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Shrew response to variable woody debris retention: Implications for sustainable forest bioenergy

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ABSTRACT

Shrews are integral components of forest food webs and may rely on downed woody debris to provide microhabitats that satisfy high moisture and metabolic requirements. However, woody biomass harvests glean downed woody debris to use as a bioenergy feedstock. Biomass Harvesting Guidelines (BHGs) provide guidance on the amount and distribution of downed woody debris retained after harvest to ensure ecological sustainability of woody biomass harvesting and limit detrimental effects on wildlife. However, the success of Biomass Harvesting Guidelines at reaching sustainability goals, including conservation of wildlife habitat, has not been tested in an operational setting. Thus, we compared shrew captures among six woody biomass harvesting treatments in pine plantations in North Carolina, USA from April to August 2011–2014 ($n = 4$) and Georgia, USA from April to August 2011–2013 ($n = 4$). Treatments included: (1) woody biomass harvest with no BHGs; (2) 15% retention with woody biomass dispersed; (3) 15% retention with woody biomass clustered; (4) 30% retention with woody biomass dispersed; (5) 30% retention with woody biomass clustered; and (6) no woody biomass harvested. We sampled shrews with drift fence arrays and compared relative abundance of shrews among treatments using analysis of variance. Additionally, we used general linear regression models to evaluate the influence of downed woody debris volume and vegetation structure on shrew capture success at each drift fence for species with >100 captures/state/year. In 53,690 trap nights, we had 1,712 shrew captures representing three species, *Cryptotis parva*, *Blarina carolinensis*, and *Sorex longirostris*. We did not detect consistent differences in shrew relative abundance among woody biomass harvest treatments, but relative abundance of all species increased over time as vegetation became established. In North Carolina, total shrew capture success was negatively related to volume of downed woody debris within 50 m of the drift fence array ($P = 0.05$) in 2013 and positively related to bare groundcover in 2013 ($P = 0.02$) and 2014 ($P < 0.01$). In Georgia, total shrew capture success was negatively related to herbaceous groundcover ($P < 0.01$) and leaf litter groundcover ($P = 0.02$) and positively related to woody vegetation groundcover ($P < 0.01$) and vertical vegetation structure ($P = 0.03$) in 2013. Our results suggest that shrews in our study area were associated more with vegetation characteristics than downed woody debris and that woody biomass harvests may have little influence on shrew abundances in the southeastern United States Coastal Plain.

1. Introduction

Shrews are key components of forest food webs and have been used as indicators of the ecological effects of forestry practices (Hamilton, 1941; Van Zyll de Jong, 1983; Carey and Harrington, 2001; Ford and Rodrigue, 2001; Matthews et al., 2009). Shrews have high nutritional and moisture requirements; therefore shrews may be sensitive to forestry practices that change forest

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floor microhabitats and microclimate (Chew, 1951; Getz, 1961; Churchfield, 1990; Matthews et al., 2009). Specifically, shrew presence and abundance have been linked positively with canopy cover, leaf litter depth and cover, and available downed woody debris (Carey and Johnson, 1995; Lee, 1995; Butts and McComb, 2000; Hartling and Silva, 2004; Greenberg et al., 2007).

Downed woody debris is an integral ecosystem component, providing cover and food for shrews and other wildlife (Harmon et al., 1986; Lattimore et al., 2009; Evans and Kelty, 2010; Janowiak and Webster, 2010; Riffell et al., 2011). For example, downed woody debris retains moisture and provides microhabitats in a range of temperature and moisture regimes, with the temperature under and inside of logs often lower than ambient (Graham, 1925; Jaeger, 1980; Kluber et al., 2009). The high metabolic rate of shrews leads to increased evaporative water loss and potential desiccation (Churchfield, 1990; Ochocińska and Taylor, 2005). Hence, shrews may be dependent on downed woody debris because they are sensitive to changes in environmental moisture (Getz, 1961).

The availability of downed woody debris, particularly coarse woody debris (debris $\geqslant$ 7.62 cm in diameter for a length of at least 0.914 m, Woodall and Monleon (2008)), has been shown to influence shrew presence and abundance in some regions of the United States, though relationships in other regions are equivocal. For example, population sizes of Trowbridge's shrew (*Sorex trowbridgii*) and montane shrew (*Sorex monticolus*) in the Pacific Northwest of the United States are positively associated with abundance of coarse woody debris (Carey and Johnson, 1995; Butts and McComb, 2000). In the southeastern United States Coastal Plain, some shrew species have positive relationships with decay state of woody debris cover and amount of log cover, whereas relationships between other shrew species and coarse woody debris are inconsistent (McCay and Komoroski, 2004; Cromer et al., 2007; Moseley et al., 2008; Davis et al., 2010). In southeastern United States pine forests, capture successes of southern short-tailed shrews (*Blarina carolinensis*) and southeastern shrews (*Sorex longirostris*) were greater in areas with abundant volumes of retained downed woody debris; yet, capture success of least shrews (*Cryptotis parva*) may not be associated with downed woody debris (Loeb, 1999; Moseley et al., 2008; Davis et al., 2010). Thus, the relationships between downed woody debris and shrews may vary based on forest type, geographic region, and shrew species.

Downed woody debris is gleaned as woody biomass, which is a major feedstock of bioenergy worldwide (Perlack et al., 2005; Hillring, 2006; Mantau et al., 2010). The southeastern United States is the largest exporter of wood pellets and is experiencing the most rapid growth of forest bioenergy production facilities in the world (Mendell and Lang, 2012; Goh et al., 2013). Domestic and foreign policies that encourage bioenergy production drive demand for forest bioenergy, which could involve increasing levels of woody biomass extraction with unknown effects on functionality and sustainability of forests in the southeastern United States (Evans et al., 2013). Further, demand for woody biomass is expected to continue to increase as renewable energy mandates are implemented in the European Union, which is supplied in great part by wood pellets produced from forests in the southeastern United States (Goh et al., 2013). Based on 2013 estimates, pellet production may increase by 87% in 2014 over the 2012 production level in the United States alone (Forisk Consulting, 2013). Woody biomass also is a feedstock of second generation biofuels, and the United States Department of Agriculture (USDA) predicts that approximately 50% of second generation biofuels needed to meet United States biofuel mandates will originate from the Southeast region by 2020 (USDA, 2010). Woody biomass harvests glean forest harvest residues, including treetops, limbs, slash, and felled small trees, generally in tandem with harvest of roundwood products. Although woody biomass has been harvested for energy production for decades (Stuart et al., 1981; Van Hook et al., 1982; Watson et al., 1986; Puttock, 1987), current levels of extraction decreased downed woody debris by up to 81% compared to sites without a woody biomass harvest in southeastern United States pine plantations (Fritts et al., in press).

Concerns about potential effects on wildlife habitat and other ecological consequences of harvesting woody biomass from decreasing volumes of downed woody debris have prompted the development of voluntary Biomass Harvesting Guideline (BHG) implementation by managers on operational forestlands (MFRC, 2007; Röser et al., 2008; PADCNR, 2008; KYDOF, 2011; Perschel et al., 2012). Because of the ecological value of downed woody debris for wildlife, nutrient cycling, and erosion control, Biomass Harvesting Guidelines typically focus on a target volume of woody biomass to be retained on the forest floor to maintain biological diversity and site productivity (Harmon and Hua, 1991; Ranius and Fahrig, 2006). Biomass Harvesting Guidelines have been created under the idea that "more" downed woody debris is better than "less," but minimum volumes and spatial arrangements of downed woody debris needed to sustain wildlife populations are not understood. Biomass Harvesting Guidelines often recommend retaining volumes of both coarse woody debris and fine woody debris (debris smaller than coarse woody debris) to meet sustainability goals; however, suggested volumes, sizes, and spatial arrangements of downed woody debris vary among Biomass Harvesting Guideline documents and have little empirical support. Thus, research is needed to determine the effects of woody biomass harvests and implementation of Biomass Harvesting Guidelines on sustainability, particularly for shrews and other wildlife species associated with downed woody debris.

Lack of consensus on associations between shrews and downed woody debris in the southeastern United States, coupled with an absence of operational-scale research on woody biomass harvesting, warrant investigation of shrew response to variations in downed woody debris retention following woody biomass harvests. Because dead wood decays relatively quickly in the Southeast (Moorman et al., 1999), the first 3–4 years post-harvest is the appropriate time to detect shrew responses. Our objectives were to: (1) evaluate the effects of different levels of woody biomass harvests on shrew relative abundance; and (2) quantify the relationships between shrew capture success and downed woody debris volume, vegetation structure, and vegetation composition.

2. Methods

2.1. Study area and design

We conducted our study on eight replicate clearcuts (i.e., unit of replication) in the Coastal Plain Physiographic Region of the southeastern United States: four in Beaufort County, North Carolina (-077°0′0″W to -076°53′50″W and 35°34′0″N to 35°38′20″N); three in Glynn County, Georgia (-081°44′40″W to -0.81°40′42″W and 31°07′31″N to 31°11′14″N); and one in Chatham County, Georgia (-081°11′26″W to -081°10′37″W and 32°18′46″N to 32°19′21″N), USA. All study sites were in intensively managed loblolly pine (*Pinus taeda*) plantations. North Carolina sites were managed for sawtimber production, had two commercial thinning entries before the final harvest, and were 32–39 years old at time of clearcut harvest. Georgia sites were managed for chip-and-saw and pulpwood production and were 25–33 years old at time of final harvest. Three Georgia sites had one commercial thinning entry and one site had two commercial thinning entries before clearcut harvest. North Carolina soils were predominately loam and silt loam. Georgia soils were predominantly loam, clay loam, and fine sandy loam.

Clearcut harvests with woody biomass removal treatments were implemented in 2010–2011. North Carolina sites were 70.5 ± 6.1 (mean ± SE) ha and Georgia sites were 64.4 ± 3.1 ha. We divided each site into six randomly-assigned treatments of 11.7 ± 0.5 ha (range = 8.4–16.3 ha) in North Carolina and 10.7 ± 0.4 ha (range = 7.6–14.3 ha) in Georgia: (1) clearcut with a traditional woody biomass harvest and no Biomass Harvesting Guidelines implemented (NOBHG); (2) clearcut with 15% retention of woody biomass evenly dispersed throughout the treatment unit (15DISP); (3) clearcut with 15% retention of woody biomass in large piles throughout the treatment unit (15CLUS); (4) clearcut with 30% retention of woody biomass evenly dispersed throughout the treatment unit (30DISP); (5) clearcut of 30% retention with woody biomass in large piles throughout the treatment unit (30CLUS); and (6) clearcut with no woody biomass harvest (i.e., clearcut only; NOBIOHARV), which served as a reference. Downed woody debris was distributed using a grapple skidder; therefore, piles retained in the CLUS and NOBIOHARV treatments were approximately the size of one grapple load. Retention targets focused on hardwoods not merchantable as roundwood from the retention areas in the four BHG treatments or from the entire treatment area in NOBIOHARV. For NOBHG treatments, we instructed loggers to follow normal operating procedures for a typical woody biomass harvest. For the NOBIOHARV treatments, roundwood was harvested, but we asked loggers to leave all woody biomass not harvested as roundwood on the ground as downed woody debris. We implemented the four BHG treatments using retention areas that represented either 15% or 30% of the total treatment plot area using ArcGIS (ESRI, Redlands, California, USA). Prior to clearcut harvesting, we located retention areas using a handheld Garmin Rino global positioning system (Olathe, Kansas, USA) and flagged boundaries. During clearcut and treatment implementation, all standing pines merchantable as roundwood were cut and transported to the logging deck with a grapple skidder, and most hardwoods from the retention areas were left intact and redistributed throughout the treatment unit with a skidder. Retention areas were clearcut after the other 85% or 70% of the non-retention treatment areas were harvested; therefore, retention area locations were placed as far from the nearest logging deck as possible so that roundwood and woody biomass from the non-retention area could be harvested easily. In the non-retention areas and NOBHG treatment units, woody biomass was recovered and chipped at the logging decks during harvest. In the retention areas, loggers retained woody biomass to be either spread evenly throughout the dispersed (DISP) treatments or placed in grapple-sized piles randomly throughout the clustered (CLUS) treatments.

Site preparation differed between states. In North Carolina, sites were sheared using a V-shaped blade following harvest and before year one of shrew sampling to reduce stumps and fell any remaining stems. Sites were bedded (i.e., the soil was pushed into continuous mounded strips approximately 3 m wide) to provide a raised growing surface for seedlings and planted fall-winter 2011–2012 (i.e., after one year of shrew sampling) at a density of ≈1100 trees ha^{-1}. Shearing moved downed woody debris into the 3-m space between pine beds, and rearranged downed woody debris into long, linear rows. Sites received two post-harvest herbicide applications of Chopper© (BASF, Raleigh, North Carolina, USA – a broadcast application (i.e., applied by aircraft) year one post-harvest and a banded application (i.e., applied only to bedded mounds) year two post-harvest.

Two of the Georgia sites were clearcut with treatments implemented in winter 2010–2011 and were available for sampling in 2011. The remaining two Georgia sites were clearcut in summer and fall 2011 and were available for sampling in 2012. Following harvest of the Georgia sites, most debris was pushed into large windrows (i.e., piles that extend for the entire length of the treatment unit) or large piles (1–100 m^3) in each treatment unit; few individual stems and no small downed woody debris piles (<1 m^3) were distributed throughout the treatment units. Two of the Georgia sites were double-bedded in summer 2011 and one site was double-bedded in fall 2011; all three were planted in winter 2012 at a density of ≈1495 trees ha^{-1}. The same three sites received a banded herbicide application of Arsenal© (BASF, Raleigh, North Carolina, USA) and Sulfometuron methyl in spring 2012. The fourth Georgia site was bedded, planted at a density of ≈726 trees ha^{-1}, and received a broadcast herbicide treatment of Chopper© in spring 2012.

2.2. Shrew sampling

We sampled shrews mid-April to early-August 2011–2014 in North Carolina and 2011–2013 in Georgia. In North Carolina, we sampled for one year post-harvesting and V-shearing (2011) and for three years after bedding and planting (2012–2014). In 2012 and 2013, we sampled all sites in both states, but we were unable to sample two of the Georgia sites in 2011 because they had not been harvested. Further, we did not sample in Georgia in 2014 because of resource constraints. Therefore, in Georgia, we sampled two sites in 2011, which was one year post-harvesting, windrowing and spot piling and all four sites in 2012 and 2013, which was for two years post-bedding and planting. Using ArcGIS, we divided each treatment unit into four equal-sized quadrants and randomly selected three of the four quadrants for a drift fence array. We constructed drift fences in a 'Y'-shape in the center of the selected quadrants with 7.6-m arms from silt-fence material >30 m apart and with a 19-L plastic bucket buried flush with the ground at each end. We placed a three-sided funnel trap modified from Burgdorf et al. (2005) in the center of one randomly selected drift fence in each treatment unit and placed a 19-L bucket buried flush with the ground in the center of the other two drift fences in each treatment unit. We drilled three small holes in the bottom of each bucket for water drainage and placed sponges in each trap that were wetted daily. We used bucket lids raised ≈25 cm to provide shade. We checked open traps daily for ten consecutive days in 2011 and five consecutive days in 2012–2014. Traps remained closed for two to three consecutive days between sampling periods. We simultaneously sampled two to four replicate clearcuts in North Carolina and one to three replicate clearcuts in Georgia. We identified each captured shrew to species and released live shrews ≈10 m from the drift fence array. All sampling and handling procedures were approved by the North Carolina State University Institutional Animal Care and Use Committee (11-022-O), the Georgia Department of Natural Resources (scientific collection permit number 29-WJH-13-156), and the North Carolina Wildlife Resources Commission (scientific collection permit number 11SC00534).

2.3. Quantifying habitat

In 2011, we measured volume of downed woody debris in each treatment unit using a line-intersect sampling technique (Van Wagner, 1968). We established 7.32-m transects radiating from the plot center point at 0°, 120°, and 240° azimuths for sampling coarse woody debris and 3.13-m transects radiating from the plot center for sampling fine woody debris. Because few piles fell within our line intersect sampling plots, we also used a visual encounter method to census piled downed woody debris. In North Carolina, we visually located and measured the length, width, height, and packing ratio (i.e., density of wood versus air or soil; 0–100%) of total woody debris of all hardwood and large pine piles. Most large hardwoods were retained for implementation of Biomass Harvesting Guideline treatments, whereas large pine trees (diameter at 1.37 m above the ground ⩾12.6 cm) were harvested as roundwood (Fritts et al., in press). We defined hardwood piles as ⩾two hardwood trees retained on the forest floor as a result of retention treatments (i.e., retention of 15%, 30% or all woody biomass), and we defined large pine piles as any pine residue pile >1.6 m in height or >3.8 m in length and estimated as having <50% soil. Pines were stripped of their limbs at harvest, and pine piles were created when pine limbs were pushed together during shearing. In Georgia, we visually located and measured the width, height, and packing ratio of all windrows and spot piles. Windrows often were the length of the entire treatment unit, so we measured the lengths using aerial photographs in ArcGIS. Georgia windrows and spot piles primarily contained pine debris. For both states, we summed the volume of piled downed woody debris estimated with the visual encounter method and the volume of scattered downed woody debris estimated using the line intersect sampling method to determine the volume (m^3 ha^{-1}) of total downed woody debris for each treatment unit. Each site contained two to three logging decks for harvesting the six treatment units. Large butts of trees from the entire clearcut (i.e., all treatment units) were retained at the logging deck, so we did not include the deck debris in the final debris volume estimates. We recorded pile locations using a Garmin Rino global positioning system and used ArcGIS to ensure no piles were double-counted. We measured the distance of each drift fence array to the nearest downed woody debris pile. In North Carolina, where downed woody debris piles were distributed throughout the site instead of in windrows or spot piles, we used ArcGIS to estimate the volume of piled downed woody debris within 50 m of each drift fence array. Additionally, we measured the distance of each drift fence array to the nearest parallel drainage ditch, which historically were constructed to lower the water table and improve pine growth. In Georgia, we measured the distance of each drift fence array to the nearest unharvested wetland depression.

In 2013 and 2014, when vegetation cover was well established in regenerating stands, we estimated vertical vegetation structure and groundcover along three 10-m transects at each drift fence array. We established transects starting at the array center and radiating outwards directly between two drift fence arms. We sampled vegetation at ten points with 1-m increments on each transect. We used the average number of times vegetation touched a 2-m tall, 4.8-cm diameter pole at each point across the 30 points as an index of vertical vegetative structure at each fence (Moorman and Guynn, 2001). We recorded all groundcover types (bare ground, coarse woody debris, fine woody debris, herbaceous, leaf litter, and woody) that touched the bottom of the pole at each point. Then, we calculated the % cover of each ground cover type at each drift fence by dividing the number of points with each ground cover type by 30. Groundcover could be >100% because more than one vegetation type may have been present at one point.

2.4. Statistical analyses

We calculated the number of captures per 100 trap nights (hereafter, relative abundance) of all shrew species combined (i.e., total shrews) and each shrew species for each treatment unit. We examined differences in total shrew relative abundance and the relative abundance of individual shrew species among treatments separately in each state and each year using randomized complete block design analysis of variance (ANOVA) with relative abundance as the dependent variable, replicate as the blocking factor, and treatment as a class predictor. We used Tukey's Studentized Range criteria to separate treatment means when models were significant at $\alpha = 0.05$ level. We conducted all analyses using statistical software program R (version 3.0.2; R Core Team, 2012).

We examined differences among treatments in downed woody debris volume, vegetation structure, and groundcover composition. We tested each response variable for normality using the Shapiro-Wilks test. When response variables were normally distributed, we used separate randomized complete block design analysis of variances (ANOVA) for each state to examine differences among treatments. When response variables were not normally distributed, we used non-parametric Friedman tests for each state to examine differences among treatments.

To determine fine-scale shrew population response to woody biomass harvesting, we determined if downed woody debris availability, vertical vegetation structure, and ground cover were predictors of shrew captures when captures of one species or total combined species were >100 in one year in one state. We used separate models for each state, year, and species (except for the total combined species analyses) because site preparation activities differed by state, retained downed woody debris volume estimates varied by state, vegetation was not established until 2013, and shrew response to downed woody debris can vary by species. We also used combined shrew captures because we had low capture success of some species. We used generalized linear models with number of shrew captures per drift fence (i.e., combined shrew captures and captures of each species) as each response variable, and volume of downed woody debris in the treatment unit, distance of drift fence array to nearest debris pile, distance of drift fence array to the nearest ditch (North Carolina) or unharvested wetland (Georgia), volume of piled downed woody debris within 50 m of the drift fence array (North Carolina only), and effort (i.e., the number of trap nights for each drift fence during the season) as independent explanatory variables. In 2013 and 2014, we included vertical vegetation structure and % cover of bare ground, coarse woody debris, fine woody debris, leaf litter, herbaceous vegetation, and woody vegetation as independent explanatory variables (Appendix A). We assessed collinearity using variation inflation factors and dropped one covariate if the factor was >3.0 (Zuur et al., 2010). We tested each response variable for normality using the Shapiro–Wilks test. When response variables were not normally distributed, we applied a Poisson GLM. We assumed overdispersion when the residual deviance divided by the residual degrees of freedom was >1 and corrected the standard errors using a quasi-GLM model when we detected overdispersion. We selected the best models at predicting shrew captures by dropping one explanatory variable, in turn, and each time applying an analysis of deviance test between the previous and current models (Zuur et al., 2009). We validated each selected model by graphically examining residuals and using Cook's distance to assess the model for influential observations (Cook, 1979; Fox, 2002; Zuur et al., 2009). We set $\alpha = 0.05$.

3. Results

We had 1,712 shrew captures, including 87 *B. carolinensis*, 771 *C. parva*, and 854 *S. longirostris*, in 53,690 trap nights in four years in North Carolina and three years in Georgia (Table 1). Trap-related shrew mortality was 63%. We did not compare relative abundance of shrews among treatments in North Carolina in 2011 or *B. carolinensis* individually in any year in North Carolina because of low capture success (Table 1). In North Carolina in 2012, the relative abundances of all shrew species combined ($F_{5,17} = 1.75$, $P = 0.18$) and *C. parva* ($F_{5,17} = 0.26$, $P = 0.93$) did not differ among treatments. The relative abundance of *S. longirostris* differed among treatments in North Carolina in 2012 ($F_{5,17} = 2.88$, $P = 0.05$), with >4× greater relative abundance in NOBIOHARV than 15DISP, but there were no differences among other treatments (Table 2). In North Carolina in 2013, relative abundances of all shrew species combined ($F_{5,17} = 0.95$, $P = 0.47$), *C. parva* ($F_{5,17} = 0.59$, $P = 0.71$) and *S. longirostris* ($F_{5,17} = 1.23$, $P = 0.34$) did not differ among treatments (Table 2).

Table 1
Captures of southern short-tailed shrews (*Blarina carolinensis*), least shrews (*Cryptotis parva*), southeastern shrews (*Sorex longirostris*), and total shrews in six woody biomass harvest treatments in loblolly pine (*Pinus taeda*) plantations in Beaufort County, North Carolina ($n = 4$) and Glynn County ($n = 3$) in 2011–2014 and Chatham County ($n = 1$), Georgia in 2011–2013. Treatments were: (1) no Biomass Harvesting Guidelines (NOBHG); (2) 15% woody biomass retention in piles (15CLUS); (3) 15% woody biomass retention distributed evenly throughout the treatment unit (15DISP); (4) 30% woody biomass retention in piles (30CLUS); (5) 30% woody biomass retention distributed evenly throughout the treatment unit (30DISP); (6) and no woody biomass harvesting (NOBIOHARV).

	North Carolina				Georgia			
	2011	2012	2013	2014	2011	2012	2013	Total
Blarina carolinensis	10	14	12	46	0	2	3	87
Cryptotis parva	7	58	329	165	0	0	212	771
Sorex longirostris	33	235	312	249	0	0	25	854
Total	50	307	653	460	0	2	240	1712

Table 2
Captures per 100 trap nights (mean ± SE) of *Blarina carolinensis* (BLCA), *Cryptotis parva* (CRPA), *Sorex longirostris* (SOLO), and total shrew captures (TOT) in clearcut upland loblolly pine (*Pinus taeda*) plantations in Beaufort County, North Carolina (NC; $n = 4$) in 2011–2014 and Glynn County ($n = 3$) and Chatham County ($n = 1$), Georgia (GA) in 2011–2013. Treatments were: (1) no Biomass Harvesting Guidelines (NOBHG); (2) 15% woody biomass retention in piles (15CLUS); (3) 15% woody biomass retention distributed evenly throughout the treatment unit (15DISP); (4) 30% woody biomass retention in piles (30CLUS); (5) 30% woody biomass retention distributed evenly throughout the treatment unit (30DISP); (6) and no woody biomass harvesting (NOBIOHARV). Treatment means were compared using two-way analysis of variance. Different letters indicate significantly different means at $\alpha = 0.05$. No *P*-value indicates a sample size too small to compare.

State	Species	Year	Treatment						P_{trt}
			NOBHGS	15DISP	15CLUS	30DISP	30CLUS	NOBIOHARV	
NC	BLCA	2011	0.09 ± 0.06	0.09 ± 0.09	0.00 ± 0.00	0.28 ± 0.15	0.06 ± 0.06	0.10 ± 0.10	
		2012	0.05 ± 0.05	0.12 ± 0.07	0.17 ± 0.17	0.24 ± 0.14	0.06 ± 0.06	0.42 ± 0.20	
		2013	0.35 ± 0.15	0.17 ± 0.10	0.08 ± 0.08	0.15 ± 0.09	0.58 ± 0.49	0.12 ± 0.12	
		2014	0.30 ± 0.22	0.50 ± 0.22	0.30 ± 0.11	0.84 ± 0.37	0.45 ± 0.20	0.41 ± 0.20	
	CRPA	2011	0.00 ± 0.00	0.12 ± 0.07	0.16 ± 0.05	0.05 ± 0.05	0.00 ± 0.00	0.05 ± 0.05	
NC	CRPA	2012	0.59 ± 0.30	0.74 ± 0.36	0.59 ± 0.07	0.69 ± 0.28	0.95 ± 0.8	0.39 ± 0.39	0.93
		2013	4.79 ± 0.96	4.51 ± 1.57	3.63 ± 1.01	4.86 ± 1.21	5.94 ± 2.50	3.27 ± 0.68	0.71
		2014	1.20 ± 0.57	1.41 ± 0.52	1.20 ± 0.67	1.30 ± 0.67	1.88 ± 0.89	1.61 ± 0.64	0.89
	SOLO	2011	0.28 ± 0.11	0.54 ± 0.11	0.34 ± 0.14	0.36 ± 0.21	0.17 ± 0.11	0.05 ± 0.05	
		2012	2.47 ± 0.69	1.09 ± 0.17	2.32 ± 0.38	2.9 ± 0.50	2.16 ± 0.37	3.7 ± 0.74	0.05
		2013	5.2 ± 1.17	3.19 ± 0.91	3.81 ± 1.26	5.11 ± 1.07	3.68 ± 0.60	3.52 ± 0.59	0.34
		2014	1.72 ± 0.37	3.54 ± 1.41	0.83 ± 0.43	2.45 ± 0.88	1.56 ± 0.58	2.86 ± 0.74	0.27
	TOT	2011	0.37 ± 0.16	0.75 ± 0.12	0.49 ± 0.16	0.70 ± 0.17	0.23 ± 0.17	0.21 ± 0.21	
		2012	3.10 ± 0.53	1.95 ± 0.18	3.08 ± 0.49	3.83 ± 0.52	3.17 ± 0.83	4.5 ± 1.31	0.18
		2013	10.34 ± 2.25	7.86 ± 1.95	7.53 ± 2.14	10.11 ± 2.29	10.2 ± 2.86	6.91 ± 1.10	0.47
		2014	3.22 ± 0.70	5.44 ± 1.86	2.33 ± 1.11	4.59 ± 1.54	3.89 ± 1.35	4.88 ± 1.17	0.52
GA	BLCA	2013	0.06 ± 0.06	0.06 ± 0.06	0.15 ± 0.15	0.24 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	
	CRPA		2.65 ± 1.14	3.08 ± 1.08	3.51 ± 1.03	2.15 ± 5.51	1.52 ± 0.38	2.74 ± 0.78	0.82
	SOLO		0.68 ± 0.28	0.30 ± 0.18	0.18 ± 0.12	0.48 ± 1.00	0.25 ± 0.18	0.19 ± 0.12	0.19
	TOT		3.39 ± 1.36	3.44 ± 1.24	3.84 ± 0.95	2.87 ± 6.52	1.77 ± 0.53	2.93 ± 0.80	0.81

In North Carolina in 2014, the relative abundances of all shrew species combined ($F_{5,17} = 0.87$, $P = 0.52$), *C. parva* ($F_{5,17} = 0.33$, $P = 0.89$), and *S. longirostris* ($F_{5,17} = 1.42$, $P = 0.27$) did not differ among treatments (Table 2).

In Georgia, we did not capture shrews in 2011, captured only two shrews in 2012, and captured three *B. carolinensis* in 2013 (Table 1). Therefore, we investigated shrew response to treatments in Georgia only for 2013 captures of all three species combined, *C. parva*, and *S. longirostris*. Relative abundance of all shrew species combined ($F_{5,17} = 0.45$, $P = 0.81$), *C. parva* ($F_{5,17} = 0.43$, $P = 0.82$), and *S. longirostris* ($F_{5,17} = 1.69$, $P = 0.19$) did not differ among treatments in 2013 in Georgia (Table 2).

Volume of retained downed woody debris was greater in NOBIOHARV than in all other treatments in North Carolina ($P < 0.01$; Table 3). The number of piles (mean ± SE) in each treatment unit in North Carolina was 63.71 ± 9.25 and the volume (m^3) of each pile was 5.06 ± 0.17. The number of piles in each treatment unit in Georgia was 15.92 ± 1.04 and the volume (m^3) of each pile was 225.62 ± 10.96). In 2013 and 2014, treatments were similar in vertical vegetation structure and groundcover in both states (Tables 3 and 4). Herbaceous vegetation comprised the majority of groundcover followed by bare ground in both states in 2013 and in North Carolina in 2014 (Tables 3 and 4).

For identifying predictors of fine-scale shrew population response in North Carolina, no covariates were collinear. No response variables were normally distributed and all were overdispersed; therefore, we used a Poisson distribution and quasi-GLM model for all data sets. We visually identified three observations as outliers and omitted the observations from the linear regressions. In 2012, *S. longirostris* capture success was positively related to effort ($\beta = 0.29$, $t = 3.01$, $P < 0.01$). In 2013, total shrew capture success was positively related to bare ground ($\beta = 0.22$, $t = 3.02$, $P < 0.01$) and negatively related to volume of downed woody debris within 50 m of the drift fence array ($\beta = -0.18$, $t = -1.99$, $P = 0.05$), and *C. parva* capture success was positively related to bare ground ($\beta = 0.21$, $t = 2.36$, $P = 0.02$). No covariates were predictors of total shrew capture success in 2012 or *S. longirostris* capture success in 2013. In 2014, total shrew ($\beta = 0.36$, $t = 4.05$, $P < 0.01$) and *S. longirostris* ($\beta = 0.45$, $t = 3.90$, $P < 0.01$) capture successes were positively related to bare ground. No covariates were predictors of *C. parva* in 2014.

For identifying predictors of fine-scale shrew population response in Georgia, no covariates were collinear. Response variables were not normally distributed and all were overdispersed; therefore, we used a Poisson distribution and quasi-GLM model for all data sets. We visually identified two observations as outliers and omitted the observations from the linear regressions. In 2013, total shrew capture success was negatively related to herbaceous groundcover ($\beta = -0.93$, $t = -2.87$, $P < 0.01$) and leaf litter groundcover ($\beta = -3.45$, $t = -2.45$, $P = 0.02$) and positively related to

Table 3
Mean ± standard error of habitat covariates estimated in six woody biomass harvest treatments in loblolly pine (*Pinus taeda*) plantations in Beaufort County, North Carolina ($n = 4$) in 2011-2014. Treatments were: (1) no Biomass Harvesting Guidelines (NOBHG); (2) 15% woody biomass retention in piles (15CLUS); (3) 15% woody biomass retention distributed evenly throughout the treatment unit (15DISP); (4) 30% woody biomass retention in piles (30CLUS); (5) 30% woody biomass retention distributed evenly throughout the treatment unit (30DISP); (6) and no woody biomass harvesting (NOBIOHARV). Covariates are defined in Appendix A. Different letters indicate significantly different means at $\alpha = 0.05$ level. * indicates data was not normally distributed and was analyzed using a non-parametric Friedman's test with a $maxT_{(5,15)}$ value and associated P-value.

Year	Covariate	Treatment							
		NOBHG	15CLUS	15DISP	30CLUS	30DISP	NOBIOHARV	$F_{5,15}$	P_{trt}
2011	DISTD	77.69 ± 24.98	66.77 ± 19.03	78.57 ± 12.88	70.84 ± 39.49	75.68 ± 14.13	69.97 ± 20.05	0.19	0.96
	DISTP	63.92 ± 28.31	22.19 ± 13.22	27.8 ± 16.7	28.68 ± 17.91	17.13 ± 10.64	11.25 ± 3.81	14.84	<0.01
	VDF50	16.73 ± 8.25	11.65 ± 4.06	40.01 ± 10.07	90.28 ± 28.10	19.86 ± 5.80	12.26 ± 4.10	0.90	0.50
	VT	20.65 ± 1.45a	37.76 ± 9.42a	40.80 ± 13.11a	55.17 ± 12.49a	55.75 ± 12.49a	108.20 ± 20.05b	12.20*	<0.01
	BG	48.33 ± 3.87	43.36 ± 5.77	50.75 ± 4.47	40.90 ± 5.05	44.33 ± 5.26	41.22 ± 6.04	0.67	0.65
2013	CWD	1.92 ± 0.96	1.82 ± 1.05	3.08 ± 0.91	2.40 ± 1.05	4.89 ± 1.67	3.56 ± 1.59	1.3	0.32
	FWD	30.33 ± 4.07	29.55 ± 4.53	29.83 ± 4.93	21.60 ± 5.36	27.44 ± 3.81	31.89 ± 3.93	0.20	0.96
	HE	70.58 ± 4.23	71.18 ± 5.05	61.50 ± 4.41	58.40 ± 8.46	66.33 ± 7.98	52.56 ± 5.25	0.63	0.68
	VEST	8.83 ± 0.70	8.28 ± 1.63	6.89 ± 0.59	7.59 ± 1.22	5.56 ± 1.07	7.29 ± 0.86	0.61	0.69
	WP	12.33 ± 2.62	6.00 ± 3.16	15.83 ± 5.54	13.10 ± 4.89	21.89 ± 9.28	14.22 ± 5.86	0.96	0.47
2014	BG	53.33 ± 9.18	34.72 ± 4.40	56.94 ± 2.84	49.17 ± 3.02	48.33 ± 0.82	46.67 ± 1.87	0.44	0.82
	CWD	18.89 ± 11.79	24.17 ± 2.20	25.00 ± 7.38	19.72 ± 3.71	28.33 ± 4.96	27.22 ± 5.84	0.56	0.73
	FWD	2.22 ± 2.43	5.56 ± 1.58	2.50 ± 0.81	3.61 ± 1.84	3.89 ± 2.42	3.61 ± 0.96	1.13	0.39
	HE	62.50 ± 7.19	86.94 ± 4.77	64.44 ± 8.92	78.89 ± 7.07	68.33 ± 6.34	78.06 ± 4.89	1.27	0.33
	VEST	7.59 ± 0.50	8.62 ± 0.28	7.56 ± 0.23	8.69 ± 0.57	8.34 ± 0.73	8.60 ± 0.78	0.77	0.59
	WP	6.11 ± 4.63	4.17 ± 2.11	3.33 ± 0.70	6.39 ± 7.13	15.56 ± 5.50	10.28 ± 7.11	0.76	0.59

Table 4
Mean ± standard error of habitat covariates estimated in six woody biomass harvest treatments in loblolly pine (*Pinus taeda*) plantations in Glynn County ($n = 3$) and Chatham County ($n = 1$), Georgia in 2011–2013. Treatments were: (1) no Biomass Harvesting Guidelines (NOBHG); (2) 15% woody biomass retention in piles (15CLUS); (3) 15% woody biomass retention distributed evenly throughout the treatment unit (15DISP); (4) 30% woody biomass retention in piles (30CLUS); (5) 30% woody biomass retention distributed evenly throughout the treatment unit (30DISP); (6) and no woody biomass harvesting (NOBIOHARV). Covariates are defined in Appendix A. Different letters indicate significantly different means at $\alpha = 0.05$ level.

Year	Covariate	Treatment							
		NOBHG	15CLUS	15DISP	30CLUS	30DISP	NOBIOHAR	$F_{5,15}$	P_{trt}
2011	DISTP	14.23 ± 1.83	14.82 ± 1.74	17.82 ± 2.98	17.77 ± 3.35	19.94 ± 3.44	13.53 ± 2.02	1.12	0.39
	VT	319.13 ± 40.8	296.17 ± 41.1	368.81 ± 41.7	359.98 ± 46.7	299.65 ± 40.5	373.39 ± 24.9	0.46	0.80
2013	BG	54.00 ± 5.34	47.00 ± 5.87	52.33 ± 5.67	43.25 ± 3.77	50.33 ± 2.81	56.33 ± 3.80	3.67	0.02
	CWD	4.25 ± 1.54	5.25 ± 1.01	4.33 ± 0.73	3.75 ± 0.66	5.00 ± 1.12	3.58 ± 0.72	0.55	0.74
	FWD	8.08 ± 1.94	10.08 ± 2.40	8.92 ± 2.62	6.67 ± 1.50	7.25 ± 1.70	4.42 ± 1.15	1.17	0.37
	HE	106.33 ± 3.97	103.67 ± 8.75	101.83 ± 11.28	98.25 ± 6.19	108.33 ± 4.56	89.42 ± 4.27	0.91	0.50
	VEST	5.34 ± 0.19	5.55 ± 0.31	5.08 ± 0.39	5.24 ± 0.31	6.27 ± 0.71	5.67 ± 0.33	1.51	0.25
	WP	15.25 ± 4.52	7.42 ± 2.30	10.08 ± 4.35	8.08 ± 2.34	7.75 ± 3.07	7.75 ± 2.09	0.38	0.86

woody vegetation groundcover ($\beta = 2.13$, $t = 3.76$, $P < 0.01$), vertical vegetation structure ($\beta = 0.18$, $t = 2.20$, $P = 0.03$), distance to nearest unharvested wet depression ($\beta = -0.002$, $t = -2.82$, $P < 0.01$), and effort ($\beta = 0.01$, $t = 5.48$, $P < 0.01$). *C. parva* capture success was positively related to woody vegetation groundcover ($\beta = 2.04$, $t = 2.91$, $P = 0.01$), herbaceous groundcover ($\beta = -1.03$, $t = 2.70$, $P = 0.01$), and distance to nearest unharvested wet depression ($\beta = -0.003$, $t = -2.82$, $P < 0.01$).

4. Discussion

Our results suggest that shrew populations are more associated with vegetation composition and structure than to downed woody debris availability in southeastern United States pine plantations and that shrews are not sensitive to current levels of woody biomass harvests in the region. The minimum volume of downed woody debris retained in a treatment unit was 16.28 $m^3\ ha^{-1}$ (7.81 tons ha^{-1}) (Fritts et al., in press), which exceeds by over three-fold the Forest Guild's volume recommendations of 2.24 tons ha^{-1} in pine forests of the Piedmont and Coastal Plain physiographic regions of the U.S. (Perschel et al., 2012). Similarly, another study conducted in North Carolina pine plantations had 15% of woody biomass retained on the sites although as much downed woody debris was experimentally removed as possible to simulate a woody biomass harvest (Homyack et al., 2013). Therefore, current levels of woody biomass harvesting in the region may retain downed woody debris volumes above the threshold needed to sustain shrew populations if a threshold exists.

Our study indicated greater relative abundance of *S. longirostris* in NOBIOHARV, but the effect was weak and only in one state during one year. Hence, *S. longirostris* may be more sensitive to woody biomass harvests than *B. carolinenesis* and *C. parva*, but our results add to the inconsistencies regarding the associations of *S. longirostris* with downed woody debris and vegetation (McCay and Komoroski, 2004; Moseley et al., 2008; Davis et al., 2010). Although some studies have revealed positive relationships between *S. longirostris* and decayed wood (French, 1980; Cromer et al., 2007; Davis et al., 2010), others documented no relationship (McCay and Komoroski, 2004). Further, Moseley et al. (2008) showed no differences in the relative abundance of *S. longirostris* among treatments with experimental downed woody debris manipulations during the first two years of the study, but relative abundance was lower in downed woody debris removal treatments during year three. *S. longirostris* was absent in Georgia during the first two years of our study, but appeared with establishment of vegetation in 2013. Similarly, other studies have demonstrated associations of *S. longirostris* with early to mid-successional disturbed woodlands with a dense understory and moderate leaf litter (Rose et al., 1990; Erdle and Pagels, 1995).

In both states and all treatments, shrew relative abundance increased in 2013, when vegetation became well-established. Although decay class of downed woody debris can affect shrew abundance (Brannon, 2000), it is unlikely shrews were responding to the increased decay of downed woody debris over time in our study. Instead, our results suggest that shrews were responding to the increase in vegetative structure. Our results are similar to two previous studies in the southeastern United States Coastal Plain that documented no relationship between *C. parva* capture success and downed woody debris (Moseley et al., 2008; Davis et al., 2010). *C. parva* has been associated with early successional vegetation, particularly fields with dense grasses and forbs (Hamilton, 1934; Davis and Joeris, 1945; Schmidly, 1983; Bellows et al., 2001), and it was suggested that competitive exclusion of *C. parva* from forested stands by *B. carolinensis* has forced *C. parva* to inhabit and adapt to open habitats at the forest edge, which have lower downed woody debris volumes (Davis et al., 2010). Further, previous research demonstrated that *B. carolinensis* has a greater positive association with canopy height and biomass of woody vines than downed woody debris in the southeastern United States Coastal Plain (Wolfe and Lohoefener, 1983; Mengak and Guynn, 2003). Therefore, vegetation likely is influencing shrew responses in the region.

Shrew captures were linked more closely with vegetative groundcover in Georgia than in North Carolina, possibly because site preparation in Georgia resulted in relatively few and large downed woody debris windrows and spot piles and vaster areas of bare ground between windrows, whereas downed woody debris in North Carolina was distributed more evenly throughout the treatment units. Although shrew capture success increased with bare ground cover in North Carolina, vast areas of bare ground were absent. Instead, small patches of loose bare soil were remnants of prior bedding and planting activities. Additionally, Georgia sites had greater mean temperatures than North Carolina sites (Fritts, 2014), which may have further increased desiccation risk, resulting in a greater association of shrews with vegetative cover.

Shrews in the southeastern Coastal Plain may not be as dependent on downed woody debris as in other regions of the United States. Although shrew abundance has been linked to presence of downed woody debris in the southeastern United States and elsewhere (Carey and Johnson, 1995; Loeb, 1996; Maidens et al., 1998; McCay et al., 1998; Butts and McComb, 2000), the only relationship we identified between capture success of shrews and downed woody debris volume was negative. Some studies have demonstrated positive relationships between volume of downed woody debris and shrews in the Pacific Northwest and central Appalachians (McComb and Rumsey, 1982; Carey and Johnson, 1995), but research conducted in the southern Appalachians showed limited shrew response to reductions of downed woody debris (Matthews et al., 2009; Raybuck et al., 2012). Further, studies in the southeastern U.S. Coastal Plain have elicited various responses of *B. carolinensis*, *C. parva*, and *S. longirostris* to experimental removal of downed woody debris (Loeb, 1999; McCay and Komoroski, 2004; Moseley et al., 2008; Davis et al., 2010). Coastal Plain forests historically were influenced by frequent, low-intensity fires; therefore, ground-dwelling wildlife in the region evolved tolerance to these frequent disturbances and the environmental conditions they promoted (Russell et al., 2004). Further, dead wood decays rapidly in the southeastern United States (Moorman et al., 1999), so volumes may have remained relatively lower than in other regions. For example, coarse woody debris volumes in unmanaged and managed pine forests in the southeastern United States have been estimated to be $\approx 18\ m^3\ ha^{-1}$ and $6\ m^3\ ha^{-1}$, respectively (McMinn and Hardt, 1996), whereas coarse woody debris volume in lodge pole pine (*Pinus contorta*) stands without recorded disturbances in the northwestern United States was estimated at $77\ m^3\ ha^{-1}$ (Herrero et al., 2014).

5. Conclusions

The minimum threshold of downed woody debris needed to sustain shrew populations may be below the volume of downed woody debris retained on our study sites. Considerable volumes of downed woody debris were retained in all treatment units, including NOBHGS, possibly because current harvest technologies or low market values prevented complete harvest of logging residues. However, future technological advances in harvest machinery or rises in wood chip prices could result in increased harvest of woody biomass, thereby leading to lower volumes of retained downed woody debris. If future woody biomass harvests intensify and downed woody debris is decreased below volumes retained on our study sites, shrew response to woody biomass harvests should be re-evaluated to inform BHG development that sustains wildlife populations.

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Appendix A

Covariates measured in six woody biomass harvest treatments in clearcut loblolly pine (*Pinus taeda*) stands in Beaufort County, North Carolina ($n = 4$) in 2011–2014 and Glynn ($n = 3$) and Chatham Counties ($n = 1$), Georgia in 2011–2013.Covariates were used in linear regression analyses to determine predictors of *Blarina carolinensis*, *Cryptotis parva*, and *Sorex longirostris* capture success.

Covariate	Definition
EFFORT	Number of buckets and funnel traps open per night per drift fence
VT	Volume ($m^3\ ha^{-1}$) downed woody debris (DWD) in the treatment unit
DISP	Distance (m) of drift fence array to debris pile
DISD	Distance (m) of drift fence array to ditch or unharvested wet depression
V50	Volume ($m^3\ ha^{-1}$) of piled DWD within 50 m of the drift fence array (NC only)
CWD	% coarse woody debris groundcover (2013 and 2014 only)
FWD	% fine woody debris groundcover (2013 and 2014only)
BG	% bare ground groundcover (2013 and 2014only)
WP	% woody groundcover (2013 and 2014only)
HE	% herbaceous groundcover (2013 and 2014only)
LL	% leaf litter groundcover (2013 and 2014only)
VEST	Vertical vegetation structure at the drift fence array (2013 and 2014 only)

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