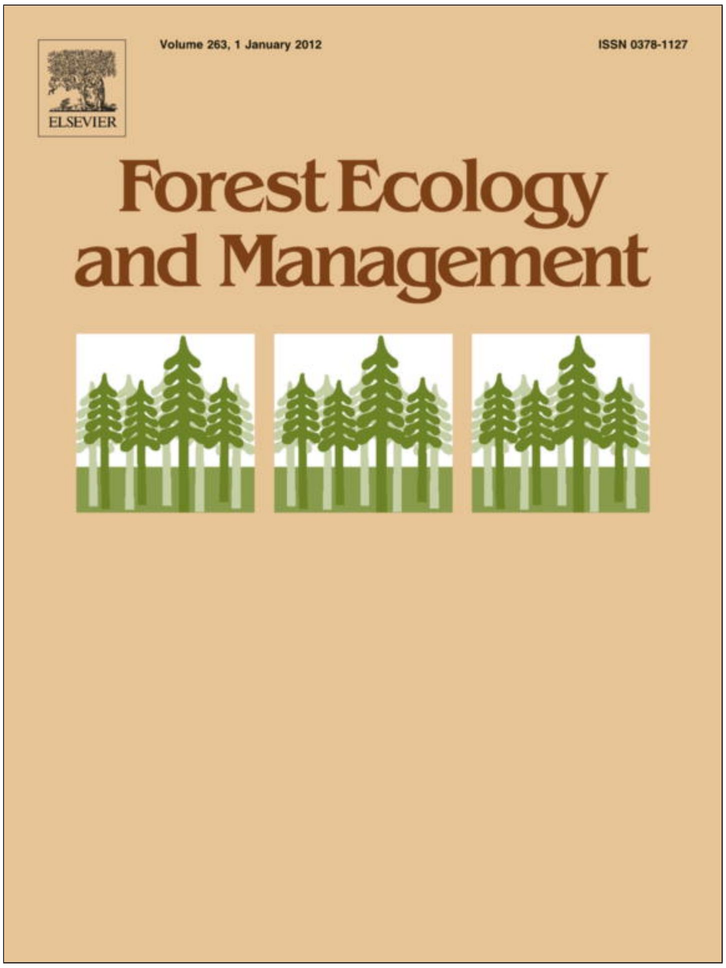
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Short-term response of small mammals following oak regeneration silviculture treatments

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ABSTRACT

Upland, mixed-oak forests in the eastern United States have experienced widespread oak regeneration failure, largely due to cessation of anthropogenic disturbance. Silvicultural practices used to promote advance oak regeneration may affect ground-dwelling mammals. From May to August 2008 (pre-treatment), 2010 (first year post-treatment), and 2011 (second year post-treatment), we trapped small mammals to assess changes in species richness and abundance following experimental tests of three silvicultural treatments (prescribed burns, midstory herbicide applications, and shelterwood harvests) used to promote oak regeneration. We trapped small mammals in five replicates of each treatment and controls using Sherman live traps (2008 and 2010) and drift fences (2008, 2010, and 2011). From pre- to post-treatment, we evaluated the change in estimated peromyscid abundance and relative abundance of masked shrews (*Sorex cinereus*), smoky shrews (*Sorex fumeus*), and northern short-tailed shrews (*Blarina brevicauda*). Additionally, we evaluated the change in species richness across treatments for both sampling techniques. For all measures analyzed (i.e., species richness, peromyscid abundance, and relative abundance of shrews), the change from pre- to post-treatment did not differ among treatments. However, more masked shrews, smoky shrews, and northern short-tailed shrews were captured in 2011 (i.e., second year post-treatment) than in 2010 (i.e., first year post-treatment). Our research indicates that, in the short-term, small mammals (e.g., mice and shrews) can tolerate a wide range of forest disturbance following oak regeneration treatments. However, delayed treatment effects (e.g., additional post-herbicide midstory dieback) or additive changes following future treatments (e.g., prescribed burns following shelterwood harvests or multiple prescribed burns) may compound effects on small mammal populations, and should be assessed with long-term research (>2 years post-treatment).

1. Introduction

Mixed-oak (*Quercus* spp.) forest occupies over 50% of the forested land base in the Central Hardwood Region of the United States and is the dominant forest type in the Southern Appalachians (Johnson et al., 2002; Sharitz et al., 1992). Ecologically, these forests are among the most productive terrestrial ecosystems providing valuable wildlife habitat and high biodiversity (Rodewald, 2003). However, mixed-oak forests are increasingly threatened by oak decline on drier sites and widespread regeneration failure on mesic, productive sites (Aldrich et al., 2005; Oak et al., 2004).

Historically, disturbance events, including low-intensity surface fires, timber harvesting, and land clearing for agriculture promoted conditions conducive to oak establishment, development, and recruitment (Abrams, 1992; Lorimer, 1993; Sharitz et al., 1992). Frequent disturbance likely reduced the abundance of species that compete with or impede the establishment and growth of oaks, such as red maple (*Acer rubrum*), sourwood (*Oxydendrum arboreum*), rhododendron (*Rhododendron* spp.), and mountain laurel (*Kalmia* spp.). During the last century, cessation of frequent disturbance and implementation of fire suppression policies have gradually changed oak forest structure and composition (Abrams, 2005; Lorimer, 1993; Spetich and Parker, 1998). Fire-intolerant species have become more prevalent and forests are dense with shade-tolerant shrubs

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and trees, especially on mesic upland sites (Brose et al., 2001; Clinton, 1989). This shift to mesophytic forest is undesirable due to the ecological and economic benefits of oak-dominated forests (Guyette et al., 2004; Nowacki and Abrams, 2008).

Various silvicultural practices have been suggested to create conditions favorable for oak regeneration and can result in a wide range of habitat changes. Following a prescribed burn, leaf litter decreases, with up to six times more litter documented in unburned areas than in recently burned sites (Greenberg et al., 2006, 2007; Waldrop et al., 2007). Shelterwood harvests reduce canopy cover and leaf litter, promote rapid re-sprouting of vegetation, and potentially increase downed woody debris (Brose et al., 1999). Additionally, removal of the canopy creates a high-light environment, resulting in greater forest floor temperatures and lower soil moisture (Chen et al., 1999; Geiger, 1965).

Small mammals (e.g., mice and shrews) can be affected by changes in forest characteristics following oak regeneration practices, largely because of their associations with coarse woody debris (CWD), forest floor humic mat, and leaf litter for cover, nesting, foraging, and thermoregulation (Lanham and Guynn, 1996; Loeb, 1996). For example, changes in the availability of foods such as acorns, fruits, seeds, arthropods, or vegetation may influence small mammal populations (Kaminski et al., 2007; Kirkland, 1990; McCracken et al., 1999; Menzel et al., 1999). Although previous studies have not documented changes in shrew populations following prescribed fire or low-intensity timber harvest (Ford et al., 1999, 2002; Keyser et al., 2001; Zwolak, 2009), shrews may be susceptible to changes in CWD (Ford et al., 2000; Ford and Rodrigue, 2001; McCay and Komoroski, 2004). Additionally, reductions in leaf litter may negatively affect shrew populations, especially following high-intensity disturbance (Ford et al., 1997; Matthews et al., 2009).

Because silvicultural practices are increasingly used to restore upland oak forests in the eastern United States, it is important to determine potential impacts on small mammals, which are an integral part of forest ecosystems. Small mammals recycle nutrients, process vegetation, disperse seeds and fungal spores, and serve as a substantial prey base for raptors, reptiles, and other mammals (Carey and Johnson, 1995; Clotfelter et al., 2007; Cork and Kenagy, 1989; Fedriani et al., 2000; Schnurr et al., 2004). Hence, small mammals are identified as potential indicators for sustainable forest management (Carey and Harrington, 2001). Our objective was to determine short-term changes to small mammal populations following three oak regeneration practices: prescribed fire, midstory herbicide application, and shelterwood harvest, and a control using pre-treatment (baseline) and post-treatment data.

1.1. Study area

Our study was conducted on Cold Mountain Game Land (CMGL) in Haywood County in western North Carolina. CMGL was managed by the North Carolina Wildlife Resources Commission primarily for diverse wildlife habitat. Located in the Blue Ridge physiographic province of the southern Appalachians, CMGL encompassed ~1333 ha of second growth, upland mixed-oak forests. Elevations ranged from approximately 975–1280 m, and terrain was mountainous with gentle to steep slopes. Oaks, hickories (*Carya* spp.), and yellow-poplar (*Liriodendron tulipifera*) were the predominant overstory trees. Species composition in the midstory consisted primarily of shade-tolerant species including sourwood, flowering dogwood (*Cornus florida*), silverbell (*Halesia tetraptera*), blackgum (*Nyssa sylvatica*), and red maple. Site index (base age 50) of oak ranged from 15 m on the xeric, poor quality sites to 27 m on mesic, high quality sites. The climate is characterized by warm summers and cool winters and precipitation averages 1200 mm annually.

2. Material and methods

Twenty, 5-ha treatment units (5 replicates each of 3 treatments plus a control) were located within CMGL. Unit locations were established in sites that met our selection criteria described below. Treatments (prescribed fire, midstory herbicide, and shelterwood harvest) were randomly assigned to each unit resulting in a completely randomized design (CRD). All units were separated by a >10-m buffer and contained mature (>70 years old), fully stocked, closed-canopied stands where oaks comprised at least 10% of the overstory tree basal area ($\geqslant$25.0-cm dbh). We selected stands that contained >1000 oak seedlings/ha, few ericaceous shrubs, ~2 m^2/ha of basal area (BA) beneath the main canopy, and no substantial disturbance within the last 15–20 years (Keyser et al., 2008).

2.1. Treatments

Treatments were designed to evaluate the effectiveness of three oak regeneration practices: (1) 3 prescribed burns at ~4-year intervals, (2) midstory removal using herbicide competition control with re-application after ~3 years, and (3) shelterwood harvest with 30–40% BA retention followed by a prescribed fire after ~3 years. Eventually, all three practices will be followed by overstory removal ~11 years following initial treatments. This study encompassed one pre-treatment year and two post-treatment years, so we evaluated the response of small mammals to the first prescribed burn, initial midstory herbicide application, shelterwood harvest prior to burning, and controls.

In April 2009, two of the five prescribed burn units were burned because weather and road conditions did not permit burning of all five units; the remaining three units were burned in April 2010. Thus, the prescribed burn treatment was separated into two treatments because of potential ecological differences related to time since burn.

In late summer 2008, prior to leaf fall, midstory trees ($\geqslant$5.0 cm and <25.0 cm dbh) were treated with herbicide using the hack-and-squirt method where ~1 ml of diluted Garlon 3A solution was sprayed into a waist-high incision of each midstory tree marked for removal (Loftis, 1990). The goal of the herbicide treatment was to reduce total BA from below by 25–30% without creating new canopy gaps, primarily to increase photosynthetically active radiation (PAR) on the forest floor to promote oak seedling growth and successful recruitment into the canopy (Loftis, 1990).

From winter 2009 to early summer 2010, the shelterwood harvest was implemented with a goal of leaving approximately 30–40% of the original stand BA and enhancing light conditions on the forest floor (Brose et al., 1999). The majority of leave trees were dominant or codominant oaks. Most slash was left on-site.

During this study, no silvicultural manipulation occurred in the control plots.

2.2. Small mammal sampling

We sampled small mammals in all 20 units during mid-May to mid August of 2008 (pre-treatment) and 2011 (second year post-treatment). In 2010 (first year post-treatment), we sampled 19 units because a shelterwood unit was not harvested until mid-summer 2010. In 2008 and 2010, we used Sherman live traps and drift fence arrays for sampling. In 2011, we only used drift fences.

In each treatment unit, we placed 60 Sherman live traps (7.7 $\times$ 9.0 $\times$ 23.3 cm) at 10-m intervals, in a rectangular 60- $\times$ 100-m trapping grid. Grids were centered approximately mid-slope of each unit and all traps were >10 m from treatment boundaries. We baited traps with raw oatmeal and supplied cotton balls for bedding. In 2008 and 2010, we trapped one replicate unit of each treatment and control concurrently during each of five trapping periods. Traps were open continuously for seven nights and checked each morning. We ear-tagged all new captures, excluding shrews, with an individually numbered tag (size-1 Monel; National Band and Tag Co., Newport KY) and released individuals at the capture site (Greenberg et al., 2006).

In 2008, we established six randomly oriented single-arm drift fence arrays within all 20 treatment and control units. Three of the drift fences were installed at a lower slope site (defined as the lower one-third of each unit) and three at an upper slope site (the upper one-third of each unit) (Greenberg and Waldrop, 2008). In two of the treatment replicates (one herbicide and one control), we were unable to establish an upper site due to steep and rocky terrain. By 2010, a fourth fence was installed at each lower and upper location of each unit to increase sampling effort.

Single-arm drift fences were >10 m apart and constructed of 7.6-m sections of aluminum flashing with a 19-L bucket buried at each end, flush with the ground. We placed a moist sponge in each bucket to provide moisture for captured animals. Drift fence arrays were continuously open from mid-May to mid-August. Animal handling methods followed guidelines approved by the American Society of Mammalogists (Gannon and Sikes, 2007) and were approved by the North Carolina State University Institutional Animal Care and Use Committee (Approval number 08-035-O).

2.3. Habitat data

We obtained elevation measurements at upper and lower slope sites with a portable GPS device; upper and lower elevation measurements were averaged per unit. We recorded overall aspect of each unit as a binary value: 0 = south- and west-facing aspects, 1 = north- and east-facing aspects. We measured canopy cover and CWD in 2008 and 2010 and ground cover in 2008, 2010, and 2011. We measured canopy cover with a spherical densiometer at each drift fence and averaged per unit (Lemmon, 1956). At each drift fence in all units, we measured ground cover and CWD along a 15-m randomly oriented transect line originating from the bucket furthest uphill on each fence. Variables measured were percent cover of bare ground, leaf litter, understory cover (i.e., plants <0.9 m), and CWD ($\geqslant$12-cm diameter). We recorded 'start' and 'stop' distance for each category along each transect (e.g., bare ground from 3.1 m to 3.3 m = 0.2 m bare ground cover) and then summed the total distance along each transect. For understory cover, the start and stop measurements were determined by the potential cover (e.g., shading) provided by each plant. Percent cover for each category in a unit was determined by dividing the total summed distance of the category by 90 m (six transects per unit). We used the average percent cover of all six transects to estimate percent cover within a given treatment unit. For each piece of CWD, we recorded total length, bark class, and amount of decay. Bark class was visually categorized from 1–5: 1 = recently dead with 100% of bark, 2 = >70% of bark, 3 = 40–69% of bark, 4 = 10–39% of bark, and 5 = <10% of bark. Amount of decay was visually categorized from 1–6: 1 = no decay visible, 2 = slight decay, 3 = moderate decay, 4 = slight fragmentation, 5 = heavy fragmentation, and 6 = completely disintegrated but still distinguishable as CWD.

2.4. Analyses

We compared the change in canopy cover and CWD characteristics from 2008 to 2010 among treatments using a one-way analysis of variance (ANOVA). When models were significant, we used Tukey's Studentized Range test to determine significant differences among treatment means. Because ground cover was measured twice post-treatment (i.e., 2010 and 2011), we performed a repeated measures ANOVA. We used a mixed model procedure with a random effect (i.e., treatment per unit) and fixed effects of treatment and year with an interaction. If significant, we tested for differences among the treatments using Tukey's Studentized Range test.

We estimated abundance of peromyscids from Sherman live traps using closed population capture-recapture in Program MARK (White and Burnham, 1999). The closed captures option allowed modeling of the initial capture probability (p) and the recapture probability (c) to estimate population size (N) (Otis et al., 1978; White and Burnham, 1999). We lumped peromyscids for analysis because deer mice (*Peromyscus maniculatus*) and white-footed mice (*P. leucopus*) occur sympatrically above 800 m in the Appalachian Mountains and are difficult to distinguish in the field because of similarities in appearance (Schnurr et al., 2004). Population estimates were log-transformed for normality. Our response variable was the change in population estimates from 2008 to 2010 (pre- to post-treatment), which we compared among treatments using a mixed model consisting of a random effect (i.e., treatment per unit) and fixed effects [e.g., treatment and two covariates (aspect and elevation)] and the interactions between treatment and the covariates. We removed covariates and their interactions from the model when they were not statistically significant. If any variable was significant, we tested for differences among the treatments using Tukey's Studentized Range test.

We calculated relative abundance of small mammals captured in the drift fence arrays as the number of animals captured per 100 trap nights. Slope position was not an important predictor of small mammal response, so to reduce complexity of the analysis we averaged the number of captures at upper and lower sites of each unit, which then were log-transformed for normality. Our response variable was the change in relative abundance from 2008 to 2010 and 2008 to 2011. We compared the change in relative abundance of masked shrews (*Sorex cinereus*), smoky shrews (*S. fumeus*), and northern short-tailed shrews (*Blarina brevicauda*) among treatments using a repeated measures ANOVA with a covariance structure of first order autoregression [AR (1)]. The mixed model consisted of a random effect (i.e., treatment per unit) and fixed effects [e.g., treatment, year, and two covariates (aspect and elevation)] and the interactions between year and treatment and covariates and treatment. We removed interactions and covariates from the model when not statistically significant. If significant, we tested for differences among the treatments using Tukey's Studentized Range test.

For both sampling techniques (i.e., Sherman live traps and drift fence arrays), we analyzed change in species richness from pre- to post-treatment. To determine species richness in each treatment, we summed the total number of small mammal species captured in each unit. For Sherman live traps, our response variable was the change in species richness from 2008 to 2010 (we did not use Sherman live traps in 2011). Therefore, our model was identical to the analysis outlined above for population estimates of peromyscids from Sherman live traps. For drift fence arrays, our response variable was the change in species richness from 2008 to 2010 or 2008 to 2011 and our model was identical to analysis outlined above for relative abundance of small mammals from drift fence arrays. All statistical tests were conducted in SAS (v. 9.1.3, SAS Institute, Cary, NC).

3. Results

3.1. Habitat

Elevation ($F_{4,\ 14}$ = 2.12, P = 0.12) and aspect ($F_{4,\ 31}$ = 1.96, P = 0.13) were similar among treatments. In the first year post-treatment (2010), all habitat variables, except understory cover and CWD length, differed among treatments. Canopy cover in the

Table 1
Change in habitat variables (±SE) from 2008 to 2010 and 2008 to 2011 for oak regeneration treatments on Cold Mountain Game Land, NC: control (CONT), herbicide (HERB), shelterwood harvest (SW), prescribed burn 2010 (RX1), and prescribed burn 2009 (RX2). Different letters indicate significantly different values ($P < 0.05$).

	Treatment						
Habitat Variable	CONT	HERB	SW	RX1	RX2	F	P_{trt}
2008–2010							
Canopy cover (%)	3.4 ± 1.1A	−2.9 ± 2.4A	−39.8 ± 6.1B	3.5 ± 2.0A	2.1 ± 2.5A	29.62	<0.001
Bare ground (%)	1.3 ± 0.7BC	−4.9 ± 1.4C	33.1 ± 5.0A	13.9 ± 7.5B	48.0 ± 10.9A	12.90	<0.001
Leaf litter (%)	1.8 ± 1.6A	−6.4 ± 1.8A	−40.9 ± 5.9BC	−37.6 ± 5.9B	−63.8 ± 1.6C	13.87	<0.001
Understory cover (%)	−4.6 ± 1.6	3.3 ± 0.6	2.9 ± 3.3	13.2 ± 1.4	9.3 ± 6.1	1.93	0.13
CWD (%)	0.18 ± 0.2B	0.75 ± 0.2AB	5.08 ± 2.0A	−0.90 ± 2.0B	−3.07 ± 0.4B	5.41	0.01
CWD Length	0.30 ± 0.2	0.13 ± 0.1	−0.92 ± 0.2	−0.97 ± 1.0	−0.53 ± 0.8	2.54	0.09
CWD Bark Class (1–5)	0.35 ± 0.1A	0.55 ± 0.2A	−1.43 ± 0.4B	0.01 ± 0.1A	−0.4 ± 0.1AB	9.36	0.001
CWD Decay Class (1–6)	0.33 ± 0.2A	−0.6 ± 0.2BC	−0.93 ± 0.2C	−0.5 ± 0.1AC	−0.71 ± 0.2C	7.11	<0.01
2008–2011							
Bare ground (%)	−2.9 ± 3.4	−1.0 ± 3.9	15.8 ± 11.7	5.8 ± 3.9	0.1 ± 10.8	1.93	0.13
Leaf litter (%)	11.4 ± 7.1AB	14.1 ± 7.8A	−46.4 ± 12.0C	−6.3 ± 5.4B	1.3 ± 2.4AB	14.47	<0.001
Understory cover (%)	22.7 ± 4.2B	27.0 ± 7.4B	57.9 ± 5.7A	14.0 ± 5.1B	50.7 ± 9.9A	13.94	<0.001

Table 2
Small mammals captured in Sherman live traps in oak regeneration treatments on Cold Mountain Game Land, NC. Traps were open for seven consecutive nights in each unit during 2008 (7648 total trap nights) and 2010 (7353 total trap nights).

Species	2008 (Pre-treatment)	2010 (Post-treatment)
Mice	217	153
Peromyscids (*P. maniculatus, P. leucopus*)	178	131
Woodland jumping mouse (*Napaeozapus insignus*)	36	21
Golden mouse (*Ochrotomys nuttalli*)	3	1
Shrews	37	21
Northern short-tail shrew (*Blarina brevicauda*)	34	20
Masked shrew (*Sorex cinereus*)	2	0
Smoky shrew (*Sorex fumeus*)	1	1
Voles	9	1
Southern redback vole (*Myodes gapperi*)	6	0
Woodland vole (*Microtus pinetorum*)	3	1
Southern flying squirrel (*Glaucomys volans*)	4	7
Eastern chipmunk (*Tamias striatus*)	1	0

shelterwood harvest declined 40% post-harvest but changed little in all other treatments. Bare ground increased in prescribed burns of 2009 and shelterwood harvests by 48% and 33%, respectively. Leaf litter cover decreased by 64%, 41%, and 38% in prescribed burns of 2009, shelterwood harvests, and prescribed burns of 2010, respectively. CWD cover in shelterwood harvests increased by 5% post-harvest but changed little in other treatments. Following the shelterwood harvest, CWD had more bark and was less decayed than the other treatments (Table 1).

In the second year post-treatment (2011), changes in percent bare ground were similar among treatments. Leaf litter declined 46% in shelterwood harvests, but recovered to pre-treatment levels in both prescribed burn treatments. Understory cover increased 58% and 51% in shelterwood harvests and prescribed burns of 2009, respectively, whereas other treatments changed less dramatically (Table 1).

3.2. Small mammal sampling

Small mammals captured in Sherman live traps included four species of mice, three species of shrews, two species of voles, southern flying squirrels (*Glaucomys volans*), and eastern chipmunks (*Tamias striatus*) (Table 2). From 2008 to 2010 (e.g., pre- to post-treatment), the change in species richness of small mammals captured in Sherman live traps was similar among treatments (Table 3).

Peromyscids were the primary species captured in Sherman live traps, composing 86% and 82% of the total mouse captures in 2008 and 2010, respectively. In 2008, we captured 178 peromyscids 367 times in 7648 trap nights. In 2010, we captured 131 peromyscids 270 times in 7353 trap nights (Table 2). In 2008 and 2010, trap-related peromyscid mortality averaged <1%. From 2008 to 2010 (e.g., pre- to post-treatment), the change in population estimates of peromyscids was similar among treatments ($F_{4,\ 14} = 1.16$, $P = 0.37$, Fig. 1).

The change in species richness of small mammals captured in drift fence arrays was similar among treatments (Table 3). We captured seven species of shrews, four species of mice, and two species of voles in drift fence arrays in 2008, 2010, and 2011 (Table 4). In 2008, we captured 768 masked shrews, 98 smoky shrews, and 91 northern short-tailed shrews in 15,552 trap nights. In 2010, we captured 671 masked shrews, 69 smoky shrews, and 164 northern short-tailed shrews in 19,848 trap nights. In 2011, we captured 597 masked shrews, 76 smoky shrews, and 203 northern short-tailed shrews in 17,800 trap nights (Table 4). From 2008–2011, trap-related shrew mortality averaged 72%. The masked shrew was the most abundant species captured, accounting for 58%, 56%, and 55% of the small mammal captures in 2008, 2010 and 2011, respectively.

From pre-treatment (2008) to post-treatment (2010 and 2011), the change in relative abundance of masked shrews ($F_{4,\ 14} = 0.70$, $P = 0.60$), smoky shrews ($F_{4,\ 14} = 0.49$, $P = 0.74$), and northern short-tailed shrews ($F_{4,\ 14} = 1.84$, $P = 0.18$) was similar among treatments (Fig. 2). However, there was a year effect for each species [masked shrews ($F_{1,\ 18} = 68.28$, $P < 0.001$), smoky shrews ($F_{1,\ 18} = 14.32$, $P < 0.01$), and northern short-tailed shrews ($F_{1,\ 18} = 21.19$, $P < 0.001$)] with a greater increase in captures in 2011 (second year post-treatment) than in 2010 (first year post-treatment).

4. Discussion

In our study, species richness and abundance of rodents and shrews were unaffected by silvicultural treatments designed to promote oak regeneration. This was likely because these species can tolerate a wide range of forest conditions. Several other studies also showed peromyscid and shrew populations were not affected by prescribed fire or timber harvests (Brooks and Healy, 1988; Ford et al., 1999, 2002; Greenberg et al., 2006; Keyser et al., 2001; Matthews et al., 2009; Stratton and Clatterbuck, 2007). In fact,

Table 3
Mean species richness (±SE) of small mammals captured in Sherman live traps and drift fence arrays in oak regeneration treatments on Cold Mountain Game Land, NC: control (CONT), herbicide (HERB), shelterwood harvest (SW), prescribed burn 2010 (RX1), and prescribed burn 2009 (RX2). Sherman live traps were open for 7648 and 7353 trap nights in 2008 and 2010, respectively. Drift fence arrays were open for 15,552 trap nights in 2008, 19,848 trap nights in 2010, and 17,800 trap nights in 2011.

Year	Sherman live traps						
	CONT	HERB	SW	RX1	RX2	$F_{4,9}$	P_{trt}
2008	2.8 ± 0.7	4.8 ± 0.7	4.3 ± 0.9	3.3 ± 0.3	2.5 ± 0.5		
2010	2.4 ± 0.7	3.4 ± 0.7	2.3 ± 0.9	2.3 ± 0.3	1.5 ± 0.5		
2010–2008	−0.4 ± 0.5	−1.4 ± 0.8	−2.0 ± 0.7	−1.0 ± 0.0	−1.0 ± 1.0	0.83	0.54
	Drift fence arrays						
	CONT	HERB	SW	RX1	RX2	$F_{4,14}$	P_{trt}
2008	6.4 ± 0.7	8.4 ± 1.3	6.8 ± 1.0	6.7 ± 0.7	6.5 ± 0.5		
2010	6.6 ± 1.5	7.8 ± 0.6	4.5 ± 0.3	6.7 ± 1.7	4.0 ± 0.0		
2011	7.0 ± 0.5	7.2 ± 1.0	7.3 ± 0.9	5.7 ± 0.9	5.5 ± 1.5		
(2010 + 2011)–2008	0.4 ± 0.6	−0.9 ± 0.6	−0.9 ± 1.1	−0.5 ± 0.6	−1.8 ± 0.6	0.62	0.65

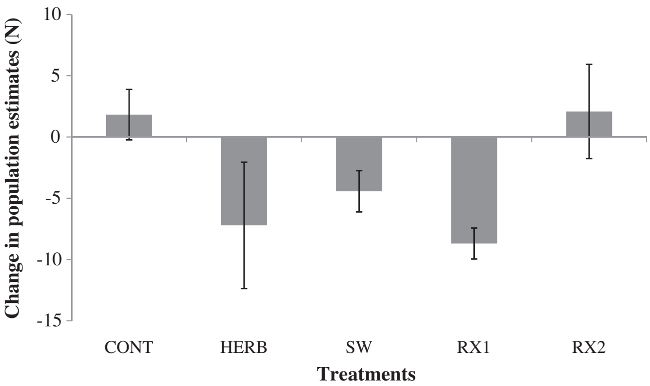

Fig. 1. Change in population estimates of peromyscids following treatments. Change in mean population estimates (N) of peromyscids (±SE) from 2008 to 2010 from Sherman live traps in oak regeneration treatments on Cold Mountain Game Land, NC: control (CONT), herbicide (HERB), shelterwood harvest (SW), prescribed burn 2010 (RX1), and prescribed burn 2009 (RX2). Traps were open for 7648 and 7353 trap nights in 2008 and 2010, respectively.

Table 4
Small mammals captured in drift fence arrays in oak regeneration treatments on Cold Mountain Game Land, NC. Drift fences were open for 15,552 trap nights in 2008, 19,848 trap nights in 2010, and 17,800 trap nights in 2011.

Species	Pre-treatment 2008	Post-treatment 2010	Post-treatment 2011
Shrews	1239	1105	1005
Masked shrew (*Sorex cinereus*)	768	671	597
Northern short-tailed shrew (*Blarina brevicauda*)	91	164	203
Smoky shrew (*Sorex fumeus*)	98	69	76
Pygmy shrew (*Sorex hoyi*)	18	8	9
Rock shrew (*Sorex dispar*)	15	5	16
Least shrew (*Cryptotis parva*)	4	6	24
Water shrew (*Sorex palustris*)	1	0	0
Voles	44	48	25
Woodland vole (*Microtus pinetorum*)	25	20	23
Southern redback vole (*Myodes gapperi*)	19	28	2
Mice	41	35	50
Deer mouse (*Peromyscus maniculatus*)	12	13	18
White-footed mouse (*Peromyscus leucopus*)	16	13	11
Woodland jumping mouse (*Napaeozapus insignus*)	11	4	15
Golden mouse (*Ochrotomys nuttalli*)	1	3	5

peromyscids are described as generalists, living under a wide range of temperatures and moisture conditions following disturbance (Brannon, 2005; Dueser and Shugart, 1978; Getz, 1961; Mitchell et al., 1997).

Absence of small mammal response to oak regeneration treatments may be partly attributed to the relatively minor changes to habitat structure in the herbicide and prescribed burn treatments, and retention of important habitat features in shelterwood harvests, such as slash piles. Following the herbicide application there were no significant changes in understory, leaf litter, or CWD cover. Increased bare ground cover following prescribed burns and shelterwood harvests disappeared by the second year post-treatment due to rapid recovery of leaf litter and increases in understory cover, which may have alleviated possible stresses on moisture-dependent shrews. Additionally, residual piles of logging slash in shelterwood harvests may have sustained small mammal populations by providing food, travel corridors, and protection from predators (Loeb, 1999; Menzel et al., 1999; Planz and Kirkland, 1992).

Fluctuating precipitation levels during sampling years may have mitigated potential effects of oak regeneration treatments on small mammal populations. Compared to 2008 (pretreatment), more individuals of all three shrew species analyzed were captured during the second year post-treatment (2011) compared to 2010, when there was less rainfall. Average precipitation for Haywood County from May to August of 2011 was 26 inches higher than May to August of 2010 (National Weather Service, 2011). Thus, greater rainfall in 2011 may have compensated for possible reductions in moisture caused by shelterwood harvests or prescribed fire. Similarly, Ford et al. (2002) concluded capture frequency of shrews was more influenced by differences in weather conditions between years than by differences in hardwood forest conditions ranging in age from recently clearcut to >60 years old. Additionally, other studies have documented rainfall as an important predictor of captures and/or activity of small mammals, including peromyscids and shrews (Brannon, 2002; Drickamer and Capone, 1977; McCay, 1996).

Delayed effects of treatments on forest composition and structure may cause long-term changes in small mammal abundance. Although a single herbicide application did not affect canopy, understory, leaf litter, or CWD cover, habitat changes may increase with future midstory dieback and increased photosynthetically active radiation (PAR) to the forest floor. Additionally, changes in food resources such as acorns or native fleshy fruits could potentially affect rodent populations in the future (Greenberg et al., 2011; McCracken et al., 1999; Schnurr et al., 2004).

Planned activities associated with these oak regeneration treatments, including repeated prescribed fires, repeated herbicide

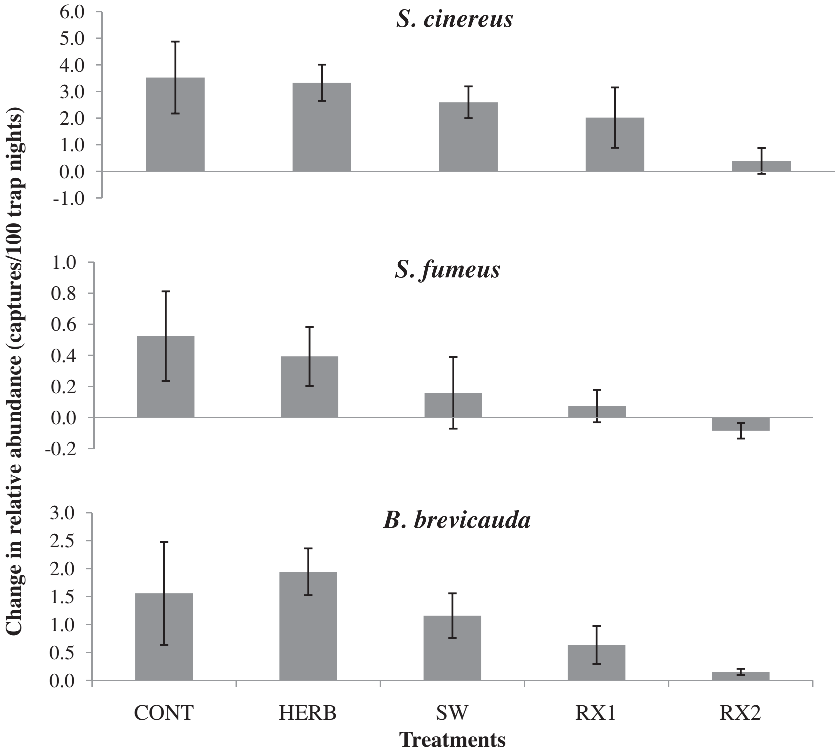

Fig. 2. Change in relative abundance of shrew species following treatments. Change in relative abundance (captures/100 trap nights) (±SE) from pre-treatment (2008) to post-treatment (2010 and 2011) in oak regeneration treatments on Cold Mountain Game Land, NC: control (CONT), herbicide (HERB), shelterwood harvest (SW), prescribed burn 2010 (RX1), and prescribed burn 2009 (RX2) for masked shrews (*S. cinereus*), smoky shrews (*S. fumeus*), and northern short-tailed shrews (*B. brevicauda*). Drift fence arrays were open for 15,552, 19,848, and 17,800 trap nights in 2008, 2010, and 2011, respectively.

applications, and prescribed burns following shelterwood harvests, may have additive effects on small mammals (Matthews et al., 2009). Repeated prescribed burning may compound treatment effects on some habitat features (e.g., reduced leaf litter or duff layer) and impact litter-dependent species such as invertebrates and shrews (Coleman and Rieske, 2006; Van Lear and Watt, 1993). Additionally, the combination of shelterwood harvests and prescribed fires could result in substantial changes to habitat conditions compared to either disturbance alone. For example, Matthews et al. (2009) caught 77% fewer southeastern shrews (*S. longirostris*) in fuel reduction treatments where the understory had been mechanically thinned followed by two prescribed burns (3 years apart) than in either mechanically thinned or twice burned treatments alone (Matthews et al., 2009).

4.1. Conclusions

In the short-term, we detected no changes in mouse or shrew abundance or species richness following oak regeneration treatments. Lack of response was likely due to the ability of peromyscids and shrews to tolerate a wide range of forest conditions following treatment disturbance, as well as rapid re-establishment of understory cover in shelterwood harvests and prescribed burns, and residual piles of logging slash in shelterwood harvests. Longer-term studies are imperative to determine response of small mammals to delayed treatment effects and additive effects from long-term oak regeneration systems such as repeated prescribed fires, prescribed burns following shelterwood harvests, and overstory removal. Silvicultural practices to promote oak regeneration likely will be performed primarily on small acreages of state wildlife management areas or other public lands where landscape-level changes would be difficult to achieve. Thus, silviculture activities in areas dominated by mature mixed-oak or xeric oak-pine forests are unlikely to affect small mammals on a regional scale. However, we recommend forest managers consider and integrate multiple objectives when making management decisions. For example, the efficacy of each oak regeneration treatment should be considered in conjunction with conservation of focal wildlife species.

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