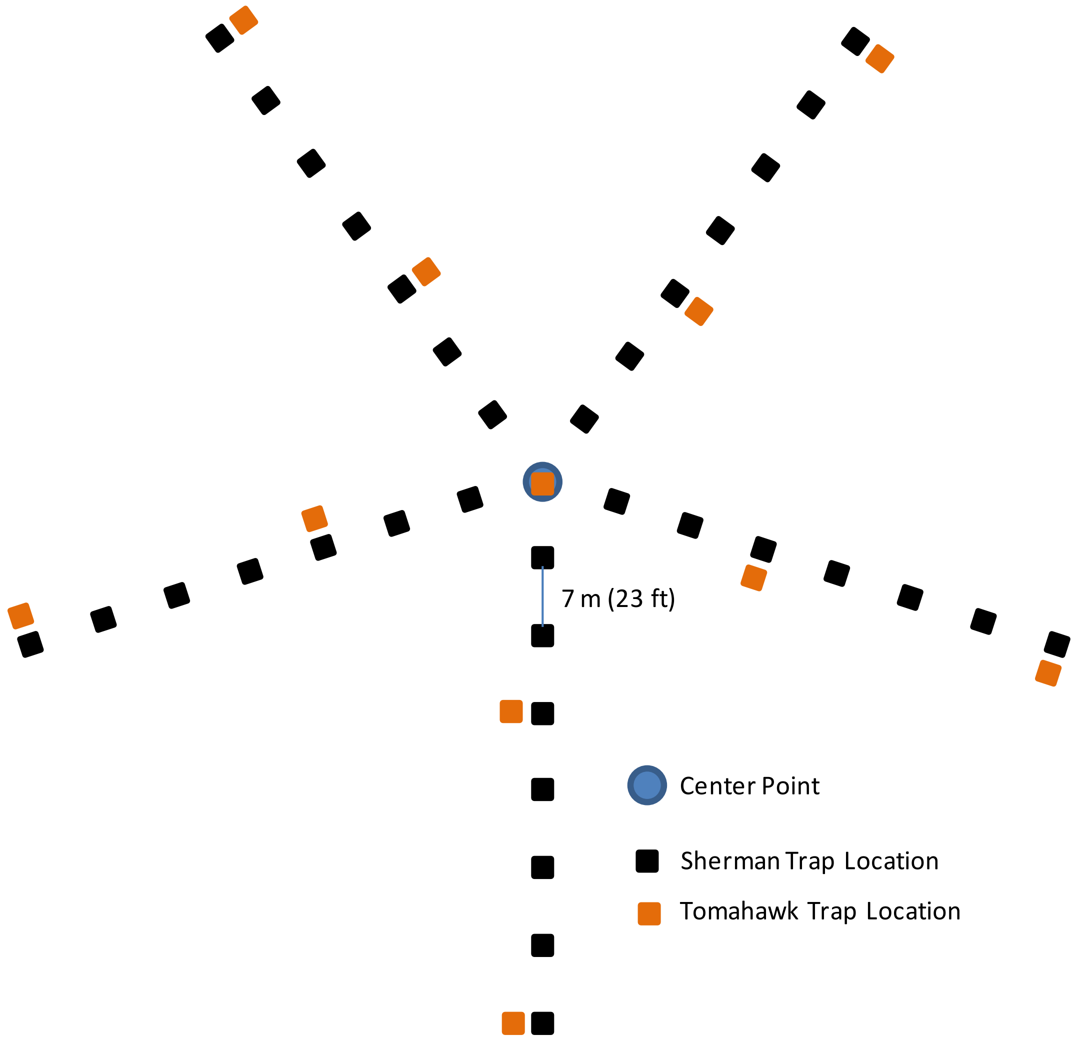


Figure 1.3.

Average volume (m^3) of downed wood per 0.75 ha by forest class and year in industrial forests of northern California, USA. Average (filled circle), median (solid horizontal bar), 75th data quartiles (shaded boxes), 95% confidence intervals (dashed lines), and extreme values (open circles) are shown.

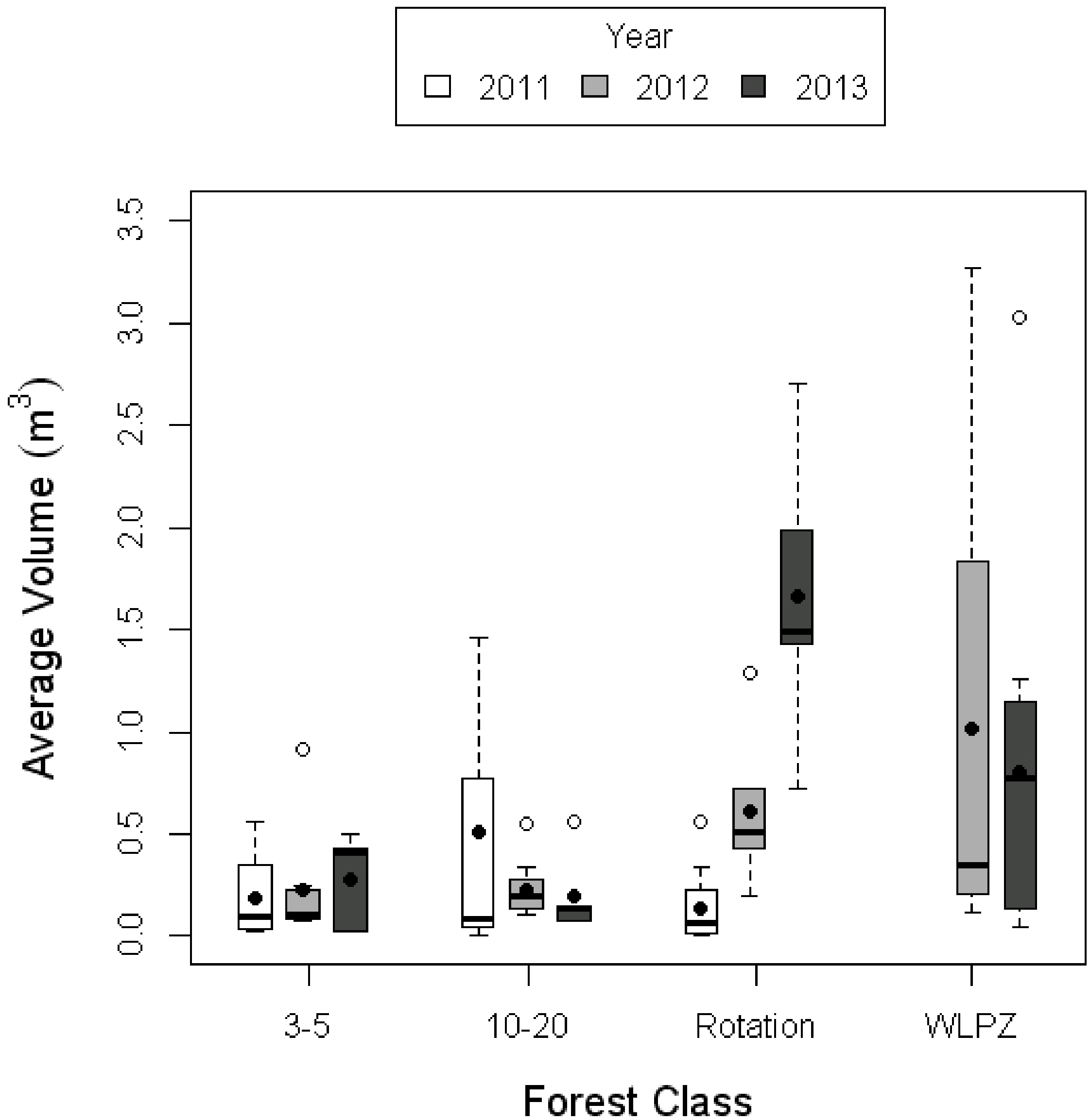


Figure 1.4.

Proportion of forest classes, by forest class containing the trapping webs and year, within a 6.35 ha buffer around small mammal trapping webs in industrial forests of northern California, USA. Average (filled circle), median (solid horizontal bar), 75th data quartiles (shaded boxes), 95% confidence intervals (dashed lines), and extreme values (open circles) are shown.

Figure 1.4. (cont'd)

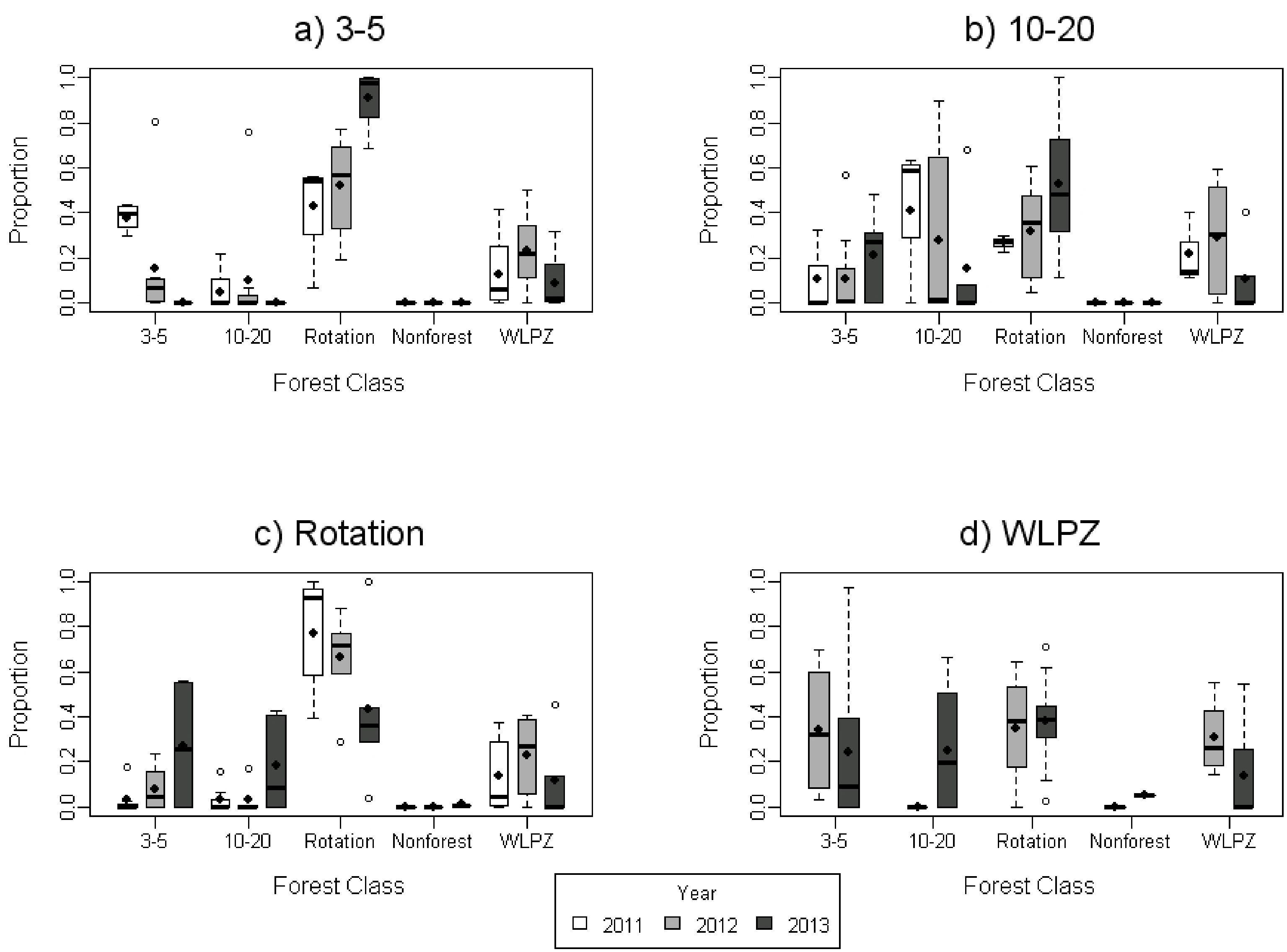


Figure 1.5.

Maximum nightly captures in forest classes containing trapping webs by small mammal species and year in industrial forests of northern California, USA.

Figure 1.5. (cont'd)

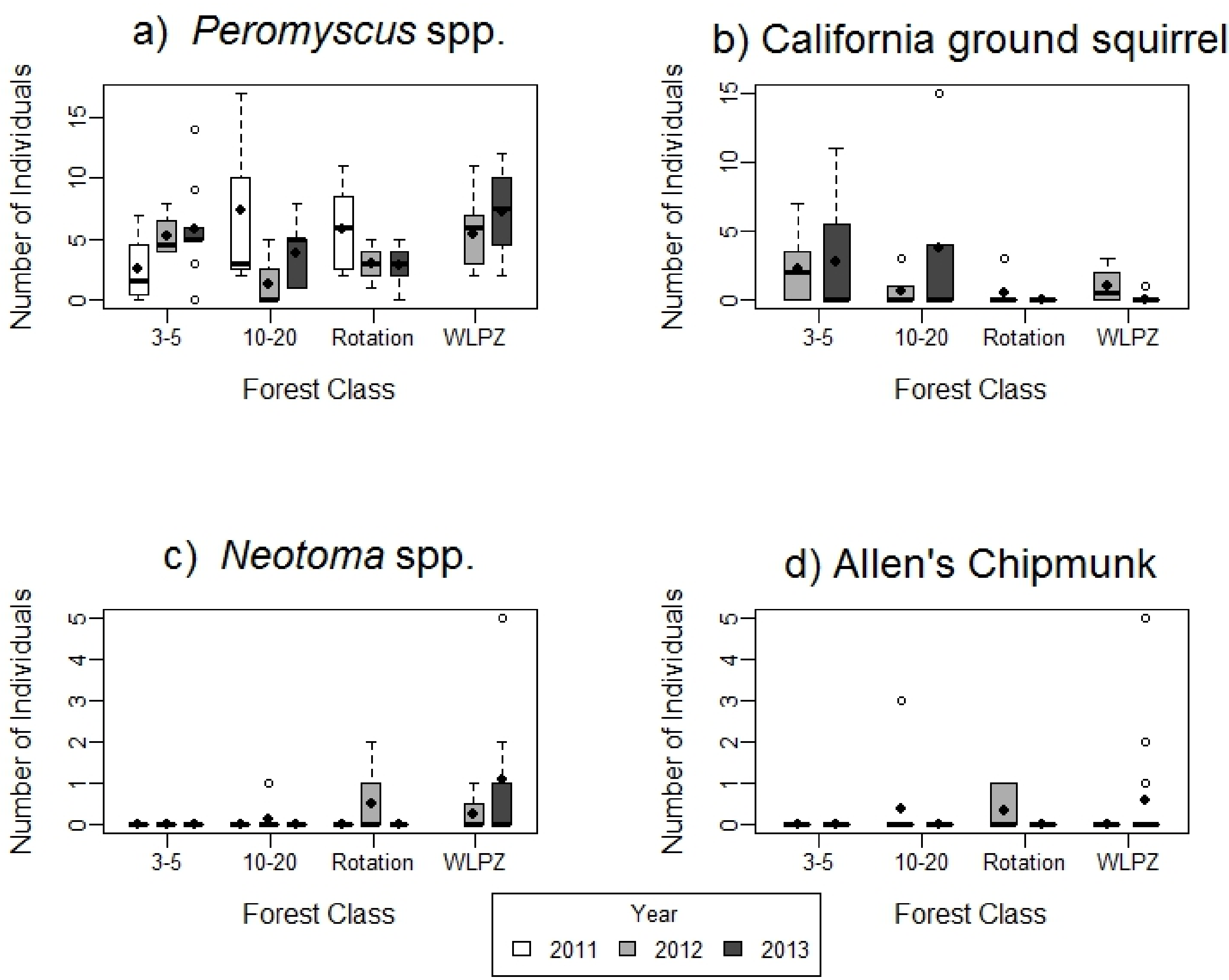


Figure 1.6.

Relationship of *Peromyscus* spp. counts to a) average volume (m^3) of downed wood per 0.75 ha and b) proportional area of WLPZ within 6.35 ha surrounding the trapping web in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

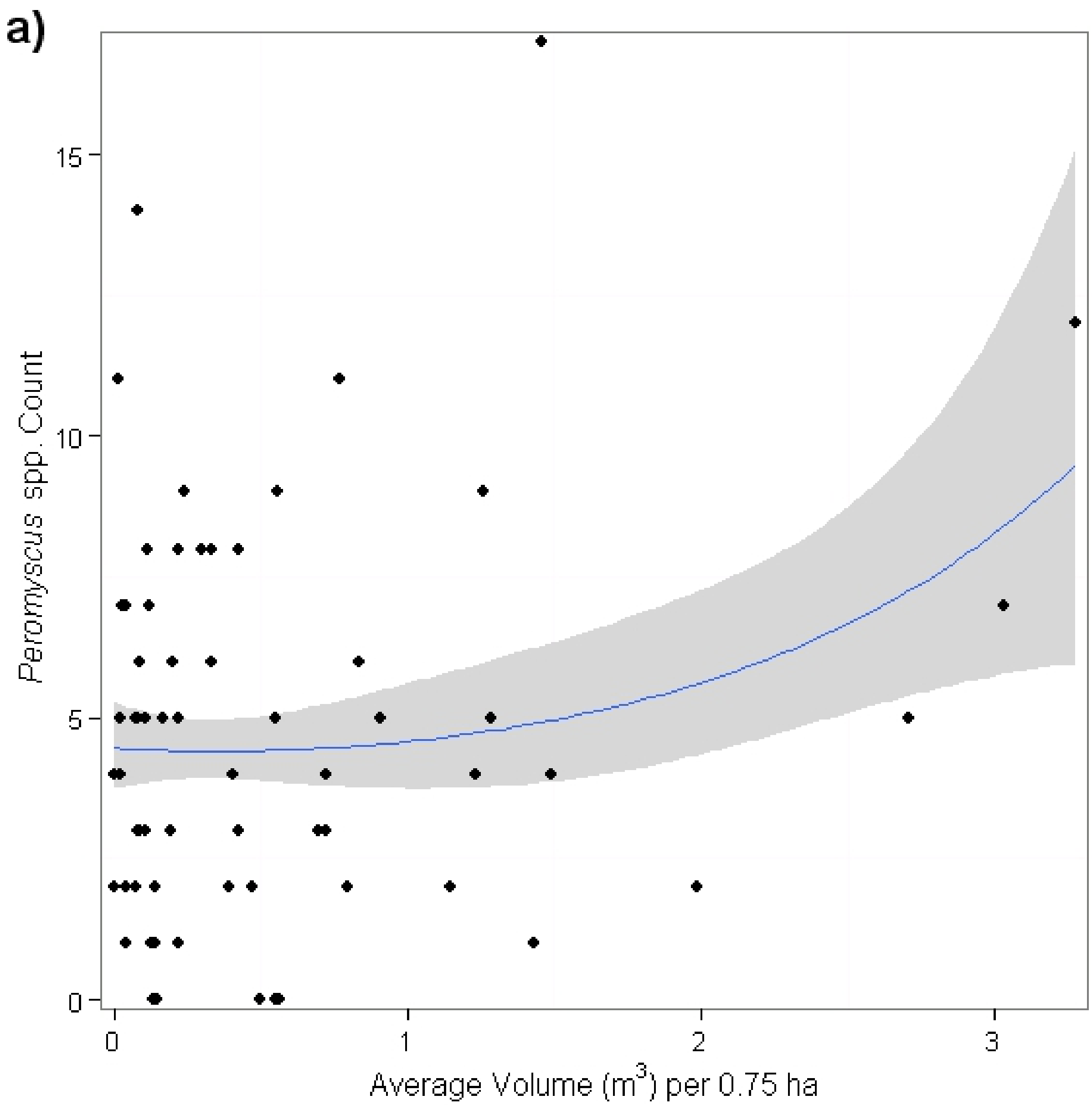


Figure 1.6. (cont'd)

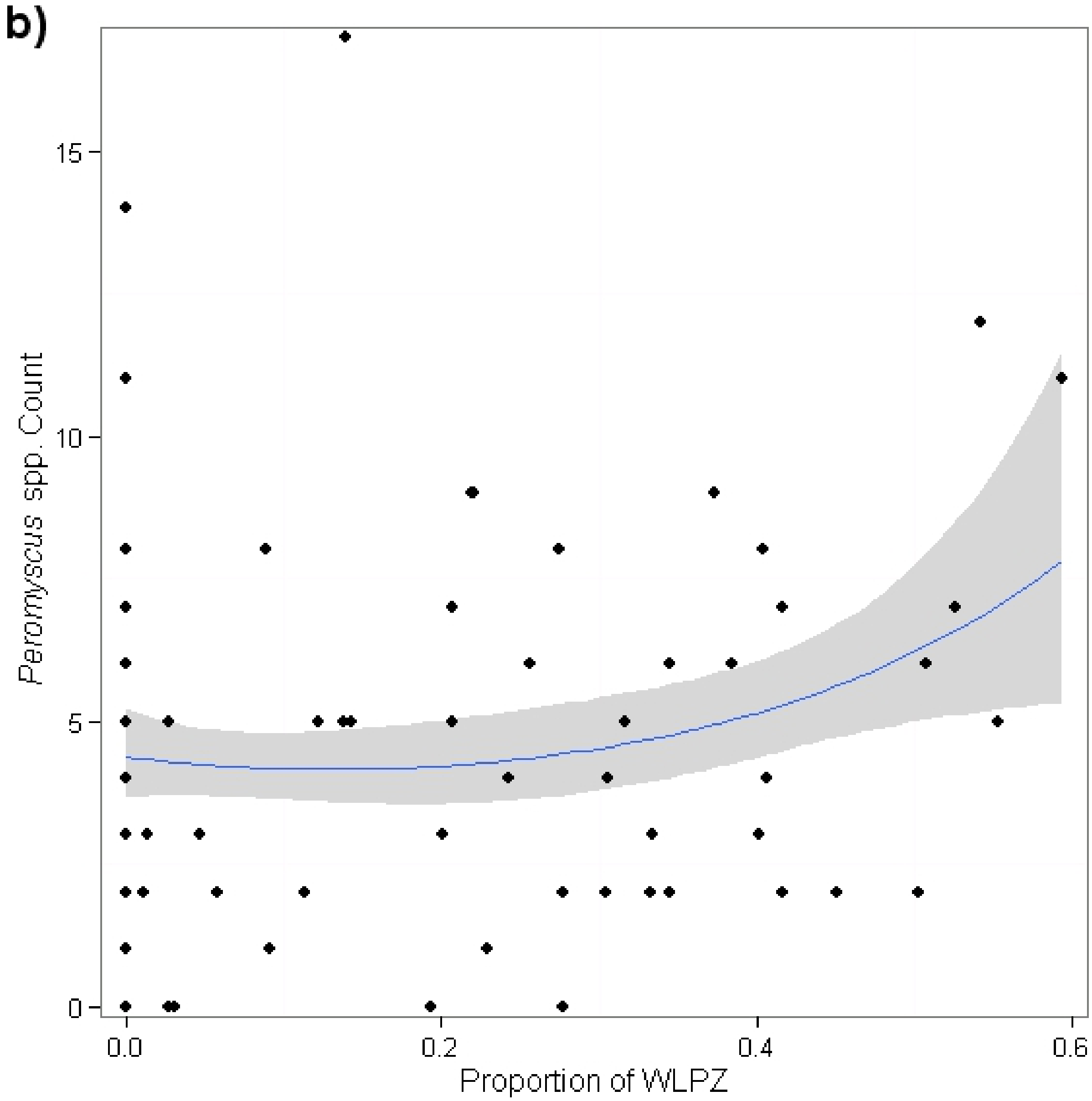


Figure 1.7.

Relationship of California ground squirrel counts to a) proportional area of 3-5 yr within 6.35 ha surrounding the trapping web and b) average volume (m^3) of downed wood per 0.75 ha in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

a)

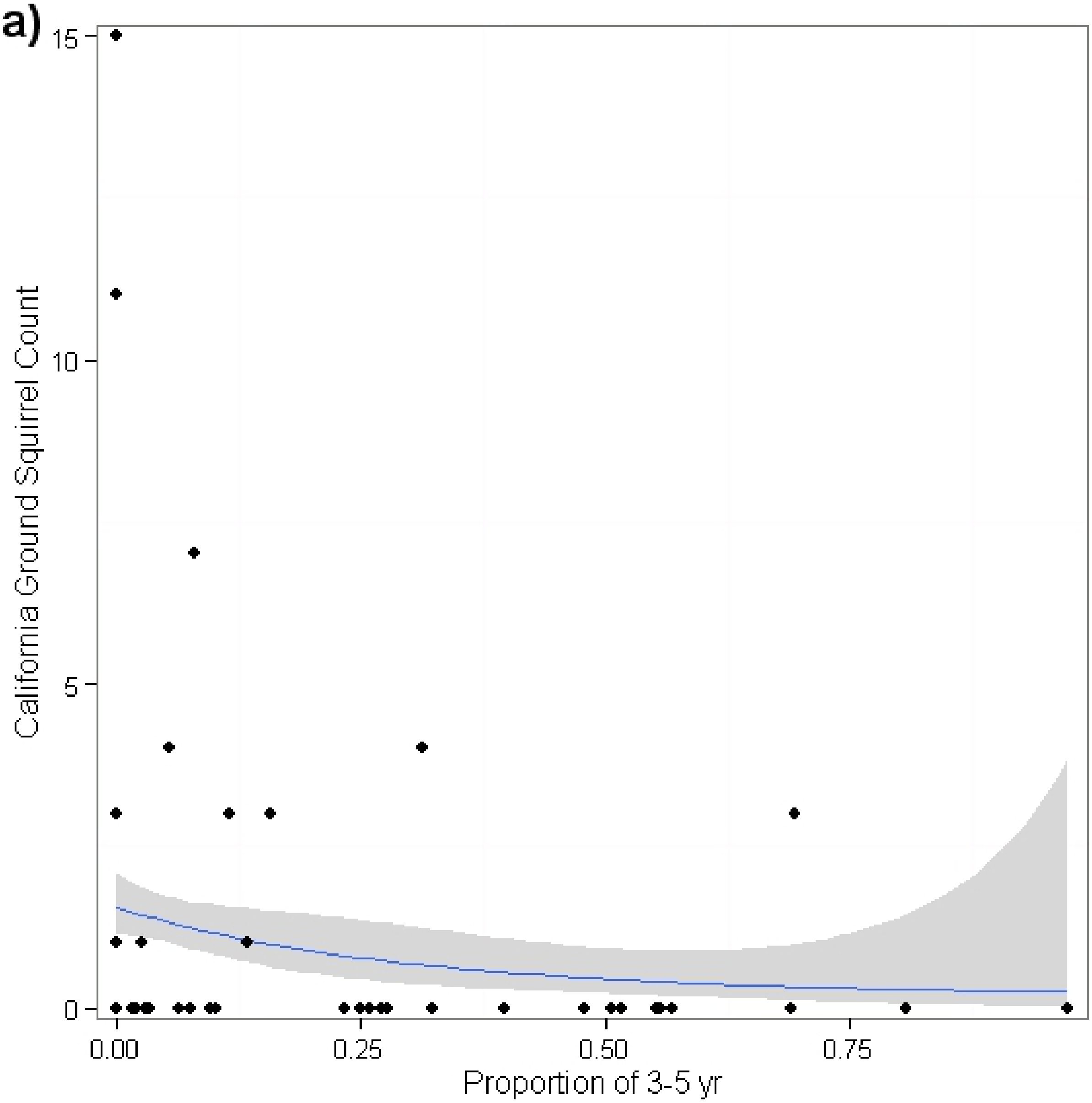


Figure 1.7. (cont'd)

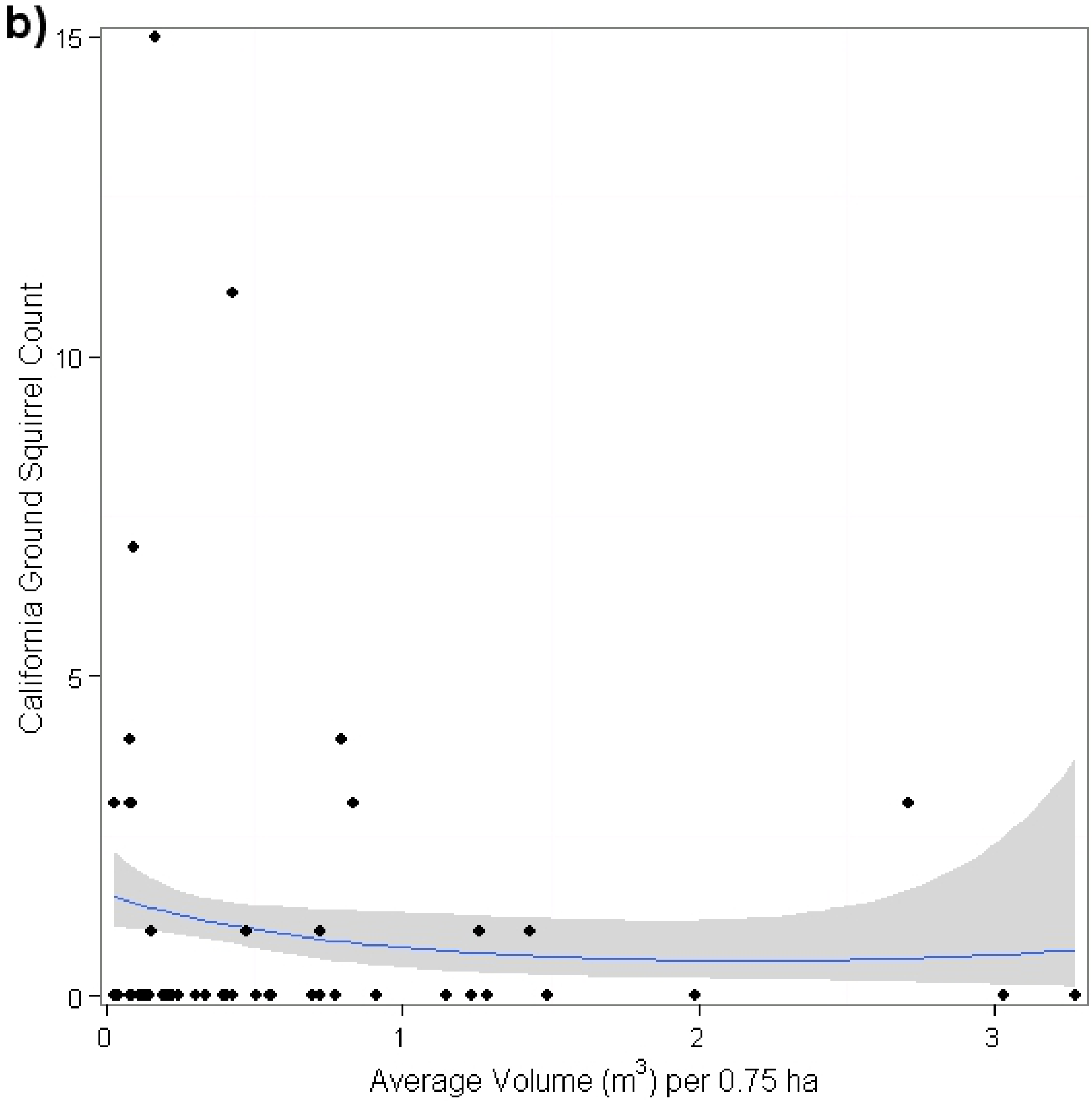


Figure 1.8.

Relationship of *Neotoma* spp. counts to proportional area of WLPZ within 6.35 ha surrounding the trapping web in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

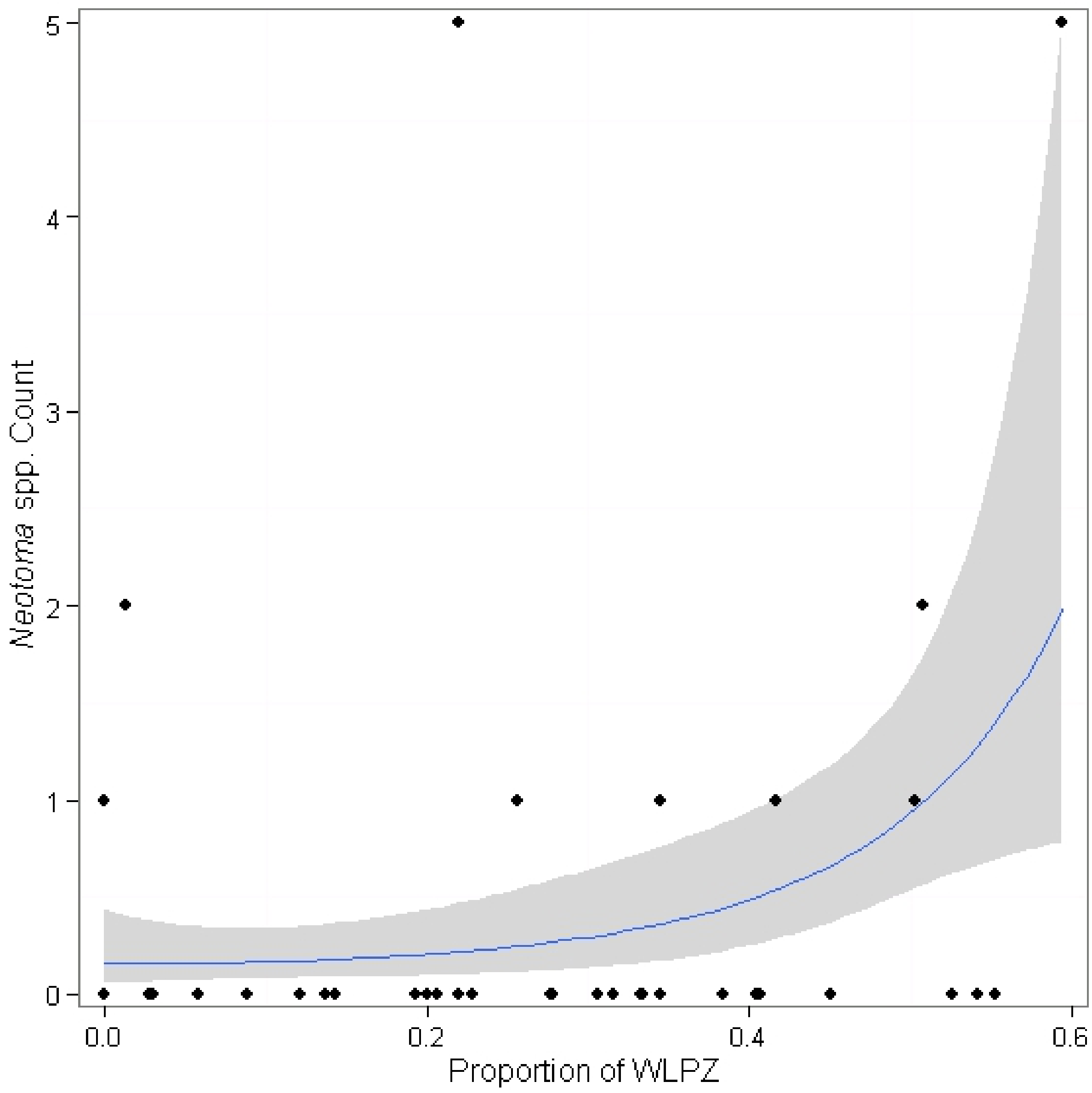


Figure 1.9.

Relationship of Allen's chipmunk counts to a) proportional area of rotation age forest class within 6.35 ha surrounding the trapping web, b) average volume (m^3) of downed wood per 0.75 ha and c) proportional area of WLPZ within 6.35 ha surrounding the trapping web in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

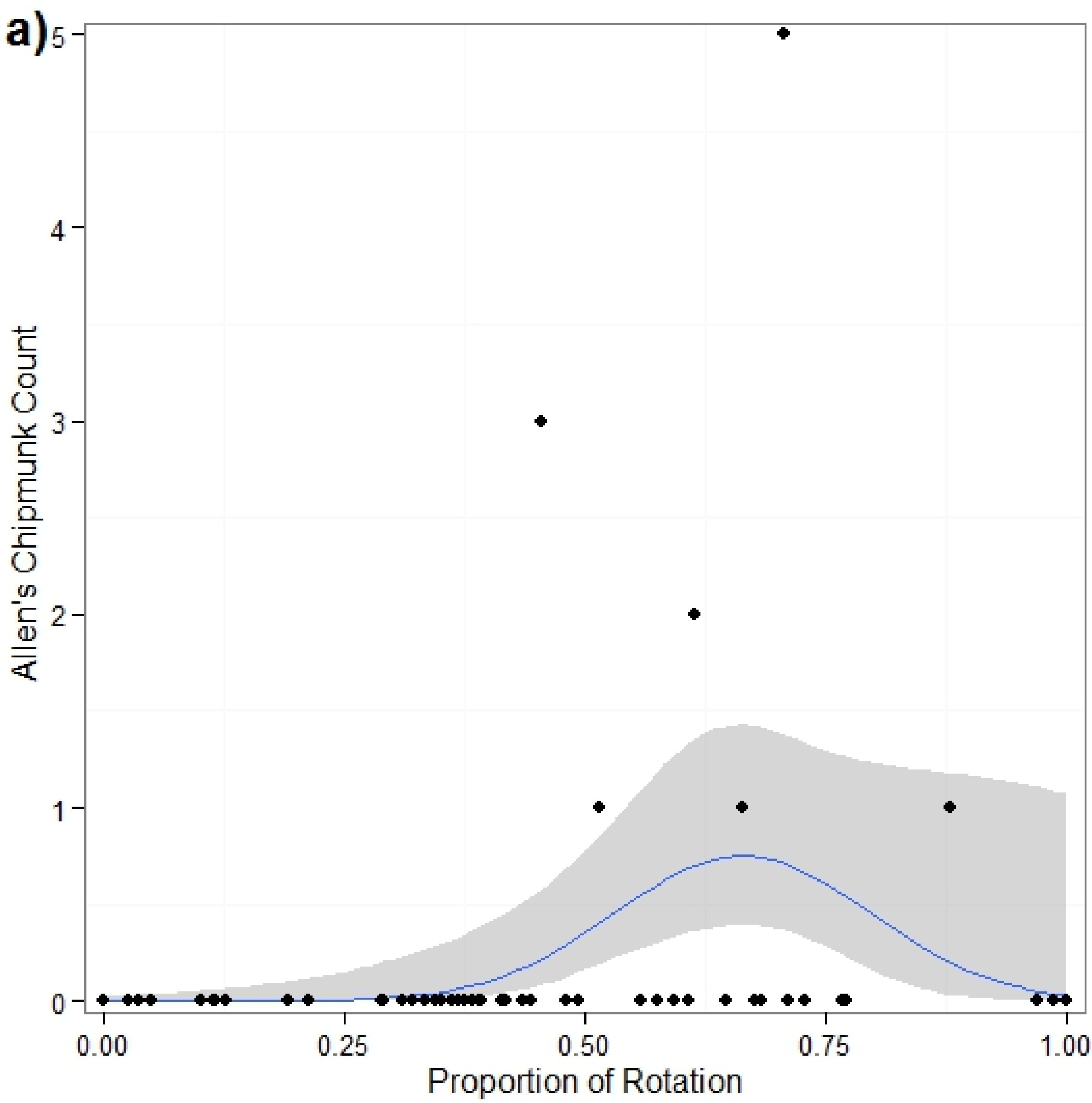


Figure 1.9. (cont'd)

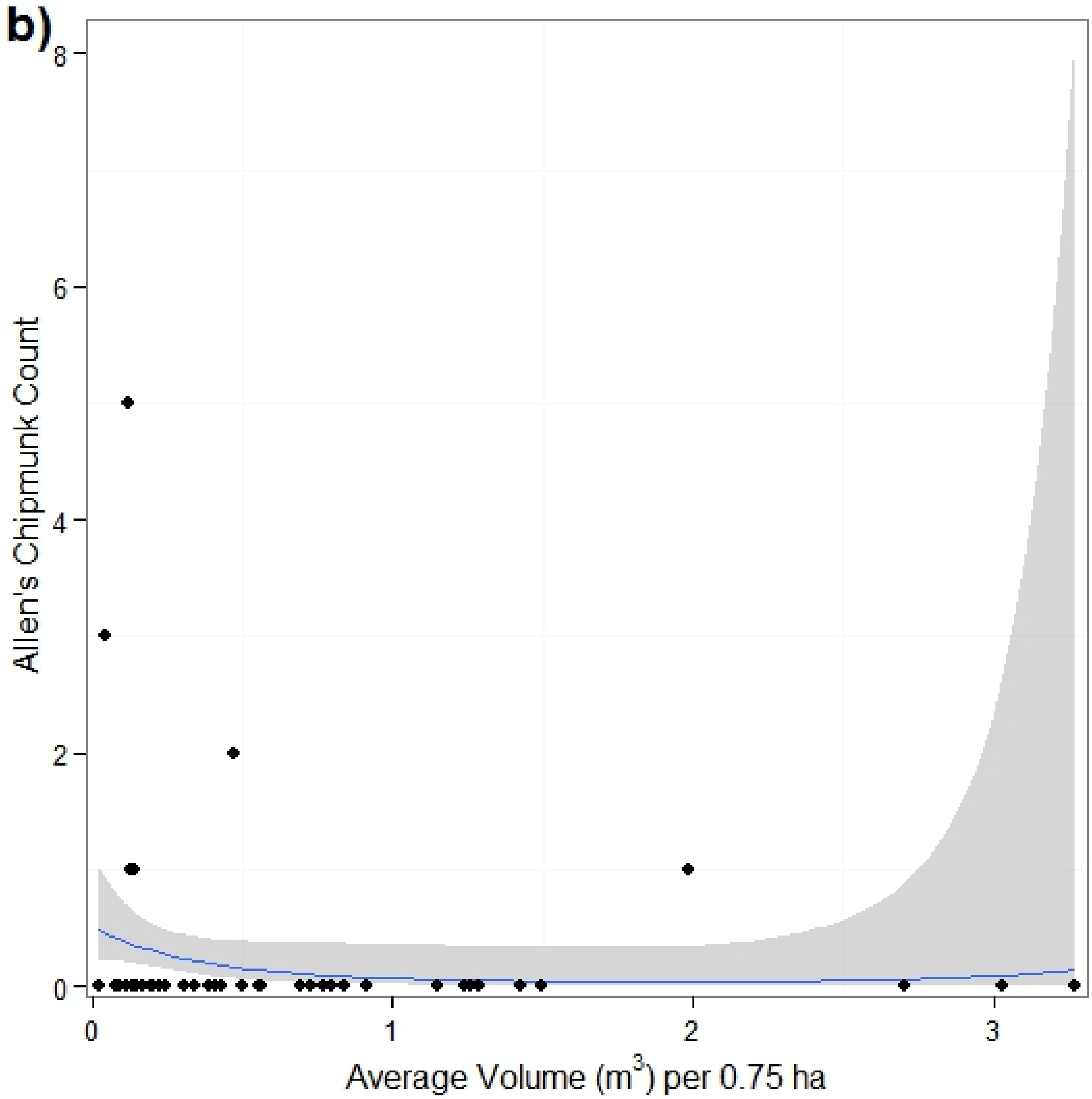
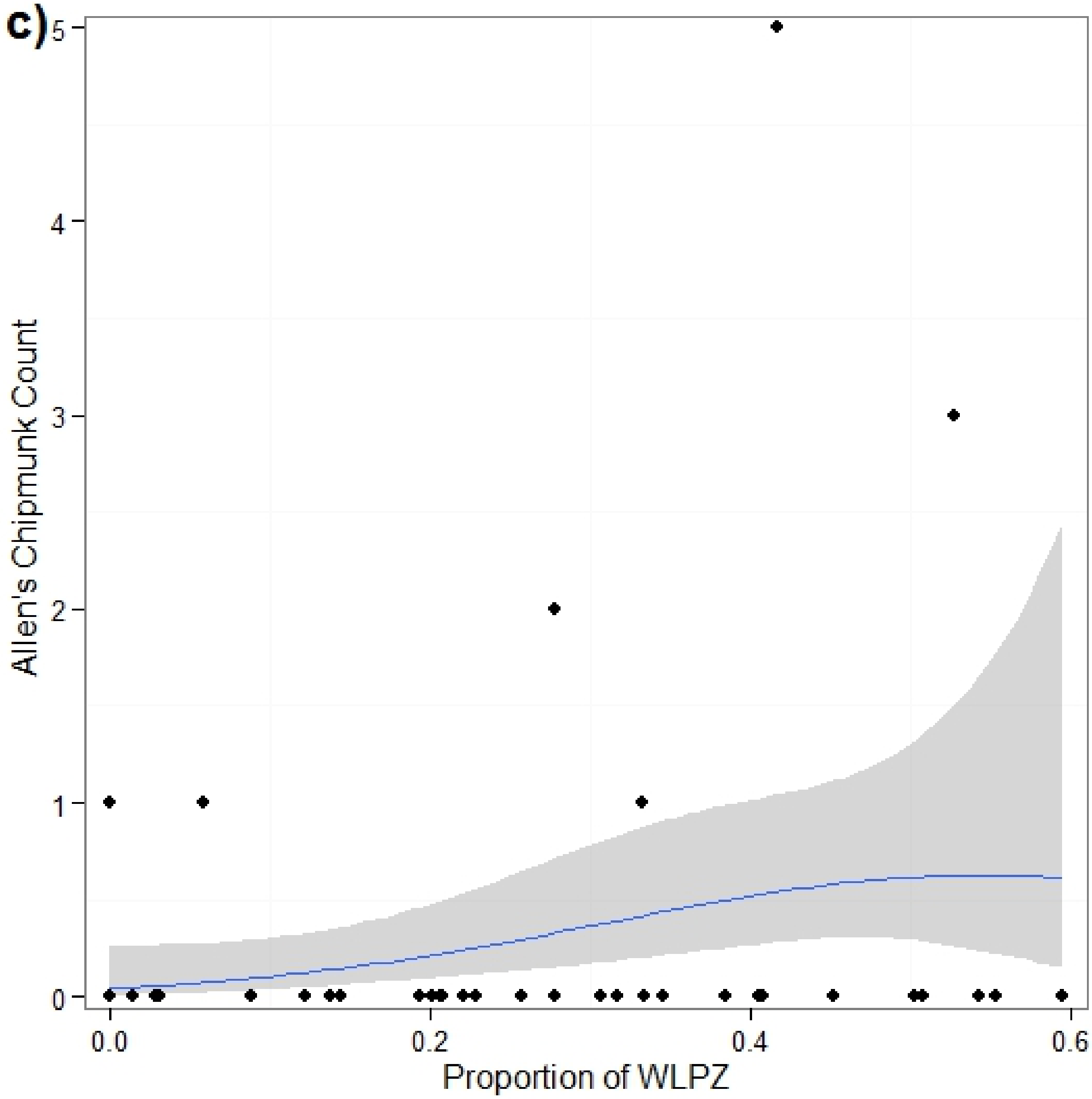


Figure 1.9. (cont'd)



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CHAPTER 2

FINE-SCALE VEGETATIVE COVER AND LAND COVER INFLUENCES ON SMALL MAMMAL USE IN INDUSTRIAL FORESTS OF NORTHERN CALIFORNIA, USA

Abstract

Limited information exists on small mammal communities in industrial forests of northern California, USA. Small mammal communities are important components of forest ecosystems and a better understanding of small mammal relationships to fine-scale habitat features in industrial forests can aid management. I developed overall and species-specific models to assess the relationships between small mammals and fine-scale ($64m^2$) habitat features (i.e., shrub, forb, grass, rock, mineral soil, forest litter, downed wood, and tree). I also assessed fine-scale land cover category (i.e., clearcut, retention, clearcut-riparian, control, or control-riparian zone). I trapped small mammals from May to August of 2011-2013 in 65 stands using a web based trapping design that consisted of both Sherman and Tomahawk live-traps. I captured 11 small mammal species with the most frequently captured species being *Peromyscus* spp. and California ground squirrels in Sherman and Tomahawk traps, respectively. Pooled small mammal captures in Sherman traps were positively influenced by shrub cover at trapping locations. This relationship was also observed in *Peromyscus* spp. and Allen's chipmunk. In addition, I found that I captured more *Peromyscus* spp and pooled small mammals when a trap was placed in retention areas than in clearcuts. In Tomahawk traps, pooled small mammal captures were positively influenced by both shrub cover and downed wood. I captured more California ground squirrels in clearcuts opposed to controls and found forest litter to negatively influence ground squirrel captures. My findings emphasize the importance of fine-scale habitat elements, primarily

downed wood, shrub cover, and retention patches on small mammal habitat use in industrial forests of northern California.

2.1. Introduction

Small mammal activity and occurrence influences numerous organisms and ecological processes in forest ecosystems. The distribution and habitat use of numerous predators can be directly linked to small mammals (Carey et al. 1992). For example, home ranges of Northern Spotted Owls (*Strix occidentalis caurina*) in southern Oregon were influenced by the abundance and diversity of medium-sized prey (e.g., flying squirrels (*Glaucomys sabrinus*) and woodrats (*Neotoma* spp.); Carey et al. 1992). Small mammals can also regulate invertebrate populations (Buckner 1966; Carey and Johnson 1995; Elkinton et al. 1996; Carey and Harrington 2001). Elkinton et al. (1996) found that white-footed mice (*Peromyscus leucopus*) effectively regulated low populations of gypsy moth (*Lymantria dispar*). Small mammals are also known seed dispersers. Maser et al. (1978) documented the importance of small mammals as dispersers of hypogeous fungal spores in the Pacific Northwest. Monitoring small mammal populations can reveal structural and functional changes within forest ecosystems (Carey and Harrington 2001; Pearce and Venier 2005).

Interest in the relationships between small mammal populations and intensive forest management has recently increased, and likely relates to the growing demand for comprehensive forest management that includes considerations for wildlife, water quality, and aesthetics. Studies on small mammals and forest management include the influence and utility of retention patches (Carey and Wilson 2001; Sullivan and Sullivan 2001; Sullivan et al. 2001;Gitzen et al. 2007), riparian zones (Anthony et al. 1987), downed wood (Carey and Johnson 1995, McComb 2003, Lee 2004, Manning and Edge 2008, Sullivan et al. 2012), and structure of the managed stand (Carey and Johnson 1995, Sullivan et al. 2000, Sullivan et al. 2009). The influence of fine-scale habitat elements like herbaceous or woody shrub cover, forest litter, small pieces of downed wood, or the amount of exposed mineral soil on small mammals is less understood.

Forest managers can manipulate several fine-scale features known to benefit small mammals. Occurrence of these fine scale habitat features are known to positively influence small mammal survival in moist environments like the Oregon Coast Range (Manning and Edge 2004). However these finer scale habitat features may be even more important to small mammals where moisture is limiting during certain times of the year, like in the drier coniferous forests that occur in some parts of the western United States. For example, understory cover was an important covariate on small mammal occupancy in dry ponderosa pine (*Pinus ponderosa*) forests of northern Arizona (Kalies et al. 2012). Similarly, shrub cover and downed wood were the most important habitat characteristics affecting small mammal densities in Arizona (Converse et al. 2006).

Some forest landowners are required or have voluntarily adopted retention strategies in timber harvest areas to supplement wildlife habitat. Retained green trees within timber harvest areas impact small mammal populations, though study results are variable. For example, Sullivan and Sullivan (2001) concluded that small mammal abundance and diversity in harvested conifer forests of British Columbia, Canada, were similar across varying levels of retention due to post-harvest colonization by generalists and early successional species. Gitzen et al. (2007) predicted that small mammal species associated with closed canopy forests would decrease, early successional species would increase, and habitat generalists would show little response to habitat retention in coniferous forests of western Oregon and Washington. Some species did not follow the expected response, leading Gitzen et al. (2007) to suggest that additional factors such as small mammal community composition, latitude, and elevation influenced the response of small mammals to green-tree retention. Green tree retention, particularly in patches, can correspond to unique fine-scale habitat features that are different from surrounding timber harvest areas (Linden and Roloff 2014).

The goal of my research was to explore how small mammals were influenced by fine-scale habitat features in dry industrial forests to better inform retention practices. My objective was to correlate the number of captured individual small mammals to fine-scale ($64m^2$) habitat elements surrounding trap locations. I also evaluated if land cover category (e.g., retention, riparian zone) at a trapping location influenced captures to determine if fine-scale habitat features corresponded to existing retention practices. I used a combination of live trapping, vegetation sampling, and generalized linear mixed models. My response variable for modeling was the number of uniquely captured individuals at a trap location; this metric represented an index to the number of animal home ranges overlapping a location. My findings provide insight into small mammal habitat use in relation to fine-scale features that can be purposefully managed in industrial forest landscapes of northern California.

2.2. Methods

2.2.1. *Study Area*

My study was conducted in the Klamath Mountain ecoregion of northern California (Trinity County, 8,309 km^2), USA. The landscape of this ecoregion features heterogeneous and intricate vegetation patterns partially resulting from diverse climate, topography, and parent materials (Sawyer et al. 1977). Soil moisture regimes are xeric with soil temperatures varying from mesic to frigid and some cryic at higher elevations (Miles and Goudey 1997). The climate is considered Mediterranean, with hot and dry summers (Skinner et al. 2006). Average maximum daily temperatures from May through August range from 25 to 34°C and average precipitation ranges from 3.4 to 0.5 cm. The coolest and wettest month is May, with the hottest (August) and driest (July) months toward the end of summer (Weaverville Ranger Station, US Forest Service, Trinity County).

Land use is predominately forestry, agriculture, tourism, and mining, with 83% of the land within the ecoregion (47,791 km^2) federally owned (Sleeter and Calzia 2008). Historically, fire was the primary disturbance in this region that shaped forest structure (Mohr et al. 2000). Current broad scale disturbances include occasional wild fires and industrial forest management. Vegetation in this region is broadly classified as Douglas-fir (*Pseudotsuga menziesii)* – Ponderosa pine (Miles and Goudey 1997), with the industrial forests managed for Douglas-fir, incense-cedar (*Calocedrus decurrens*), and ponderosa pine, and secondarily supporting diverse hardwoods including canyon live oak (*Quercus chrysolepis*), black oak (*Q. kelloggii*), and madrone (*Arbutus menziesii*).

I conducted this project on timberlands owned and managed by Sierra Pacific Industries (SPI). The dominant silviculture regime is small-scale (<8 ha) clearcutting followed by site preparation that includes various combinations of chemical, mechanical, and fire treatments. Stands in this study were clearcut but contained a diversity of retained structures including riparian buffers (which are called Watercourse and Lake Protection Zones (WLPZ) in California regulatory parlance), retention patches, and occasional single, isolated leave trees. Harvested stands were later replanted (within 1 year of harvest) and monitored periodically for regeneration success. Stands used for trapping averaged approximately 7-8 ha and were located north and south of Weaverville, CA on elevations ranging from 679 to 1,467 m.

2.2.2. *Experimental Design*

I trapped from May to August of 2011-2013 in 65 stands that represented four broadly defined forest classes (Figure 2.1.): 1) recent clearcuts (3-5 years old; 15 stands), 2) 10-20 year-old plantations (16 stands), 3) rotation-aged stands (60-80 years old; 16 stands), and 4) Watercourse and Lake Protection Zones (WLPZ; 18 stands). I used a web-based trapping design with a combination of Sherman (Model LFA, 7.6 x 8.9 x 22.9 cm; H.B. Sherman Traps, Inc., Tallahassee, Florida) and Tomahawk (Model 202, 48.3 x 15.2 x 15.2 cm; Tomahawk Live Trap Co., Tomahawk, Wisconsin) live traps (Parmenter and McMahon 1989; Figure 2.2.). The web-based design was first described by Anderson et al. (1983) and has become a favorite design among small-mammal researchers because it requires fewer assumptions and is more robust to smaller sample sizes (Parmenter and McMahon 1989, Parmenter et al. 2003, Bagne and Finch 2010).

During trapping, I placed a single array in a stand. I trapped each array for 3 (2011) to 5 (2012-2013) nights, which constituted a trapping period. After each trapping period I moved the trapping arrays to the next set of replicate stands. When feasible, one stand of each forest class was trapped during a sampling period to account for broad-scale small population fluctuations of small mammals that impacted all stands collectively. Each individual stand was trapped once. A trapping array consisted of 5 spokes containing 7 nodes with nodes separated by 7 m (Figure 2.2.). I placed a Sherman live trap at each node, resulting in 35 Sherman traps per web. At the web center and the 3rd and 7th nodes I also placed a Tomahawk live trap, resulting in 11 Tomahawk traps per web. I baited traps with a mixture of whole oats, raisins, creamy peanut butter, and molasses. Traps were set under or beside ground cover such as logs or heavy foliage and those at risk of exposure to direct sunlight were shaded. I also applied cotton batting to all traps. For stands containing riparian zones or leave patches, I placed arrays so that one or more spokes intersected those retention elements. In the WLPZ forest class, webs were centered on the stream channel yet some spokes extended beyond the WLPZ and into adjacent areas (because some WLPZs were narrow).

Traps were checked daily between daybreak and noon. Captured animals were marked with a 9-mm passive integrated transponder (PIT) tag injected via a 12-gauge needle subcutaneously in the flank (Model HPT9, Biomark, Boise, ID). I used PIT tags instead of ear tags so that individuals could be identified during subsequent captures with minimal handling, to increase accuracy of individual identification, and to shorten animal handling time (Schooley et al. 1993; Morley 2002). Schooley et al. (1993) found no evidence that PIT tagging increased small mammal mortality.

After marking, animals were released on site for potential recapture. Animals that were seldom captured or those that were not conducive to tagging (e.g., shrews) were released without administering a PIT tag. Capture and handling of animals followed guidelines recommended by the California Department of Fish and Wildlife under scientific collection permit SC-11913, and was considered exempt by the Institutional Animal Care and Use Committee at Michigan State University.

2.2.3. *Vegetation Sampling*

At each web array, a 9m-diameter plot was centered on each individual trap location. The north-south and east-west diameters of the plot were used for point-line transect surveys of ground cover. Points were spaced 1 m apart, starting at 1.5 m and ending at 4.5 m from the individual trap location. I recorded if the point intersected shrub, forb, grass, rock, mineral soil, forest litter, downed wood, or tree. Forest litter included leaves, needles, pine cones, ash and pulverized slash from timber harvest. Downed wood was defined as downed logs, branches, and discernible woody slash. I did not set a size limit for inclusion in the downed wood category; therefore, this category could be considered an amalgam of coarse and fine downed wood. I also recorded whether the trap locations were in a clearcut, retention, clearcut-riparian, control, or control-riparian zone. Here, control patches correspond to rotation-aged forests and riparian areas were based on buffer requirements associated with the California Forest Practice Rules (CAL FIRE 2014).

2.2.4. *Data Analysis*

I calculated the proportion of each ground cover category within the 9m-diameter plot at all individual trap locations. I generated a correlation matrix of the predictor variables using a Kendall tau rank correlation coefficient and identified correlated variables ($P < 0.05$); correlated variables were not included in the same candidate model. My response variable was the number of unique individuals captured at a trap location over the course of one trapping period (i.e., 5 nights) for each species. I used generalized linear mixed models (GLMM) with a Poisson distribution in program *R* 3.0.2 for estimating the impact of localized ground cover measures on small mammal species abundance. I also investigated whether the year of sampling or land cover category (i.e., clearcut, retention, clearcut-riparian, control, or control-riparian zone) of where the trap was placed influenced small mammal counts for each species. A Kruskal-Wallis rank sum test was used to determine the significance of these factors on individual small mammal captures and if I found a significant effect I included the factors in the GLMMs. I included a trapping web identifier as a random effect in models to account for differences in small mammal abundance and catchability among trapping arrays that might be caused by broad-scale environmental phenomenon (e.g., elevation). I used AICc to rank candidate models and deemed model parameters significant if the 95% confidence intervals did not overlap 0 (Burnham and Anderson

2002).

2.3. Results

2.3.1. *Vegetation Measures and Land Cover Category at Trap Locations*

I sampled 65 stands and recorded vegetation and small mammal data at 2,913 trap locations during the summers of 2011-2013. For the $64m^2$ surrounding each trap location, average cover of forest litter was 31% (SE = 0.4; range = 0 – 100), followed by grass (16%; SE = 0.3; range = 0 – 94), downed wood (14%; SE = 0.3; range = 0 – 94), forb (11%; SE = 0.3; range = 0 – 88), mineral soil (9%; SE = 0.3; range = 0 – 100), shrub (9%; SE = 0.3; range = 0 – 100), tree (8%; SE = 0.2; range = 0 - 94), and rock (2%; SE = 0.2; range = 0 - 81). Traps were most commonly placed in the clearcut land cover category (45%), followed by control (34%), control riparian (13%), retention (5%), and clearcut-riparian (2%) areas.

Vegetation measures also varied by land cover classification (Table 2.1.). The most common land cover category at Sherman trap locations was clearcut (*n* = 1,394) followed by control (*n* = 1,176), control-riparian (*n* = 380), retention (*n* = 166), and clearcut-riparian (*n* = 88).

A Kruskal-Wallis rank sum test was used to compare small mammal counts to land cover category. I found land cover category to significantly influence pooled small mammal counts in Sherman (χ^2 = 17.594, *P* = 0.001) and Tomahawk traps (χ^2 = 29.423, *P* = <0.001), *Peromyscus* spp. (χ^2 = 17.875, *P* = 0.001), and California ground squirrels (χ^2 = 57.272, *P* = <0.001). Land cover category did not significantly influence Allen's chipmunk counts (χ^2 = 6.300, *P* = 0.178). In addition, I tested the relationship between counts and year. I found that the year of sampling significantly influenced pooled small mammals counts in Tomahawks (χ^2 = 7.431, *P* = 0.024) and California ground squirrels (χ^2 = 7.294, *P* = 0.026). Year did not significantly influence *Peromyscus* spp. (χ^2 = 2.662, *P* = 0.264), Allen's chipmunk (χ^2 = 0.277, *P* = 0.871), or pooled small mammal counts in Sherman traps (χ^2 = 1.865, P = 0.394)

2.3.2. *Small Mammals*

I accumulated 12,261 trap nights (87% of the potential trap nights) and caught 11 small mammal species: white-footed deer mouse (*P. maniculatus*), brush mouse (*P. boylii*), California ground squirrel (*Spermophilus beecheyi*), Allen's chipmunk (*Tamias senex*), dusky-footed woodrat (*N. fuscipes*), bushy-tailed woodrat (*N. cinerea*), Trowbridge's shrew (*Sorex trowbridgii*), Douglas Squirrel (*Tamiasciurus douglasii*), striped skunk (*Mephitis mephitis*), western harvest mouse (*Reithrodontomys megalotis*), and the California vole (*Microtus californicus*). I pooled white-footed deer mice and brush mice into *Peromyscus* spp. because field differentiation was not accurate. I marked 380 individuals with a PIT tag; 284 *Peromyscus* spp., 60 California ground squirrels, 13 Allen's chipmunks, 14 dusky-footed woodrats, 5 bushy-tailed woodrats, 3 Douglas squirrels, and 1 California vole. *Peromyscus* spp. was the most frequently captured species in Sherman traps (75% of all captures) whereas California ground squirrel was the most frequently captured species in Tomahawk traps (16% of all captures).

I tested 18 candidate GLMMs for commonly captured species in Sherman and Tomahawk traps (Table 2.2.); I also ran the models for pooled small mammal species by trap type. The top-ranking model for combined small mammal captures in Sherman traps included the proportion of shrub ($ß_1$) and downed wood ($ß_2$) per $64m^2$ and land cover category ($ß_3$ = retention; $ß_4$ = clearcut-riparian; $ß_5$ = old-growth; $ß_6$ = old-growth riparian; Table 2.3.). This model accounted for 54% of the evidence weight (Table 2.3.) with shrub and retention being significant ($ß_1$ = 1.43, 95% CI = 0.86, 1.75; $ß_3$ = 0.44, 95% CI = 0.06, 0.83). My findings indicate that counts of individual small mammals captured in Sherman traps increased as proportions of shrub increased (Figure 2.3.a) and that I caught more small mammals when a trap was placed in the retention land cover category.

In Tomahawk traps, a top-ranking model and two competing models were identified (i.e., ΔAICc < 2.0; Table 2.4.). The top-ranking model included the proportion of shrub ($ß_1$) and downed wood ($ß_2$) within $64m^2$ plots, year ($ß_3$ = 2012, $ß_4$ =2013) and land cover category ($ß_5$ = retention, $ß_6$ = clearcut-riparian, $ß_7$ = old-growth, $ß_8$ = old-growth-riparian). In this model only downed wood was significant ($ß_2$ = 1.55, 95% CI = 0.25, 2.86); as downed wood cover increased at Tomahawk trap locations the number of individual small mammals increased (Figure 2.4.). The top competing model consisted solely of the proportion of downed wood ($ß_1$) and this parameter was significant ($ß_1$ = 1.43, 95% CI = 0.12, 2.73); more individual small mammals were caught at Tomahawk trap locations as downed wood increased. The second competing model from the Tomahawk traps included the proportion of forest litter ($ß_1$), which was also significant ($ß_1$ = -1.18, 95% CI = -2.34, -0.02); more forest litter resulted in lower small mammal captures in Tomahawk traps but I caution that this result is heavily influenced by captures of California ground squirrels.

I identified two top-ranking models for the number of individual *Peromyscus* spp. captured in Sherman traps that both accounted for 34% of the evidence weight (Table 2.3.). One top-ranking model included the proportion of shrub ($ß_1$) per $64m^2$ and land cover category ($ß_2$ = retention; $ß_3$ = clearcut-riparian; $ß_4$ = old-growth; $ß_5$ = old-growth riparian; Table 2.3.). In this model, both shrub and retention were significant ($ß_1$ = 1.39, 95% CI = 0.79, 1.99; $ß_2$ = 0.44, 95% CI = 0.05, 0.83). The other top-ranking model included the proportion of shrub ($ß_1$) and downed wood ($ß_2$) per $64m^2$, and land cover category ($ß_3$ = retention; $ß_4$ = clearcut-riparian; $ß_5$ = old-growth; $ß_6$ = old-growth riparian; Table 2.3.) with the proportion of shrub and the retention land cover category significantly influencing counts ($ß_1$ = 1.44, 95% CI = 0.84, 2.05 ; $ß_3$ = 0.40, 95%

CI = 0.01, 0.80). Both of these models indicate that the number of individual *Peromyscus* spp. at a trap increased as the proportion of shrub increased (Figure 2.5.) and I caught more individual *Peromyscus* in traps placed in retention areas opposed to clearcuts.

The top-ranking model for Allen's chipmunks captured in Sherman traps included shrub cover ($ß_1$) per $64m^2$. Shrub cover was significant ($ß_1$ = 2.99, 95% CI = 5.63, 0.34) indicating that more individual Allen's chipmunks were captured as shrub cover increased at the trap locations (Figure 2.7.). I also identified 4 competing models (Table 2.3.), but only shrub cover was significant in any of these models.

California ground squirrels were the most frequently captured species in Tomahawk traps. The top-ranking model for California ground squirrel included the proportion of forest litter ($ß_1$) in the $64m^2$ trap area. Forest litter was significant ($ß_1$ = -1.71, 95% CI = -3.25, -0.16) indicating that individual California ground squirrel counts increased as the amount of forest litter decreased (Figure 2.6.). In a competing model, the proportion of downed wood ($ß_1$ = 1.98, 95% CI = 0.23, 3.73) and land cover category were significant; I captured more California ground squirrels as downed wood increased and fewer individual California ground squirrels when traps were in controls compared to clearcuts.

2.4. Discussion

During the 2011-13 fields seasons, I captured 11 small mammal species in Sherman and Tomahawk live-traps on dry industrial managed forests in northern California. The most frequently captured species were *Peromyscus* spp. and California ground squirrels in Sherman and Tomahawk traps, respectively. Captures of small mammal species other than *Peromyscus spp.* were low thereby limiting the number of species-specific models that would converge. I found that shrub cover was positively correlated to the number of individual small mammals captured; this relationship held across multiple taxon and trap types. In Tomahawk traps, downed wood cover was also found to positively influence pooled small mammal counts. This result is consistent with other studies from drier environments of the western United States and Canada that collectively found that fine-scale retention of shrubs and downed wood positively affects small mammal habitat use (Manning and Edge 2004; Smith and Maguire 2004; Converse et al. 2006; Coppeto et al. 2006; Kalies et al. 2012). I further found that the land cover class at the trap location had impacted small mammal captures, with higher small mammal counts being recorded in retention areas. California ground squirrels showed a different trend, with counts of this species being higher in clearcuts opposed to controls. Collectively, my results indicate that small mammal habitat use corresponds to fine-scale ($64m^2$) habitat features as well as certain land cover designations. This fine-scale finding somewhat contradicts patterns observed at larger scales. For example, Gray (2014:Chapter 1) found that land cover designation was not related to the likelihood of capturing small mammals in a 6.35ha area surrounding trapping webs.

My species-specific analyses found that *Peromyscus* spp. were positively associated with the presence of shrub cover and the retention land cover category. Research results on *Peromyscus* and its relationship with shrub and downed are variable. Smith and Maguire (2004) observed little response by deer mice to shrub cover. In contrast, other studies have found a positive response by deer mice to shrub cover (Carey and Johnson 1995; Kyle and Block 2000). Research findings on deer mice in relation to retention practices are contradictory to the relationship I observed. Several studies have found retention patches to have little influence on deer mouse abundance. Sullivan and Sullivan (2001) found deer mice to be more abundant in clearcuts than in retention areas while other studies did not observe significant differences in deer mouse abundance between clearcuts and retention prescriptions (Klenner and Sullivan

2003; Sullivan and Sullivan 2008).

I found that Allen's chipmunk captures in Sherman traps were positively influenced by the localized amount of shrub cover. Smith and Maguire (2004) found higher abundances of yellow-pine chipmunks (*Tamias amoenus*; a similar species to Allen's chipmunk) in areas of high shrub cover. It is likely that Allen's chipmunks rely on shrub cover for forage and cover. Chipmunks use shrubs as cover and have been observed placing burrows near the base of shrubs (Smith and Maguire 2004). In addition, shrubs are used to minimize heat exposure (Chappell 1978) and may produce edible nuts and berries.

I caught more individual California ground squirrels in areas with sparse forest litter, likely reflecting the relationship between established forests and litter accumulation. California ground squirrels tend to occur in open areas, likely related to their apparent affinity for disturbed areas and habitats where predators can visually be detected (Grinnell and Dixon 1918; Owings and Borchert 1975; Ordeñana et al. 2012). In my study area, recently harvested stands apparently provide the fine-scale features conducive to California ground squirrels.

My results emphasize the importance of downed wood, shrub cover, and forest litter to small mammals, however some current forest practices likely reduce these habitat elements in recent clearcuts. The application of herbicides to control competing vegetation lowers the amount of living woody and herbaceous vegetation during site preparation, although the herbicide effect typically lasts for <5 years (Morrison and Meslow 1984; Harrington et al. 1995). Fire is also commonly used in some landscapes after clearcutting to release nutrients, however, burning will also reduce vegetative cover and residual downed wood. The adoption of timber management practices that retain habitat elements like downed wood, green-tree, and riparian buffers likely help ameliorate these negative impacts on small mammal habitat. Furthermore, it also appears that the retention land cover category is important to small mammals. I found retention patches to positively influence counts of *Peromyscus* spp. and pooled small mammals. In forest management, retention patches are used to provide wildlife refuge as well as aiding seeding and regeneration after a site has been harvested. My findings are consistent with others that have deemed retention areas an important component in sustaining small mammal species (Moses and Boutin 2001; Rosenvald and Lohmus 2008; Lindenmayer et al. 2010).

I acknowledge that the fine-scale habitat associations I documented for the pooled small mammal community were heavily influenced by the most frequently captured species, *Peromyscus* spp., hence my results should be cautiously applied to other species. I also acknowledge that the analytical model I used did not include spatial autocorrelation among trap locations within a web, which potentially resulted in a negative bias in the variability of my data. As a result, those relationships that are marginally significant (i.e., the 95% CI approaches 0) may be spurious. I used a web-based random effect to account for unmeasured environmental conditions (e.g., weather, elevation) that may have influenced the localized small mammal community and thus did not have the ability to explicitly evaluate factors that are known to affect small mammal capture probability like temperature and precipitation (Converse et al. 2006). In several of my models I detected a year effect on small mammal counts that could be attributed to weather or population differences among years.

My findings emphasize the importance of fine-scale retained elements, primarily downed wood and shrub cover, on small mammal habitat use. I observed the downed wood effect at multiple scales, including the patch (~6.35ha; Gray 2014:Chapter 1) and micro-site ($64m^2$; this study). Collectively these results indicate a close, multi-scale relationship between small mammal abundance and downed wood in dry managed forests. Downed wood is important to small mammals because it provides food, cover and nesting sites (Hallet et al. 2003). Shrub cover also provides food and vertical cover for small mammal species. Retention of these features in an industrial forest could potentially increase small mammal abundance and diversity and contribute to management prescriptions for threatened and endangered predators. However, it is also important to note that increasing habitat elements such as downed wood and shrubs in dry forest ecosystems will increase forest floor fuel and could potentially amplify risk of wildfire. My results for downed wood suggest that a moderate amount of wood may be optimal for small mammals (i.e., I observed a weak quadratic relationship) and thus I caution against a management philosophy that strives to leave downed wood in abundance. Finding optimal amounts of retention elements without increasing wildfire risk or compromising the ability of forest landowners to regenerate harvested sites for desirable tree species would be particularly useful to forest managers. My study provides insight into fine-scale retention that can be used to enhance small mammal habitat.

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APPENDIX

Table 2.1.

Average percent cover within 64 m^2 plots at individual trap locations by vegetation and land cover category in industrial forests of northern California, USA, May-August 2011-13.

Table 2.1. (cont'd)

Land Cover Category	Vegetation Category	Average Percent	Standard Error	Range
Clearcut	Shrub	7	0.003	0 – 100
	Forb	10	0.004	0 – 78
	Grass	26	0.006	0 – 94
	Rock	3	0.002	0 – 63
	Mineral Soil	15	0.005	0 – 100
	Forest Litter	19	0.005	0 – 89
	Downed Wood	14	0.004	0 – 75
	Tree	6	0.002	0 – 63
Retention	Shrub	7	0.012	0 – 100
	Forb	4	0.006	0 – 33
	Grass	15	0.014	0 – 69
	Rock	1	0.014	0 – 25
	Mineral Soil	11	0.010	0 – 50
	Forest Litter	38	0.020	0 – 100
	Downed Wood	17	0.013	0 – 81
	Tree	7	0.008	0 – 50
Clearcut-riparian	Shrub	12	0.020	0 – 78
	Forb	14	0.019	0 – 89
	Grass	15	0.020	0 – 75
	Rock	2	0.004	0 – 19
	Mineral Soil	8	0.019	0 – 100
	Forest Litter	37	0.032	0 – 100
	Downed Wood	9	0.014	0 – 56
	Tree	4	0.009	0 – 31
Control	Shrub	7	0.004	0 – 94
	Forb	9	0.004	0 – 81
	Grass	6	0.003	0 – 81
	Rock	1	0.001	0 – 56
	Mineral Soil	4	0.002	0 – 56
	Forest Litter	43	0.008	0 – 100
	Downed Wood	12	0.004	0 – 94
	Tree	9	0.006	0 – 94
Control-riparian	Shrub	17	0.010	0 – 88
	Forb	19	0.010	0 – 88
	Grass	5	0.005	0 – 63
	Rock	4	0.005	0 – 81
	Mineral Soil	2	0.004	0 – 100
	Forest Litter	30	0.011	0 – 89
	Downed Wood	13	0.007	0 – 88
	Tree	9	0.006	0 – 56

Table 2.2.

Candidate generalized linear mixed models used to estimate the number of small mammal captures at individual trap locations in industrial forests of northern California, USA, May-August 2011-13.

Candidate Models[a]	
1. Forb + Rock + Shrub	10. Grass + Downed Wood
2. Forb + Rock + Tree	11. Forb
3. Grass + Rock	12. Forest Litter
4. Rock + Tree	13. Grass
5. Forb + Shrub	14. Mineral Soil
6. Forb + Rock	15. Rock
7. Forb + Tree	16. Shrub
8. Rock + Shrub	17. Tree
9. Shrub + Downed Wood	18. Downed Wood

[a] Proportion forb, rock, tree, grass, shrub, downed wood, mineral soil, and forest litter around individual trap locations. Year and land cover category were included in species models when identified as significant via a separate analysis of variance.

Table 2.3.

Five top-ranking generalized linear mixed models used to estimate the number of individual small mammals (pooled across all species), *Peromyscus* spp., and Allen's chipmunks in industrial forests of northern California, USA, May-August 2011-13. K[b] = the number of estimated model parameters, AICc = Akaike Information Criteria adjusted for small sample sizes, ΔAICc = difference in AIC from top-ranking model, and *w* = weight of evidence.

Species	Model	K	AICc	ΔAICc	*w*
All small mammals[a]	Downed Wood + Shrub	8	2635.23	0.00	0.54
	Shrub	7	2636.80	1.57	0.24
	Forb + Shrub	8	2638.78	3.54	0.09
	Rock + Shrub	8	2638.78	3.55	0.09
	Forb + Rock + Shrub	9	2640.75	5.52	0.03
Peromyscus spp.	Shrub	7	2483.13	0.00	0.34
	Downed Wood + Shrub	8	2483.14	0.00	0.34
	Rock + Shrub	8	2484.91	1.78	0.14
	Forb + Shrub	8	2485.08	1.95	0.13
	Forb + Rock + Shrub	9	2486.85	3.71	0.05
Allen's chipmunk	Shrub	3	155.95	0.00	0.26
	Downed Wood	4	157.09	1.14	0.15
	Forest Litter	3	157.18	1.23	0.14
	Rock + Shrub	4	157.58	1.63	0.11
	Forb + Shrub	4	157.93	1.98	0.10

Table 2.3. (cont'd)

[a] Captures of individual *Peromyscus* spp., dusky-footed woodrats, bushy-tailed woodrats, California voles, California ground squirrels, Allen's chipmunks, Douglas squirrels, and Trowbridge's shrews.

[b] Models also included an intercept, random effect (Web ID), and year (2011, 2012, 2013) and category (clearcut, retention, clearcut-riparian, control, or control-riparian zone) factor if significant via an analysis of variance.

Table 2.4.

Five top-ranking generalized linear mixed models used to estimate the number of individual small mammals and California ground squirrels caught in Tomahawk traps in industrial forests of northern California, USA, May-August 2011-13. K = the number of estimated model parameters, AICc = Akaike Information Criteria adjusted for small sample sizes, ΔAICc = difference in AIC from top-ranking model, and *w* = weight of evidence.

Species	Model	K	AICc	ΔAICc	*w*
All small mammals[a]	Shrub + Downed Wood	10	581.81	0.00	0.25
	Downed Wood	9	582.25	0.44	0.20
	Forest Litter	9	582.39	0.58	0.19
	Grass + Downed Wood	10	583.87	2.06	0.09
	Shrub	9	584.87	3.06	0.05
California ground squirrel	Forest Litter	9	410.04	0.00	0.28
	Downed Wood	9	410.61	0.57	0.21
	Mineral Soil	3	412.08	2.03	0.10
	Shrub + Downed Wood	10	412.09	2.04	0.10
	Grass + Downed Wood	10	412.59	2.55	0.08

[a] Captures of individual *Peromyscus* spp., dusky-footed woodrats, bushy-tailed woodrats, California ground squirrels, Allen's chipmunks, and Douglas squirrels.

Figure 2.1.

Four common forest classes in industrial forests of northern California, USA. Top left = recent clearcuts (3-5 years old), top right = 10-20 year-old plantations, bottom left = rotation-aged stands, bottom right = Watercourse and Lake Protections Zones (WLPZs).

Figure 2.2.

Small mammal trapping web design, northern California, USA, 2011-13.

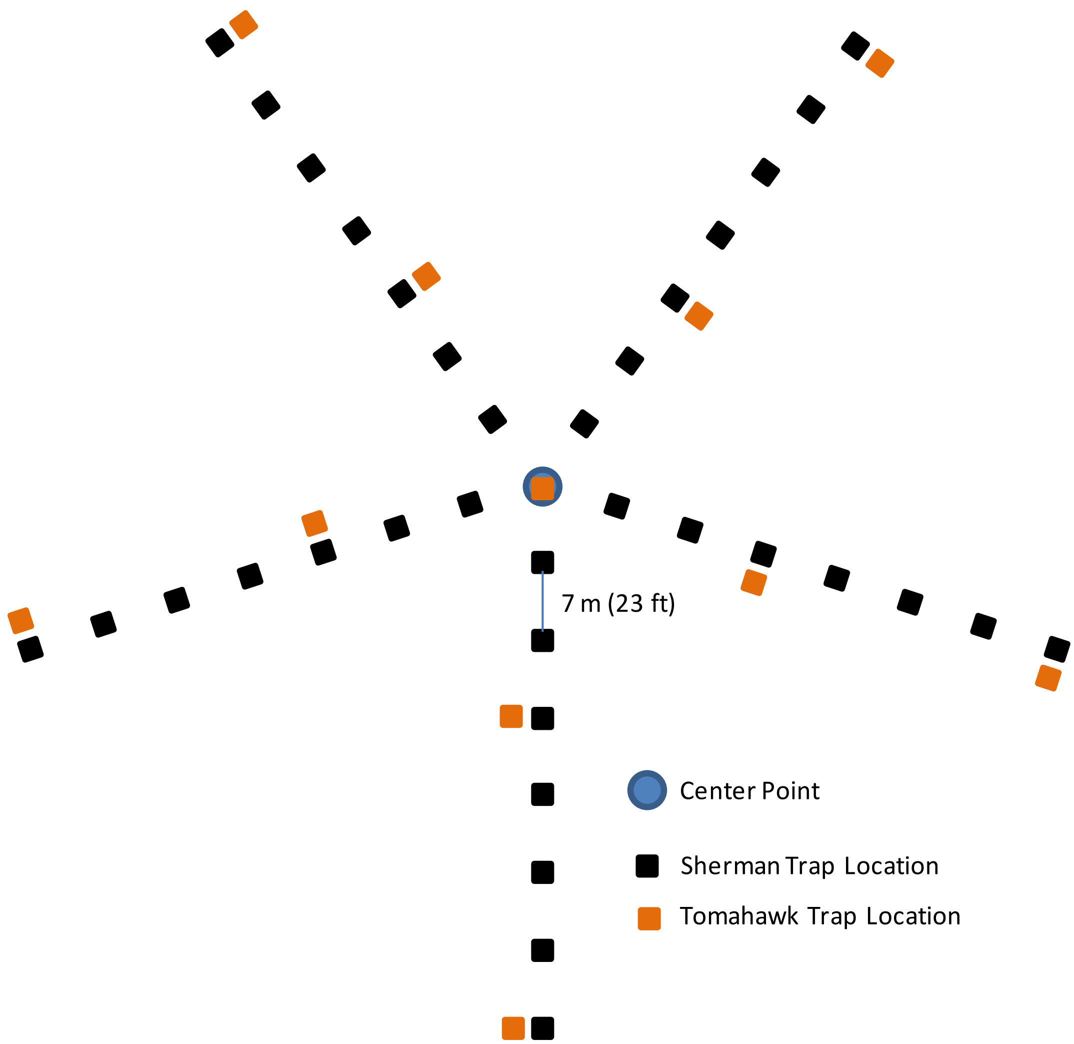


Figure 2.3.

Relationship of small mammal counts to proportion of shrub within the $64m^2$ surrounding Sherman traps in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

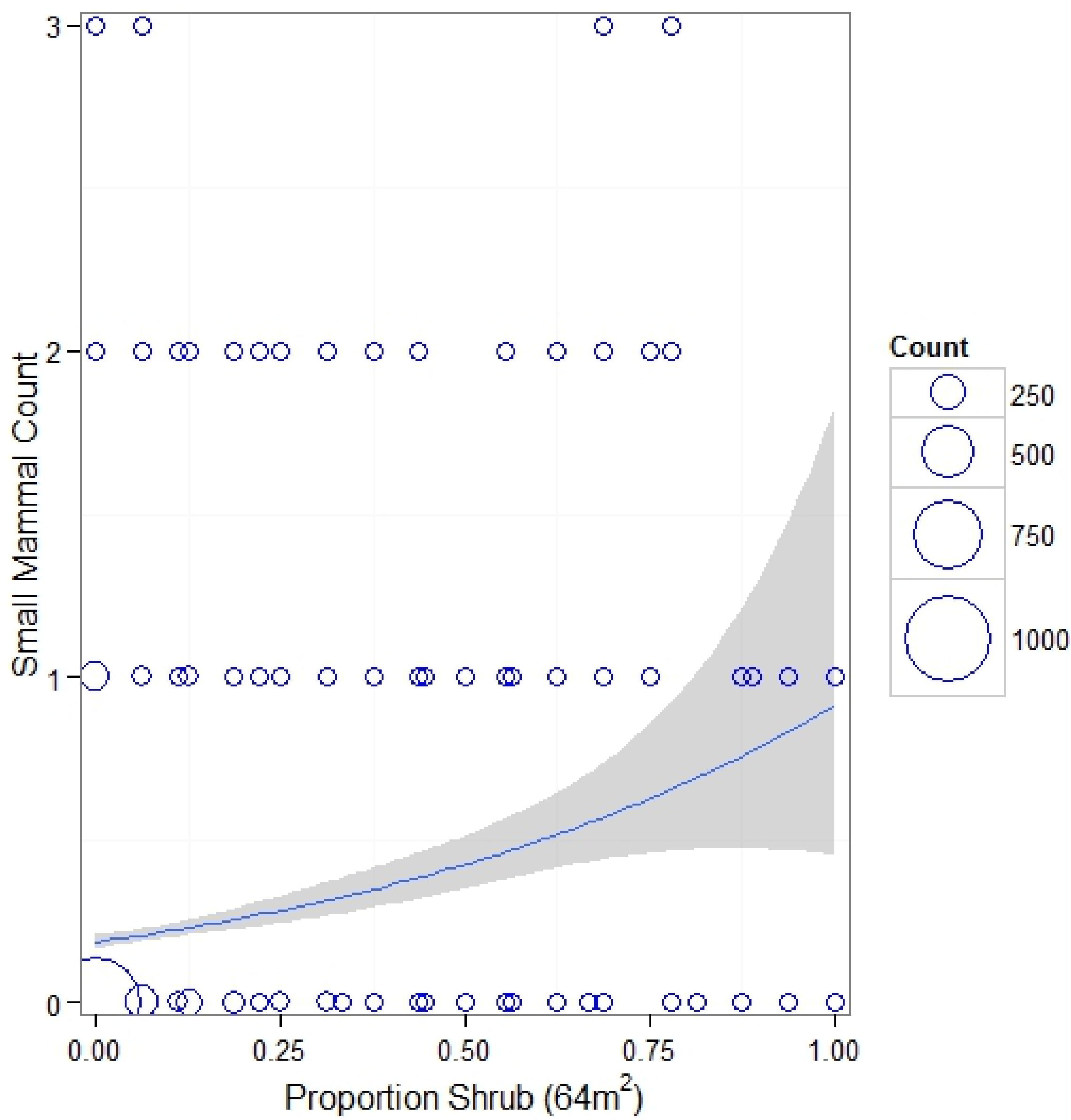


Figure 2.4.

Relationship of all small mammal counts to a) proportion of shrub and b) proportion of downed wood within $64m^2$ surrounding Tomahawk traps in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

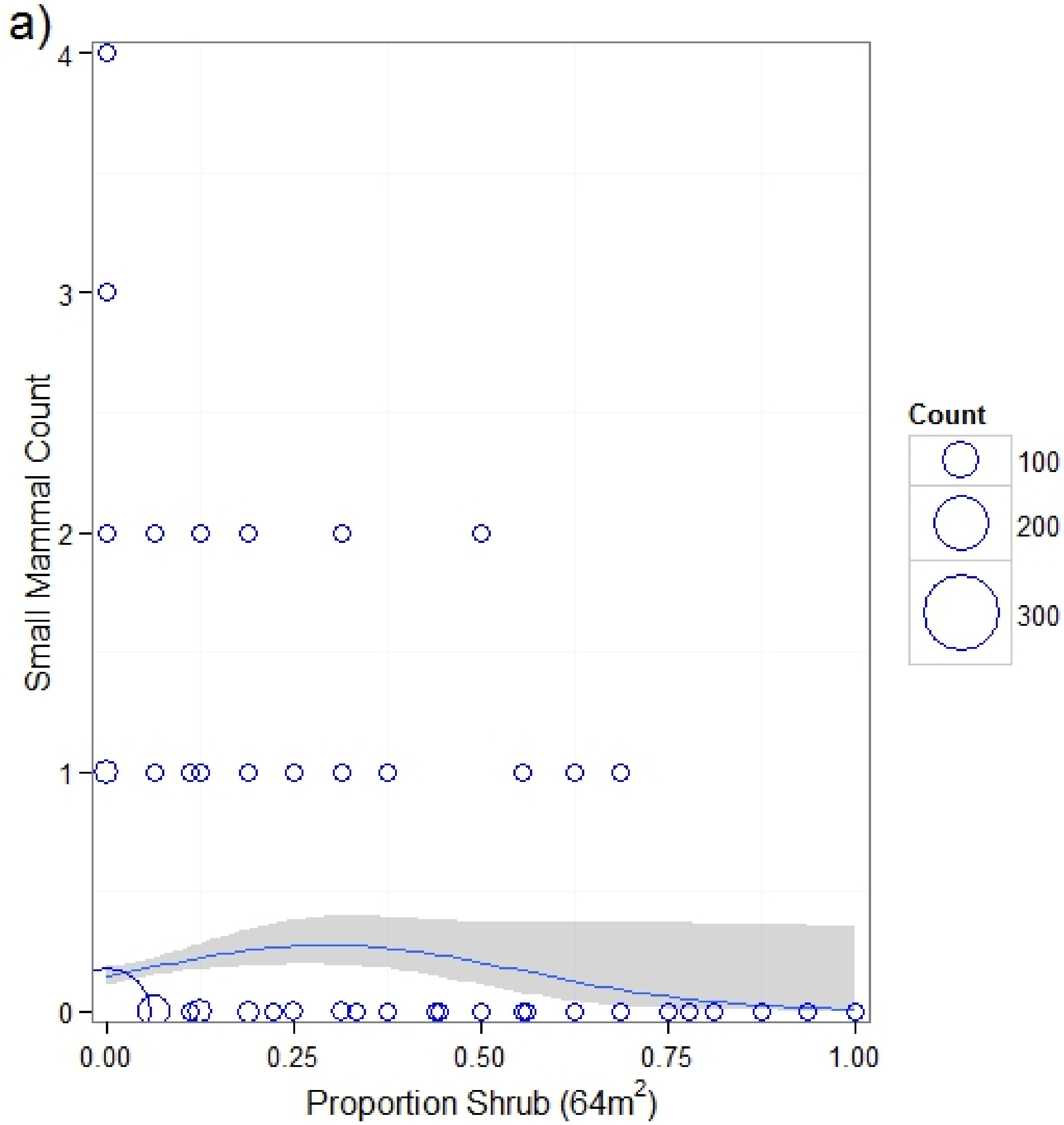


Figure 2.4. (cont'd)

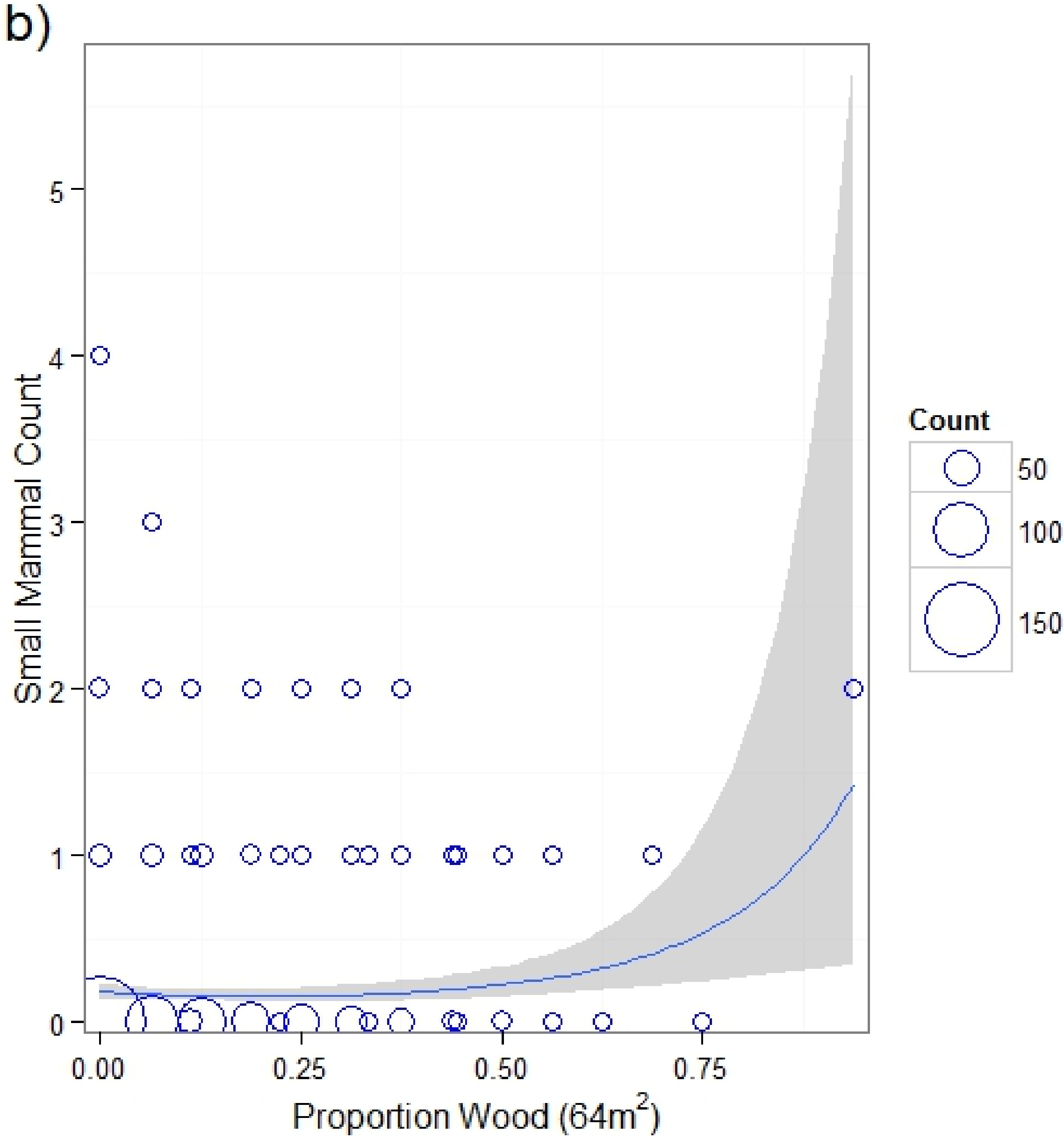


Figure 2.5.

Relationship of *Peromyscus* spp. counts to proportion of shrub within $64m^2$ surrounding Sherman traps in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

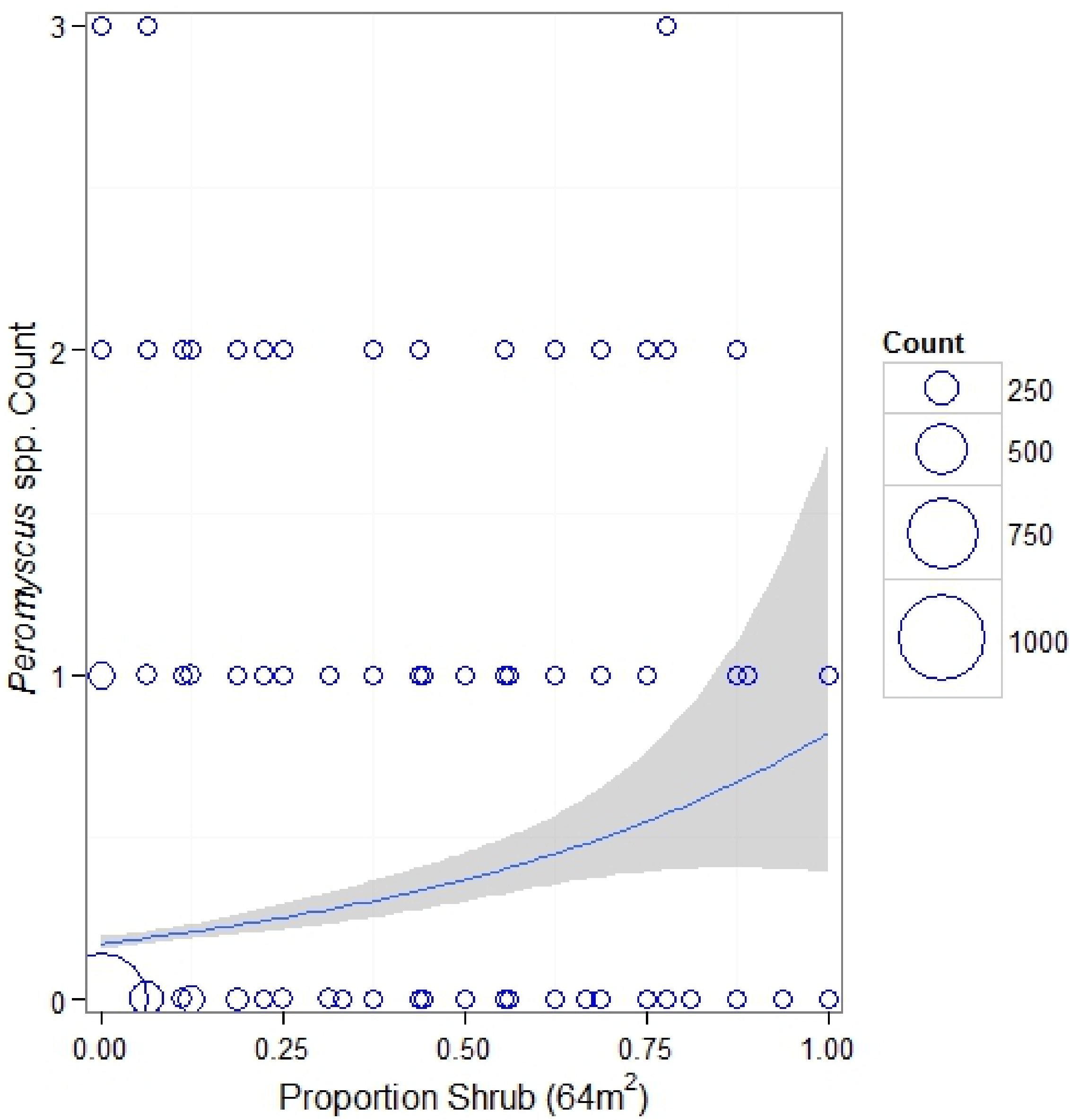


Figure 2.6.

Relationship of California ground squirrel counts to the proportion of forest litter within 64m^2 surrounding Sherman traps in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.

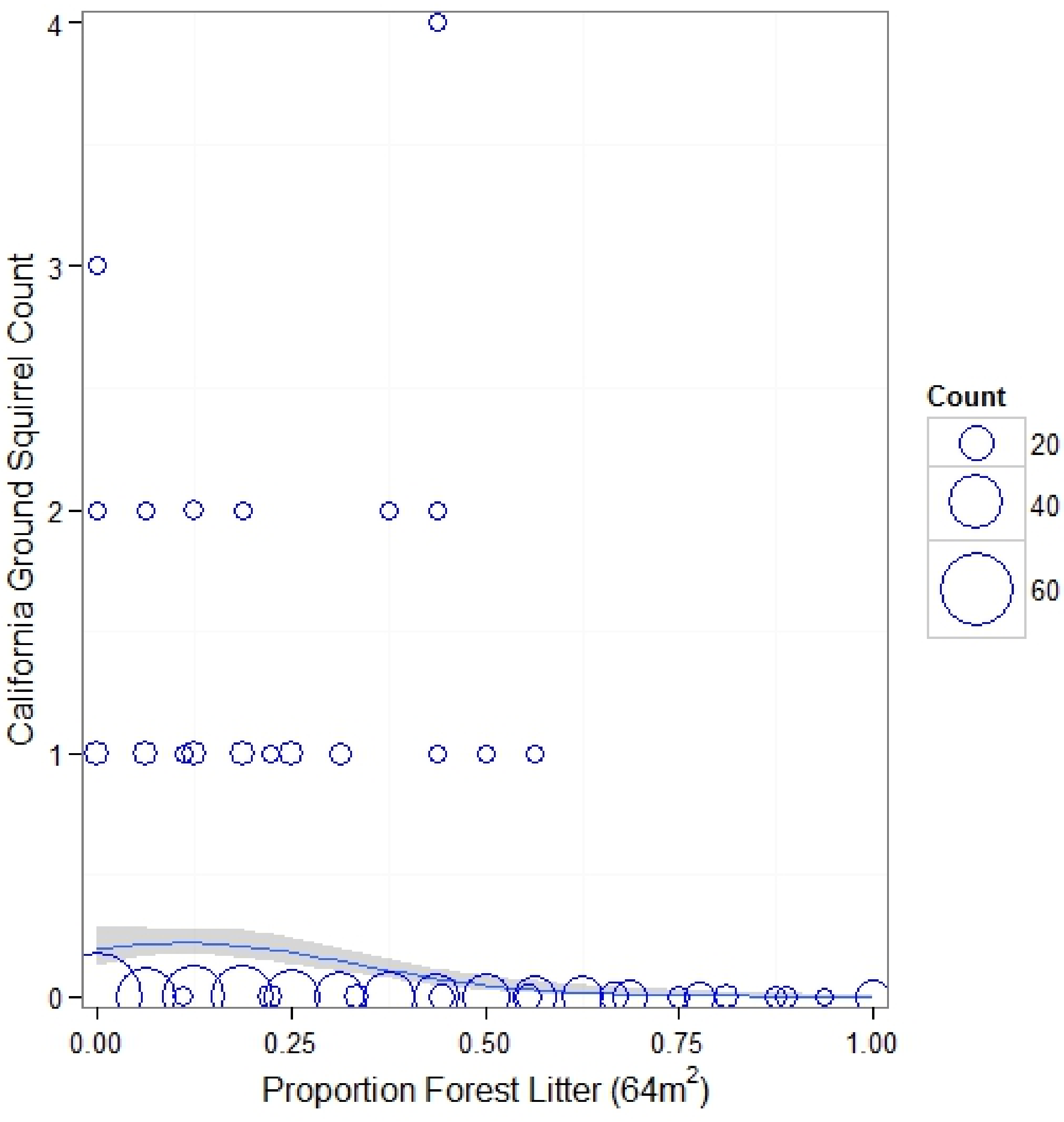
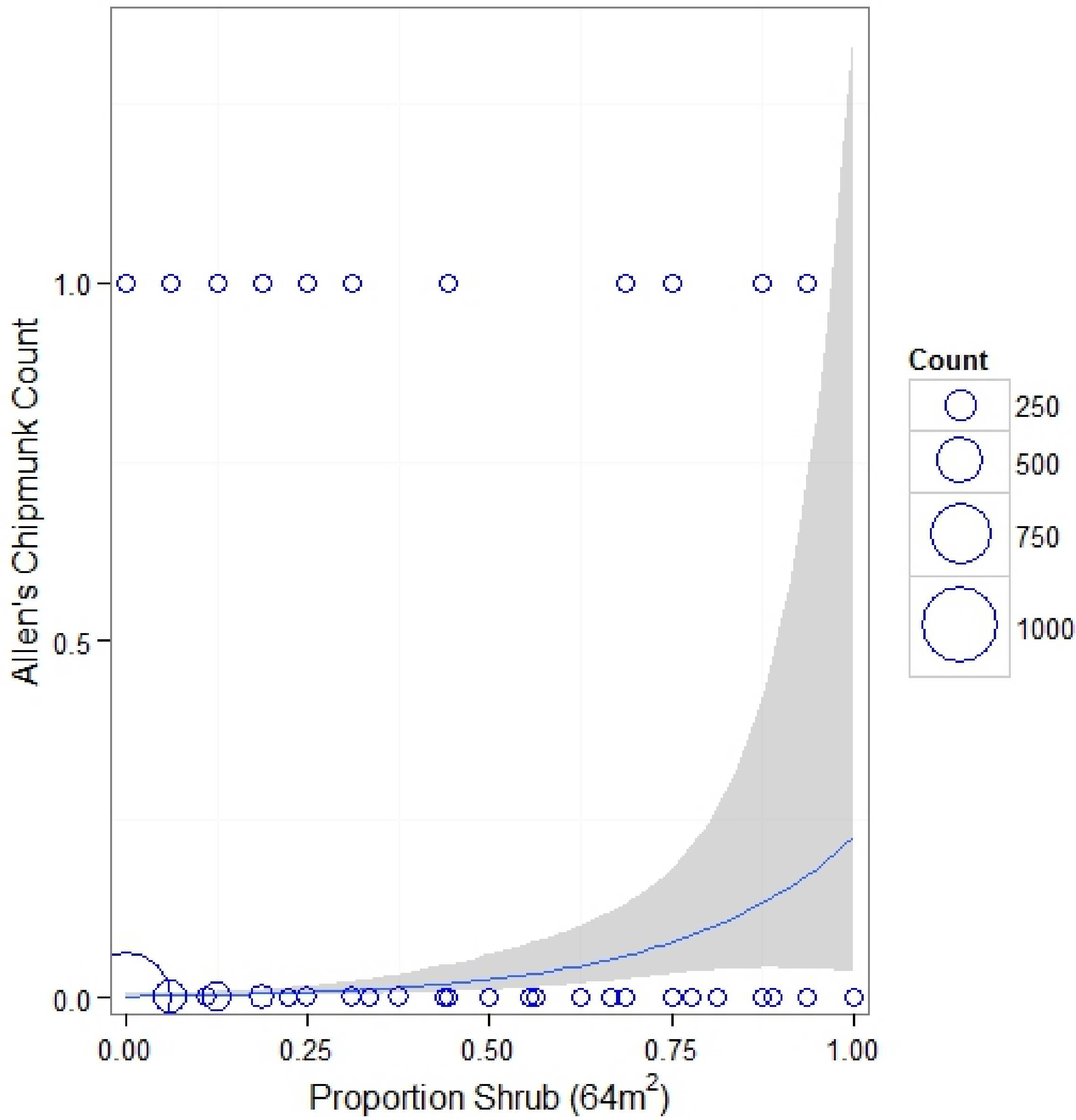


Figure 2.7.

Relationship of Allen's chipmunk counts to the proportion of shrub within 64m^2 surrounding Sherman traps in industrial forests of northern California, USA, 2011-2013. Shaded area represents the 95% confidence limits.



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CONCLUSIONS

My thesis focused on small mammal communities and how they relate to timber management in industrial forests. Specifically, I examined overall and species-specific responses to forest type and retention elements at two scale: 1) patch-level (~6.35ha), and 2) and fine scales ($64m^2$). This research informs forest managers and provides detail on habitat elements that are important to small mammals in industrial forest landscapes. The strengths of this research are that: 1) the analysis of populations were conducted at multiple scales (patch-level ~6.35 ha; fine-scale ~$64m^2$), 2) the research was conducted in relation to current forest management practices, and 3) the results provide a ranking and graphic portrayal of the species-specific relationships of small mammals to varying habitat elements. The limitations of my study include: 1) low captures for some small mammals that made inference difficult for those species, 2) inability to directly account for weather impacts on small mammal numbers, and 3) lack of a spatial autocorrelation term (Chapter 2) in my models potentially biasing my parameter estimates. I recommend that future research focuses on downed wood and shrubs, recognizing that a balance must be reached among forest operational needs (e.g., ability to regenerate trees, control wildfire risk) and the provision of wildlife habitat. For example, the retention of slash piles and windrows has been a topic of recent study (e.g., Sullivan et al. 2012) but additional research is needed.

In Chapter 1, I used generalized linear mixed models to evaluate how forest class, downed wood volume, and proximate forest classes influenced localized (~6.35 ha) abundances for commonly captured small mammal species. I found proximate forest class and downed wood volume to be more influential than the forest class containing trapping grids on small mammal abundance. *Peromyscus* spp. and *Neotoma* spp. displayed a positive relationship with proximate

WLPZ forest class. *Peromyscus* spp. captures also increased with increasing downed wood volume, however, the opposite pattern was observed in California ground squirrels and Allen's chipmunks. My findings indicate that the diverse habitat mosaic commonly associated with forest practices in northern California creates a variety of habitats and corridors conducive to the small mammal species that I commonly captured.

In Chapter 2, I assessed the relationship between fine-scale ($64m^2$) habitat features and land cover category at trapping locations to small mammal counts. I developed overall and species-specific GLMMs and found shrub and downed wood to be significant parameters influencing small mammal captures in Sherman and Tomahawk live-traps. Shrub and downed wood also positively influenced *Peromyscus* spp. captures. Allen's chipmunk counts were positively associated with shrub cover while California ground squirrel counts responded negatively to forest litter. My findings emphasize the importance of fine-scale retained elements, primarily downed wood and shrub cover, on small mammal habitat use in industrial forests of northern California.

It appears that current practices that influence patch configuration and fine-scale habitat elements on industrial timberlands encourage small mammal occupancy and abundance. However, I note that responses to timber practices are often species-specific. In addition, management recommendations and relationships observed in this study are relative to industrial forests of northern California but may be applicable to forests in other arid regions. Continuous research on retention practices is needed to inform discussions on Forest Practices Rules and management so that landowners can adapt when necessary. This study, along with others in the Pacific Northwest, indicate that retention practices on industrial forests influence small mammal species and findings should be used to inform future forest management.

LITERATURE CITED

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