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Research Article

Northern Bobwhite Breeding Season Habitat Selection in Fire-Maintained Pine Woodland

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ABSTRACT Despite the acknowledged importance of prescribed fire in creating northern bobwhite (*Colinus virginianus*) breeding cover, little research has investigated bobwhite breeding season habitat selection relative to time since fire. In 2016 and 2017, we monitored radio-tagged bobwhite on a 17,000-ha portion of a military installation managed with frequent (every ~3 years) prescribed fires, applied during the growing and dormant seasons. We monitored bobwhite to determine which vegetation characteristics associated with prescribed burning were important to bobwhite breeding season habitat selection at the microsite (i.e., telemetry location compared to nearby random location) and the macrosite scale (i.e., the burn-unit containing the location compared to study area availability). During 2 breeding seasons, we collected 2,315 bobwhite locations and compared percent cover of vegetation, days since burn, basal area, and distance to key landscape features (e.g., stream, wildlife opening) at a subset of microsite locations (301 locations during 2016 and 890 locations during 2017) to paired random locations. At the microsite scale, bobwhite selected lower basal area of hardwoods, greater woody understory cover, greater other (not wiregrass [*Aristida stricta*]) grass cover, and greater forb cover than at random points. At the macrosite scale, bobwhite selected units with <4.6 m^2/ha basal area (combined hardwoods and pines) in 2016 and units with <9.2 m^2/ha basal area in 2017. At the macrosite scale, bobwhite selected for areas burned in the dormant season of the same year, avoided areas burned in the growing season of the same year, and used other times since last burn categories proportionate to their availability. The selection for a low basal area at both scales indicates prescribed fire effects would be limited by shading from dense overstory, and the shrubs, grasses, and forbs that provide essential cover for bobwhite during the breeding season will not develop. In lower productivity soil regions similar to our study area, we advise that thinning operations set target basal areas below 10 m^2/ha to create and maintain breeding season habitat for northern bobwhite. © 2019 The Wildlife Society.

KEY WORDS basal area, breeding season, *Colinus virginianus*, fire frequency, habitat selection, northern bobwhite, prescribed fire, Sandhills region.

Northern bobwhite (*Colinus virginianus*, hereafter bobwhite) populations have declined rangewide, primarily because of habitat loss (Burger 2003, Hernández et al. 2013, Sauer et al. 2014), including loss of grass-forb-shrub communities that provide nesting and brood cover during the breeding season (Richardson 2016, Brooke et al. 2017). Maintenance of nesting and brood cover is imperative to maintain bobwhite populations because productivity influences bobwhite population demography (Roseberry and Klimstra 1984). Vegetation that contributes to nest concealment (i.e., shrubs, forbs, grasses) is important for nest-site selection and subsequent nest success, whereas high forb cover and bare ground are important for brood cover and foraging (Stoddard 1931, Taylor et al. 1999, Lusk et al. 2006, Richardson 2016). Thus, an ideal landscape for breeding bobwhite should at least contain the aforementioned vegetation conditions that allow for nesting and brood cover (Riddle et al. 2008, Bowling et al. 2014).

Fire helps maintain the vegetation conditions required by breeding bobwhite, but habitat availability may vary with season and frequency of prescribed burning. Growing-season prescribed burning is more effective at reducing hardwood tree and shrub cover than dormant-season fires (Brender and Cooper 1968, Glitzenstein et al. 1995, Hardy 2003) and is often used to restore native grass and forb cover where woody plants have encroached (Waldrop et al. 1987, Streng et al. 1993, Glitzenstein et al. 1995), improving nesting and foraging cover for bobwhite. Also,

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growing-season fires result in increased insect biomass, a critical component of bobwhite chick diet, in post-burn conditions (Hurst 1972, Provencher et al. 1998) and provide a greater abundance of insects throughout brood-rearing months (Brennan et al. 2000). Additionally, fire frequency influences subsequent plant community composition and structure (Sparks et al. 1998, Harper 2007, Knapp et al. 2009). For example, frequently (once every 1–2 years) burned areas typically are dominated by grasses and forbs (Streng et al. 1996), which provide excellent nesting and brood cover for bobwhite (Brooke et al. 2017). Conversely, less frequently (every 3–5 years) burned areas contain a greater abundance of woody plants (Streng et al. 1996), which may provide escape cover or an additional component of nesting cover for bobwhite (Taylor and Burger 2001, Cram et al. 2002, Brooke et al. 2017, Rosche 2018). In summary, the provision of brood and nesting cover depends on application of the appropriate fire regime that fosters grasses and forbs along with a mix of woody understory cover without allowing the encroaching woody component to reach the point where it shades the understory.

The influence of fire on availability of bobwhite habitat during the breeding season, March–September, may vary regionally because of differences in the length of the growing season, the vegetation communities, or the soil conditions. Deep, coarse-textured sandy soils have poor water retention and create xeric conditions that may favor certain plant species, such as turkey oak (*Quercus laevis*) or longleaf pine (*Pinus palustris*; Christensen 1988). Conversely, soils with greater clay content retain more moisture and are more fertile, generally favoring mesic-loving plant species and a more abundant herbaceous layer (Gilliam et al. 1993). Moreover, vegetation on nutrient-poor soils is slower to return to pre-burn conditions following a prescribed fire than areas with more fertile soils (Hardy 2003). Thus, areas with nutrient-poor soils might require a relatively longer fire return interval when managing for bobwhite to allow adequate woody understory cover to develop post-disturbance. A fire return interval that is too long, however, will allow extensive woody encroachment, which may reduce habitat for bobwhite because the dense midstory and overstory blocks sunlight from reaching the forest floor and does not promote grass or forb growth. Further, too frequent application of growing-season prescribed fires may remove large areas of woody escape and nesting cover for bobwhite during the breeding season (Simpson 1972, Rosche 2018).

Despite the acknowledged importance of fire in creating vegetation communities favored by northern bobwhite, little research has been conducted to investigate bobwhite breeding season habitat selection of burned areas relative to time since last burn. Therefore, we determined how time since fire and associated vegetation characteristics related to bobwhite habitat selection in a longleaf pine ecosystem of the Sandhills physiographic region of central North Carolina, USA. We hypothesized that bobwhite would select areas with greater woody understory because of its importance as nesting and escape cover during the breeding season, select areas with greater grass and forb cover because of their importance as nesting and brooding cover, and select the intermediate time since burn and lower basal area conditions that maintained woody-grass-forb understory cover.

STUDY AREA

We assessed northern bobwhite breeding season habitat selection in 2016 and 2017 on a 17,000-ha portion of Fort Bragg Military Installation (i.e., Fort Bragg; Fig. 1). Fort Bragg is an active army base owned and managed by the United States Department of Defense and located within Cumberland, Hoke, Harnett, and Moore counties, North Carolina, USA (35.1°N, −79.2°W, elevation 99 m). The study area was located in the Sandhills physiographic region of North Carolina and thus the topography was characterized by rolling hills with uplands of longleaf pine overstory on well-drained, coarse sandy soils and interspersed with lowland drainage areas (Franklin 1997, Sorrie et al. 2006). Because of the well-drained, sandy soils present, the Sandhills are considered low productivity (Shea and Osborne 1995, Sorrie et al. 2006). The pine-scrub oak (*Quercus* spp.) sandhill (Sorrie et al. 2006) is the most widespread plant community, which mostly consisted of a longleaf pine canopy, oak subcanopy, and wiregrass (*Aristida stricta*) ground layer. The average monthly rainfall from January through June was similar between the 2 years, with 8 cm/month in 2016 and 10.7 cm/month in 2017.

Land management at Fort Bragg was influenced by efforts to conserve habitat for the federally endangered red-cockaded woodpecker (*Picoides borealis*), which requires mature pine woodlands maintained by frequent prescribed fire, and to maintain a herbaceous understory for ease of military training. In forested uplands, growing-season (mid Mar–Aug) prescribed fires were applied primarily (Apr–Jun) on a 3-year return interval to limit woody understory encroachment into the forest midstory and to promote herbaceous groundcover. The start of the growing season is determined by the Fort Bragg Forestry Branch and is usually 15 March (±3 days; Kilburg et al. 2014), and the start of bobwhite breeding season is determined by the start of covey break up and is usually late April or early May through August. Non-forested areas (e.g., open parachute drop zones) were burned annually or biennially to remove most woody growth. To meet burn quotas in some forest stands, prescribed fires were applied during the dormant season (Dec to early Mar; Fig. 2). In 2016, 45% of prescribed fires were applied during the dormant season, and in 2017, 49% were during the dormant season. Overall, in 2016, 28% of the study site was burned (13% dormant and 15% growing season) and during 2017, 45% was burned (22% dormant and 23% growing season; Fig. 2). Lowland forest areas were burned on the same 3-year rotation as forested uplands but had saturated soils that sometimes suppressed prescribed fire, creating a mixed broadleaf-pine plant community within forested stands. Firebreaks and streams divided the study area into 34-ha (average) burn units (range = 0.4–136 ha) and helped facilitate prescribed burning. Burn units were typically lit with a backing fire, which is considered the safest and least intense firing technique (Wade and Lundsford 1990). Once the fires

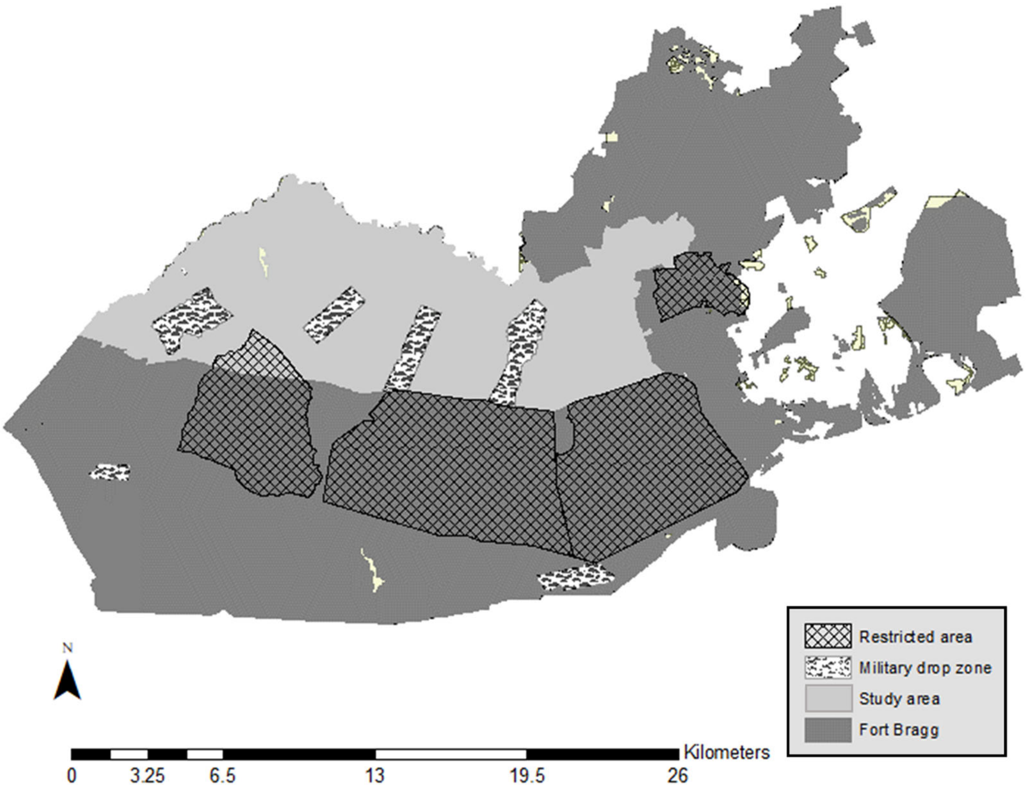

Figure 1. Study area for investigating bobwhite breeding season habitat selection on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

moved a sufficient distance from the firebreak, additional fires were set around other boundaries using the ring fire and strip head fire techniques (Lashley et al. 2014).

We classified 5 vegetation community types on Fort Bragg. Upland pines (63% of study area) included vegetation dominated by longleaf pine in open canopy stands with an understory of wiregrass, dwarf huckleberry (*Gaylussacia dumosa*), turkey oak, and blackjack oak (*Quercus marilandica*). Ecotone (12% of study area) included lowland pine communities located alongside streams and transitional areas between bottomland hardwoods and upland pines. We estimated land coverage for ecotone by constructing a 20-m buffer adjacent to the bottomland hardwoods vegetation type. Loblolly (*Pinus taeda*), pond (*P. serotina*), and longleaf pine commonly occurred in the overstory. Understory

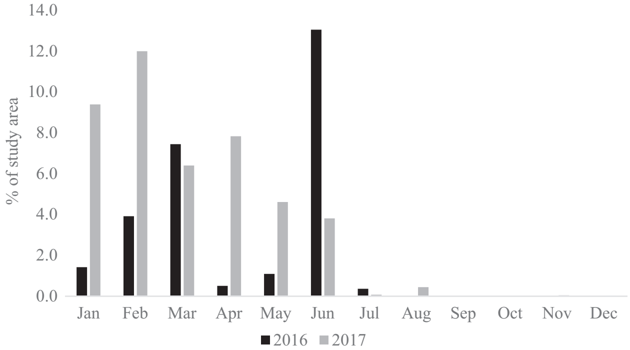

Figure 2. Percent of the study area burned in each month of each year for study on northern bobwhite breeding season habitat selection on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

communities consisted of switchcane (*Arundinaria tecta*), huckleberry (*Gaylussacia frondosa*), inkberry (*Ilex glabra*), wild blueberry (*Vaccinium* spp.), swamp redbay (*Persea palustrus*), cinnamon fern (*Osmunda cinnamomea*), and bracken fern (*Pteridium aquilinum*). Bottomland hardwoods (9% of study area) included sweetgum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), and tulip-poplar (*Liriodendron tulipifera*), which formed closed canopy stands along perennial streams. Dense thickets of fetterbush (*Lyonia* spp.), gallberry (*Ilex coriacea*), inkberry (*Ilex glabra*), and greenbrier (*Smilax* spp.) were common along edges. Drop zones (9% of study area) were treeless, and were burned or mowed annually or biennially to reduce woody vegetation. Four parachute drop zones (100–450 ha) were dominated by a variety of grasses and forbs, including weeping lovegrass (*Eragrostis curvula*), sericea lespedeza (*Lespedeza cuneata*), broomsedge (*Andropogon virginicus*), and wiregrass. Small patches of brambles (*Rubus* spp.) and shrub cover were located along low-lying areas that meandered the outskirts of the drop zones. Other (8% of study area) included any vegetation community that did not fall within the previous 4 categories. These included managed wildlife openings, small pockets of upland hardwoods, and areas containing military training structures.

METHODS

Bobwhite Capture and Telemetry

We captured bobwhite from 2 February to 22 April 2016 and 1 January to 21 April 2017 using modified walk-in funnel cage traps (Stoddard 1931). We placed traps in areas of known covey locations or in areas with dense shrub cover adjacent to managed wildlife openings and checked traps every evening starting no earlier than 30 minutes before sunset. We aged, sexed, weighed, and marked captured birds. We divided captured individuals into 2 age classes, juvenile and adult, according to plumage characteristic and molting stages (Rosene 1969). We classified birds as adults if solid gray-brown colored covert feather tips were present, and juveniles if buffy tips of the upper primary coverts were present (Haugen 1957). We determined sex by observing plumage pattern and coloration (Stoddard 1931). We weighed birds by placing them individually in a cotton handling bag hung from a 300-g spring scale. To ensure the weight of the radio-transmitter (6.2 g) did not exceed 5% of the individual bird's weight, we fitted only individuals weighing greater than 130 g with necklace-style radio-transmitters (model AWE-Q; American Wildlife Enterprise, Monticello, FL, USA). We marked individual bobwhite using size 7 (5.56 mm) aluminum butt-end bands (National Band & Tag Company, Newport, KY, USA). The North Carolina State University Animal Care and Use Committee (number 15–136-0) approved all capture and handling protocols.

We located radio-marked individuals 3–5 times/week starting at the initiation of spring covey break up, which we considered to be the start of the breeding season. We determined the breeding season to be 23 April–3 September in 2016 and 28 April–2 September in 2017. We located birds using R4000 very high frequency receivers fixed with 3-element Yagi-style antennas (Advanced Telemetry Systems, Isanti, MN, USA) by homing towards the individual to within 50 m (White and Garrott 1990). We used a handheld Garmin eTrex 20 global positioning system navigator (Garmin International, Olathe, KS, USA) to collect Universal Transverse Mercator locations for each observed individual. If an individual could not be located, we searched the last known location expanding outward using an omnidirectional antenna mounted on a truck. We continued searches ≥2 days a week until we located the individual or declared it lost if we could not locate it within 2 weeks.

Vegetation Surveys

We measured microsite (i.e., recorded telemetry location of observed bobwhite) vegetation cover at a subset of recorded bobwhite locations and at paired random locations collected between 23 April and 31 July 2016 and between 28 April and 31 July 2017. We determined each paired random location with a randomized azimuth (1–360°) and a randomized distance (10–250 m) from each recorded telemetry location. The maximum distance for random points (250 m) was based on the average home range of bobwhite in an area with similar land cover (Terhune et al. 2006). For any random point falling outside of a vegetated area (i.e., road, body of water, and military building), we decreased the random distance measurement until the entire plot could be measured outside of these obstructions. We did not measure vegetation at nest sites; we considered a bobwhite to be nesting if we found it in the same location on 2 consecutive tracking days.

We collected vegetation measurements within 10 days of recording a telemetry location. We collected vegetation measurements on the same day for a telemetry location and its paired random location. Vegetation plots consisted of 2, 10-m transects with perpendicular intersecting midpoints at the recorded telemetry and paired random location. We recorded vegetation cover using a 2-m-tall Wiens pole at each meter along both transects and at the center point for 21 readings/plot (Moorman and Guynn 2001). We noted only presence or absence of each plant species that touched the pole and did not count the number of times a species touched the pole. We calculated percent horizontal cover for wiregrass, other grasses, woody understory, and forbs from the Wiens pole data by dividing the number of sampling points where the specified vegetation type touched anywhere on the pole by the number of sampling points at each plot (21). At each center point, we visually estimated the percentage of tree canopy cover as 1 of 5 categories (0–20%, 21–40%, 41–60%, 61–80%, and 81–100%) and measured the basal area of hardwoods and pines using a 10-factor prism. We later used fire history data in a geographic information system (GIS) layer made available by Fort Bragg personnel to determine the number of days since the last prescribed fire for each location. We also used data from a GIS layer to determine distance to the nearest stream and nearest wildlife opening.

Data Analysis

Microsite habitat selection.—We developed a generalized linear mixed model using the lme4 package in R to compare vegetation characteristics between telemetry locations and paired random locations (R Core Team 2017). We evaluated days since last prescribed fire (binned into 30-day categories), 7 covariates that described vegetation cover (canopy coverage, percent cover of wiregrass, other grass, forbs, understory woody cover, and basal area of pines and hardwoods), and 2 covariates that described distance to key landscape features (stream and wildlife opening). We standardized all covariates before entering them into the models. We tested for collinearity among predictor variables using Pearson's correlation coefficient with a threshold of 0.6. We included all covariates as fixed-effects but included individual bird as a random effect (random intercepts) in the mixed-effect model because we had repeat observations of individual birds. Because of limited data and to ensure the model was still parsimonious and provided precise estimates, we ran all possible combinations of a maximum of 4 covariates (all subsets of the 10 measured covariates) in the model. Models with larger numbers of covariates often failed to converge or showed evidence of over-fitting and instability (e.g., unrealistic standard errors that exceeded 1,000). We used Akaike's Information Criterion corrected for small sample size (AIC_c) to rank model fit and chose the model with the lowest AIC_c value as the best model (Anderson and Burnham 2002). In addition, we selected 2 variables *a priori* that we thought would have a potential quadratic effect and added them to the top model. If the quadratic effect of each variable was significant ($P < 0.05$), we retained it in the model but removed it if it was not significant. Because woody understory provides nesting and escape cover, but too much woody cover leads to dramatic reductions in grass and forb cover, we postulated that bobwhite selection would increase with increased percent woody understory cover initially and then decline beyond a threshold. Additionally, we sought to identify whether there was a threshold of basal area for bobwhite above which selection would decline dramatically.

Macrosite habitat selection.—Firebreaks divided the study site into sections we called burn units ($\bar{x} = 34$ ha), which we used to compare bobwhite use to availability across the entire study site. For this scale, we binned the days since last fire for a burn unit into season by year groupings (i.e., current year growing season, current year dormant season, previous year growing season, previous year dormant season, 2 growing seasons previous, 2 dormant seasons previous, 3 growing seasons previous, and 3 dormant seasons previous). We analyzed each study year separately because the amount of burning, and hence the amount of each time since fire grouping, changed dramatically between years. We calculated the proportion used in each time since fire category by dividing the total number of bobwhite locations in each category by the total number of locations during the year. We calculated the proportion available in each time since fire category by summing the total area of each category and dividing by the total area of the study site. The prescribed burns that occurred during that year's growing season presented a challenge because availability of that time since fire grouping changed continuously while we collected telemetry locations. To address this issue, we divided the area of prescribed burns conducted after 1 May (i.e., the date of the first prescribed fire that occurred after the start of the breeding season) equally into zero growing seasons since last burn and time since that unit was previously burned. For example, if a unit was burned on 1 June of the current year and had been burned 25 February 2 years previously, the area of the unit was split equally into current year growing season and 2 dormant seasons categories.

We used a chi-square test to determine selection of time since burn categories and Bonferroni confidence intervals to distinguish selection among the time since burn categories (Neu et al. 1974). Similarly, we used a chi-square test and Bonferroni confidence intervals to determine selection of basal area classes and vegetation community types. We determined average basal areas and vegetation community type for burn units from a GIS layer provided by Fort Bragg managers. We binned the basal area for burn units into the following groups: 0–4.7, 4.8–9.3, 9.4–13.9, 14–18.5, 18.6–23.1, 23.2–27.7, and 27.8–36.7 m^2/ha. We calculated the proportion available in each binned basal area group by summing the area in each category and dividing it by the area of the study site. We included drop zones in the 0–4.6 m^2/ha category. We calculated proportion used by dividing the number of bobwhite locations in each category by the number of bobwhite locations. Based on the GIS layers, we delineated the 5 vegetation community types (upland pines, bottomland hardwoods, ecotone, drop zone, and other). We calculated the proportion available in each vegetation community type by summing the area of each type and dividing it by the area of the study site. We calculated proportion used by dividing the number of bobwhite locations in each vegetation community type by the number of bobwhite locations.

Table 1. The corrected Akaike's Information Criterion (AIC_c), difference in AIC_c (ΔAIC_c), and model weight (ω) for the top 10 models, all including the random effect of individual bird, for the assessment of influence of covariates on northern bobwhite breeding season habitat selection on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Model[a]	AIC_c	ΔAIC_c	ω
Hardwood, woody cover, other grass, forb	2,738.1	0.00	0.563
Hardwood, woody cover, forb, stream	2,742.1	3.98	0.077
Hardwood, woody cover, other grass, stream	2,742.3	4.19	0.069
Hardwood, woody cover, forb, WO	2,742.8	4.74	0.053
Hardwood, pine, woody cover, forb	2,743.3	5.17	0.042
Hardwood, woody cover, other grass, WO	2,743.4	5.30	0.040
Hardwood, woody cover, wiregrass, other grass	2,743.6	5.51	0.036
Hardwood, woody cover, other grass, days since fire	2,743.7	5.58	0.035
Hardwood, woody cover, wiregrass, forb	2,743.7	5.60	0.034
Hardwood, pine, woody cover, other grass	2,743.8	5.67	0.014

[a] Covariates included basal area of hardwood (hardwood) or pine (pine); percent coverage of woody cover (woody cover), other grass (other grass), forb (forb), or wiregrass (wiregrass); distance to nearest stream (stream) or wildlife opening (WO); and number of days since last prescribed fire, binned by every 30 days (days since fire).

RESULTS

In 2016, during 3,420 trap nights, we captured 59 individuals (52 juveniles and 7 adults), and in 2017, during 9,646 trap nights, we captured 71 individuals (50 juveniles and 21 adults). All 130 captured individuals received a transmitter, but only 87

Table 2. The mean and standard error of the microsite covariates collected at bobwhite telemetry locations and paired random locations on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Covariates	Location	$\bar{x}$	SE
Canopy (2 = 21–40% cover)	Telemetry	2.19	0.04
	Random	2.18	0.04
Basal area pine (m^2/ha)	Telemetry	5.40	0.19
	Random	6.81	0.19
Basal area hardwood (m^2/ha)	Telemetry	1.77	0.09
	Random	3.52	0.14
Days since burn	Telemetry	586	17.71
	Random	567	17.73
Other grass cover (%)	Telemetry	26	1
	Random	18	1
Wiregrass cover (%)	Telemetry	17	1
	Random	18	1
Woody cover (%)	Telemetry	32	1
	Random	21	1
Forb cover (%)	Telemetry	22	1
	Random	18	1
Stream distance (m)	Telemetry	240.45	5.33
	Random	246.47	5.22
Wildlife opening distance (m)	Telemetry	292.35	5.47
	Random	300.15	5.44

Table 3. Parameter estimates from the top model, and including significant quadratic relationships, for assessing the influence of vegetation characteristics on northern bobwhite breeding season habitat selection on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Covariates	Estimate	SE	*Z*	*P*
Hardwood basal area	−2.66	0.35	−7.57	<0.001
Hardwood basal area^2	−1.57	0.18	−8.80	<0.001
Woody cover	1.07	0.09	12.05	<0.001
Woody cover^2	−0.36	0.06	−5.86	<0.001
Other grass cover	0.17	0.06	3.10	<0.001
Forb cover	0.7	0.05	3.09	<0.001
Individual bird random effect	18.53	0.09		

survived to the start of the breeding season (i.e., the average date of covey breakup). We collected 752 individual locations for 42 birds during the 2016 breeding season (23 Apr–3 Sep) and 1,563 individual locations for 45 birds during the 2017 breeding season (28 Apr–2 Sep). Because of time and personnel limitations, we collected vegetation data at only 301 telemetry locations and 301 paired random locations during 2016 and 890 telemetry locations and 890 paired random locations during 2017. During the breeding season, 7 individuals left the study area, the transmitter malfunctioned on an additional 15 individuals, and 2 individuals moved into restricted access areas on Fort Bragg (Fig. 1) where we could not monitor them.

The best model for characterizing microsite selection on Fort Bragg included the basal area of hardwoods, percent

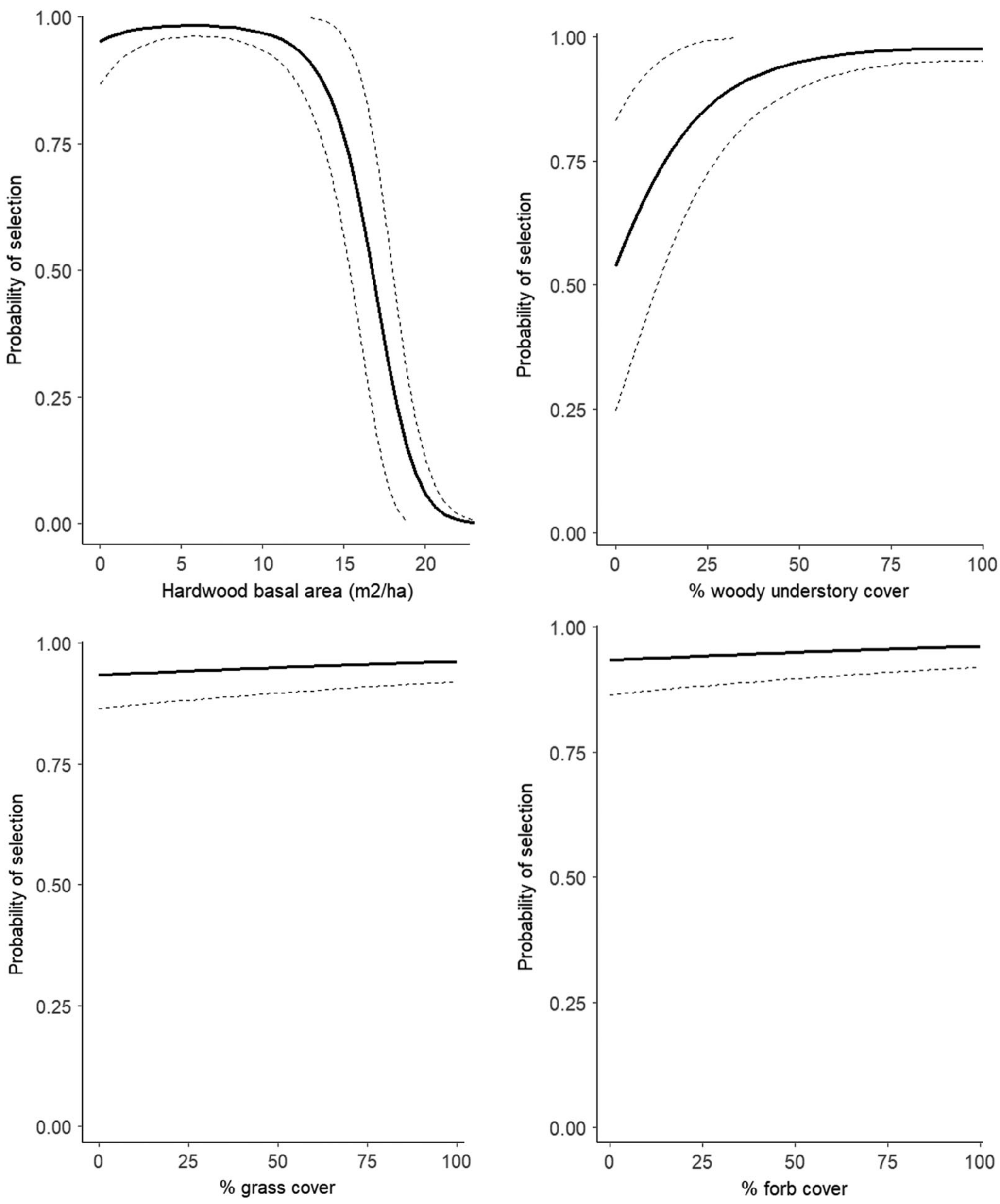

Figure 3. Probability of bobwhite habitat selection (and 95% CI) related to the basal area of hardwoods, percent woody understory cover, percent other grass cover, and percent forb cover, Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

woody understory cover, percent forb cover, and percent other grass cover (i.e., grasses not including wiregrass; Tables 1 and 2). The quadratic effect of hardwood basal area and percent woody understory cover were both significant when included with the top model (Table 3). The probability of bobwhite breeding season habitat selection declined dramatically once hardwood basal area exceeded 10 m^2/ha (Fig. 3). The probability of bobwhite habitat selection increased with increasing percent woody understory cover and exceeded 90% when percent woody understory cover reached 50% (Fig. 3). The probability of bobwhite habitat selection plateaued when percent woody understory cover reached 60% (Fig. 3). Percent forb cover and other grass cover were relatively weakly associated with probability of habitat selection (Fig. 3).

In 2016, approximately 25% of the study site was 1 dormant season post-fire and nearly another 25% was older than 3 dormant seasons (Table 4). The other time since burn categories were less available (range = 1–13%). During the 2016 breeding season, 25% of bobwhite locations were in units burned >3 dormant seasons previously and 21% were in units burned 1 growing season previously (Fig. 4). Few bobwhite were located in units burned 0 growing, 3 growing, and 3 dormant seasons since last burn. An increase in burning in 2017 led to 23% of the study area in the 0 dormant seasons since last burn category and only 10% in areas burned more than 3 dormant seasons prior (Table 4). Areas burned 0, 1, and 2 growing seasons since last fire were similarly available at 18%, 15%, and 21%, respectively (Table 4). The other time since burn categories were less available (2–5%). Almost half (42%) of the 2017 breeding season bobwhite locations were in units burned in the current dormant season. Bobwhite were similarly located in areas burned 1 (14%) and 2 (16%) growing seasons prior. Relatively few bobwhite locations were in areas burned >2 growing seasons previously (Fig. 4).

Time since fire affected bobwhite habitat selection in both years ($\chi^2_8 = 81.14$, $P \leq 0.001$ for 2016, $\chi^2_8 = 437.86$, $P \leq 0.001$ in 2017). Constructed Bonferroni confidence intervals ($\alpha = 0.05$, $k = 9$, $z_{1-\alpha/2k} = 2.75$) indicated that bobwhite selected for areas burned in the current dormant season and avoided areas burned in the current growing season in 2017 (Table 4). Bonferroni confidence intervals indicated that bobwhite used units in all time since burn categories equal to their availability in 2016.

Burn unit basal area affected bobwhite habitat selection in both years ($\chi^2_5 = 25.59$, $P \leq 0.001$ for 2016, $\chi^2_5 = 418.94$, $P \leq 0.001$ for 2017). Bonferroni confidence intervals indicated bobwhite selected areas with 0–4.7 m^2/ha basal area in 2016 (Table 5). In 2017, bobwhite selected areas with 0–4.7 m^2/ha and 4.8–9.3 m^2/ha basal area and avoided areas with 14–18.5 m^2/ha basal and 18.6–23.0 m^2/ha basal area (Table 5).

Bobwhite used vegetation community types disproportionate to availability in both years ($\chi^2_4 = 75.87$, $P \leq 0.001$ for 2016, $\chi^2_4 = 795.51$, $P \leq 0.001$ for 2017). Bonferroni confidence intervals ($\alpha = 0.05$, $k = 5$, $z_{1-\alpha/2k} = 1.31$) showed bobwhite used ecotone vegetation types equal to their availability for both years, but other vegetation types (e.g., bottomland hardwood, upland pines, and drop zones) were used inconsistently between the 2 years (Table 6).

Table 4. Macrosite selection by northern bobwhite of units 0 (current year), 1, 2, and 3 growing (G) and dormant (D) seasons since last burn on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Time since burn	Area (ha)	% of area[a]	Number of bobwhite locations	Expected number of bobwhite locations[b]	% observed in each area	Confidence interval on proportion of occurrence[c]	Used more, less, or same as available
2016							
0G	1,231	8	28	62	4	0–0.14	Same
0D	1,907	13	102	97	14	0.04–0.23	Same
1G	3,709	25	160	188	21	0.12–0.30	Same
1D	463	3	57	23	8	0–0.17	Same
2G	1,878	13	104	95	14	0.05–0.23	Same
2D	1,300	9	78	66	10	0.01–0.20	Same
3G	785	5	32	40	4	0–0.14	Same
3D	127	1	0	6	0	Not enough data	
≥4	3,425	23	191	174	25	0.17–0.34	Same
Total	14,826	100	752	752	100		
2017							
0G	2,732	18	119	288	8	0.01–0.14	Less
0D	3,376	23	657	356	42	0.37–0.47	More
1G	2,231	15	213	235	14	0.07–0.20	Same
1D	320	2	26	34	2	0–0.23	Same
2G	3,068	21	255	323	16	0.10–0.23	Same
2D	318	2	18	34	1	0–0.08	Same
3G	740	5	65	78	4	0–0.11	Same
3D	495	3	98	52	6	0–0.13	Same
≥4	1,548	10	112	163	7	0–0.14	Same
Total	14,826	100	1,563	1,563	100		

[a] Percentages of total area represent expected bobwhite observation values as if bobwhite occurred in each post-burn interval in exact proportion to its availability.

[b] Calculated by multiplying proportion of total area × total number of observed bobwhite locations.

[c] Represents the theoretical proportion of occurrence; if proportion of total area fell within the confidence interval for proportion of occurrence, we could not reject the null hypothesis of proportional use.

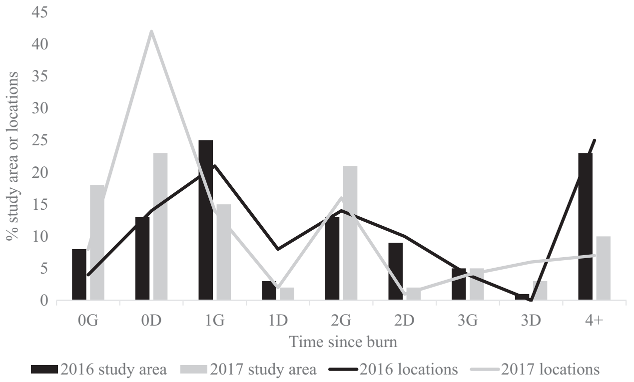

Figure 4. Percent of the study area and percent of the bobwhite breeding season locations within each time since burn categories to determine habitat selection on Fort Bragg Military Installation, North Carolina, USA, 2016–2017. Time since burn categories include growing season burn the same year (0G), dormant season burn the same year (0D), growing season burn 1 year prior (1G), dormant season burn 1 year prior (1D), and so on.

DISCUSSION

Bobwhite used the time since burn categories proportionate to their availability in 2016, but selected units that were burned in the current dormant season in 2017, likely because these areas contained a mix of grass, forb, and bare groundcover and resprouting woody cover that provided foraging and nesting areas (Hardy 2003, Sparks et al. 1998). Bobwhite avoidance of areas burned in the current growing season (in 2017) can be explained by the lack of understory cover, especially the lack of woody structure, that provides important escape or nesting cover (Brooke et al. 2017, Rosche 2018). The importance of woody understory cover for bobwhite on Fort Bragg during the breeding season was evident given the strong selection for woody understory cover at the microsite scale. As time since fire increases, however, the woody understory component eventually encroaches to levels where it shades grasses and forbs beneficial to bobwhite (Stoddard 1931, Brockway and Lewis 1997, Cain et al. 1998). Additionally, wiregrass forms a matted structure over time without repeated burning, restricting movement by bobwhite and other ground-dwelling birds (Burger 2001, Burke et al. 2008, Taillie et al. 2015).

Similar to other studies across their range, bobwhite on Fort Bragg selected for areas with lower basal area at multiple scales (DeVos and Mueller 1993, Fuller 1994, Burke et al. 2008). Forests with lower basal area allow more sunlight to reach the forest floor, promoting shrubs and herbaceous plants that provide food resources and nesting cover for bobwhite (Stoddard 1931, Rosene 1969, Moser and Palmer 1997, Brennan 1999). Bobwhite on Fort Bragg strongly selected areas with basal area $<10\,m^2/ha$, which was lower than the average ($12.2\,m^2/ha$, range = 0–43.2 m^2/ha) across the study site. Additionally, the drop zones were included in the 0–4.6-m^2/ha basal area category and accounted for a substantial percentage of the areas selected by bobwhite on Fort Bragg. Moreover, >50% of the Fort Bragg study site had a basal area between 9.4 and 18.4 m^2/

Table 5. Macrosite selection of basal area categories by northern bobwhite on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Basal area (m^2/ha)	Area (ha)	% of area[a]	Number of bobwhite locations	Expected number of bobwhite locations[b]	% observed in each area	Confidence interval on proportion of occurrence[c]	Used more, less, or same as available
2016							
0–4.7	3,485	20	189	149	25	0.21–0.30	More
4.89.3	1,413	8	44	60	6	0.01–0.11	Same
9.4–13.9	4,583	26	202	196	27	0.23–0.31	Same
14–18.5	4,728	27	176	202	23	0.19–0.28	Same
18.6–23.1	2,541	14	120	109	16	0.11–0.21	Same
23.2–36.7	821	5	21	35	3	0–0.08	Same
Total	17,571	100	752	752	100		
2017							
0–4.7	3,485	20	564	310	36	0.31–0.36	More
4.8–9.3	1,413	8	184	126	12	0.09–0.15	More
9.4–13.9	4,583	26	418	408	27	0.24–0.30	Same
14–18.5	4,728	27	305	421	20	0.17–0.23	Less
18.6–23.1	2,541	14	48	226	3	0–0.07	Less
23.2–36.7	821	5	44	73	3	0–0.07	Same
Total	17,571	100	1,563	1,563	100		

[a] Percentages of total area represent expected bobwhite observation values as if bobwhite occurred in each post-burn interval in exact proportion to its availability.
[b] Calculated by multiplying proportion of total area × total number of observed bobwhite locations.
[c] Represents the theoretical proportion of occurrence; if proportion of total area fell within the confidence interval for proportion of occurrence, we could not reject the null hypothesis of proportional use.

Table 6. Macrosite selection of vegetation community types by northern bobwhite on Fort Bragg Military Installation, North Carolina, USA, 2016–2017.

Vegetation type	Area (ha)	% of area[a]	Number of bobwhite locations	Expected number of bobwhite locations[b]	% observed in each area	Confidence interval on proportion of occurrence[c]	Used more, less, or same as available
2016							
Ecotone	2,036	12	70	89	9	0.05–0.14	Same
Bottomland hardwood	1,433	8	93	63	12	0.08–0.16	Same
Upland pine	10,844	63	508	474	68	0.65–0.71	More
Drop zone	1,470	9	76	64	10	0.06–0.15	Same
Other	1,421	8	5	62	1	0–0.06	Less
Total	17,204	100	752	752	100		
2017							
Ecotone	2,036	12	131	185	8	0.0–0.12	Same
Bottomland hardwood	1,433	8	163	130	10	0.07–0.14	Same
Upland pine	10,844	63	847	985	54	0.52–0.56	Less
Drop zone	1,470	9	422	134	27	0.24–0.30	More
Other	1,421	8	0	129	0	0.00–0.01	Less
Total	17,204	100	1,563	1,563	100		

[a] Percentages of total area represent expected bobwhite observation values as if bobwhite occurred in each post-burn interval in exact proportion to its availability.
[b] Calculated by multiplying proportion of total area × total number of observed bobwhite locations.
[c] Represents the theoretical proportion of occurrence; if proportion of total area fell within the confidence interval for proportion of occurrence, we could not reject the null hypothesis of proportional use.

ha, which indicates a large portion of the fire-maintained longleaf pine woodland on the base is not bobwhite habitat. Fort Bragg and other properties within the Sandhills region are characterized by low-fertility soils and require relatively low basal area to promote habitat conditions ideal for bobwhite. However, timber density management options in some longleaf pine communities may be influenced by habitat requirements and recovery guidelines for the red-cockaded woodpecker; red-cockaded woodpeckers have distinct lower thresholds for pine stem density and basal area (Garabedian et al. 2017), thereby limiting opportunities to manage to lower basal areas for bobwhite.

At a microsite scale, bobwhite selected locations with woody understory structure that provide critical thermal protection or escape cover, but they also selected locations with a greater percentage of grasses and forbs that likely provided nesting or foraging cover. An interspersion of woody understory with grasses and forbs provides nesting and brood cover (DeVos and Mueller 1993, Tayler et al. 1999, Cram et al. 2002). Additionally, forbs can attract insects and can produce seeds that provide food sources for bobwhite chicks (Cross 1956, Hurst 1972, DeVos and Mueller 1993). Although grass and forb cover is a component of bobwhite habitat, bobwhite selection for woody understory on Fort Bragg corroborates the importance of the woody understory component demonstrated by other studies across the species' range (Kopp et al. 1998, Taylor and Burger 2001, Cram et al. 2002, Ransom et al. 2008).

MANAGEMENT IMPLICATIONS

In lower productivity soil regions, we advise that thinning operations set target basal areas below 10 m^2/ha, with the added incentive of economic returns on any timber sold. On more productive soils, populations generally can be maintained with a basal area of 9.2–13.7 m^2/ha. Where bobwhite and red-cockaded woodpeckers both are priority, emphasis should be placed on removal of hardwood midstory and overstory trees during thinning operations.

Our results suggest that a 2-year return interval of growing season fire is too frequent for bobwhite habitat conservation in the Sandhills region. Bobwhite avoided areas burned in the current year's growing season, and bobwhite selected areas 1 and 2 years since last burn as nesting cover (Rosche 2018); hence, return intervals more frequent than every 3 years may remove vast areas of nesting cover or destroy nests when fires occur later in the growing season (Rosche 2018). However, fire return intervals should not be longer than 3 or 4 years because matted wiregrass is likely to develop and inhibit bobwhite movement and hardwoods are likely to expand into the midstory and shade the herbaceous layer.

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