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INTEGRATION OF LONG-TERM RESEARCH INTO A GIS-BASED LANDSCAPE HABITAT MODEL FOR THE RED-COCKADED WOODPECKER

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Abstract. **The Red-cockaded Woodpecker *(Picoides borealis)* population at the Savannah River Site in South Carolina has been the subject of intensive management and research activities designed to restore the population. By late 1985, the population was on the verge of being extirpated with only four individuals remaining. Older live pine trees that Red-cockaded Woodpeckers require for cavity construction were limited as the result of timber harvesting that had occurred primarily prior to the 1950s. To prevent the loss of this population and to provide for population growth, the habitat is now managed intensively, including construction of artificial cavities, control of cavity competitors, and removal of the hardwood mid-story to improve nesting habitat quality. Along with careful monitoring of the birds, translocations are being undertaken to enhance the number of breeding pairs and the overall population size as well as to minimize potential adverse genetic consequences of a small, virtually isolated population. During 19861996, we completed 54 translocations, installed 305 artificial cavities, and removed 2,304 southern flying squirrels (*Glaucomys volans*) (a user of Red-cockaded Woodpecker cavities). During this period, the number of breeding pairs of Red-cockaded Woodpeckers increased from 1 to 19 and the overall population size grew from 4 to 99 individuals. Additional data collected pursuant to arthropod prey base, foraging behavior, and home range studies, have provided information that is helping us better understand and manage this species. We are in the process of synthesizing these data into a GIS-implemented computer based landscape model to assess the possible impacts of various management options on the long-term viability of the Red-cockaded Woodpecker on the site.**

Key Words: **landscape habitat model, long-term research, *Picoides borealis,* Red-cockaded Woodpecker, Savannah River Site.**

Red-cockaded Woodpeckers *(Picoides borealis)* are an endangered species that evolved in a fire-dependent pine ecosystem within the southeastern United States. They are cooperative breeders whose breeding unit, known as a group, consists of a breeding pair and sometimes one or more helpers, usually male offspring that the group has produced. Declines in population sizes and distribution of the species are the result primarily of extensive land use conversion from forest, short rotation lengths (Jackson 1986, Ortego and Lay 1988, Conner and Rudolph 1989), hardwood encroachment around cavity trees (Van Balen and Doerr 1978, Locke et al. 1983, Conner and Rudolph 1989, Costa and Escano 1989, Loeb et al. 1992), shortage of potential cavity trees (Hooper 1988, Costa and Escano 1989, Rudolph and Conner 1991), and demographic isolation (Costa and Escano 1989). Habitat quality and a limited number of cavities also may play a role (Copeyon et al. 1991, Walters et al. 1992a,b).

HISTORY OF THE RED-COCKADED WOODPECKER AT THE SAVANNAH RIVER SITE

A description of the Savannah River Site (SRS) including land use and management history is provided by White and Gaines *(this volume)*. In 1951, the Department of Energy (DOE) acquired 80,269 ha of contiguous land to develop the SRS as a nuclear production facility. Contracted to manage a portion of the site for DOE, the USDA Forest Service began an intensive reforestation program to replant longleaf *(Pinus palustris)*, loblolly *(P. taeda),* and slash *(P. elliottii)* pines. The management arm of the USDA Forest Service on the site is referred to as the Savannah River Natural Resources Management and Research Institute (SRI). The research arm of the USDA Forest Service on the site is the Southern Research Station.

Information on the historical population size of the Red-cockaded Woodpecker at the Savannah River Site is not available. By the end of 1985, the population consisted of a breeding pair and two other single males. The stark reality was that trees that were suitable for new cavity construction were scarce and older trees that had cavities were becoming senescent and dying, thus making the continued existence of the bird on the site doubtful. In addition, the limited number of cavities that were present were used by a variety of species.

In this paper we summarize the research at the SRS that has been designed both to enhance this perilously small population and to aid in the recovery of this species throughout its range. In addition, we describe a GIS-based simulation model we are developing that incorporates our knowledge of the Red-cockaded Woodpecker into a landscape oriented assessment of potential population growth and timber cutting options.

RED-COCKADED WOODPECKER RESEARCH AND RELATED MANAGEMENT ACTIONS AT THE SAVANNAH RIVER SITE

Management activities at the SRS designed to benefit the Red-cockaded Woodpecker have focused on improving habitat quality by controlling the encroachment of the hardwood midstory, by installing cavity inserts, and by minimizing use of Red-cockaded Woodpecker cavities by southern flying squirrels (*Glaucomys volans*) and other cavity users (Gaines et al. 1995). Research has been directed at improving our understanding of the population status, genetics of small populations, translocation protocols, foraging behavior, home range characteristics, and the arthropod prey base.

MIDSTORY CONTROL

Beginning in 1985, an active midstory control program has included prescribed burning, commercial thinning, and other mechanical means that is essential to maintain or create suitable nesting habitat by minimizing midstory development. Without such midstory control, Red-cockaded Woodpeckers will abandon cavities once the midstory reaches a certain height or basal area and the area is no longer characterized as the open, mature pine forest that the species prefers (Conner and Rudolph 1989, Costa and Escano 1989, Hooper et al. 1991, Loeb et al. 1992). Although it is not known why Red-cockaded Woodpeckers abandon these clusters, Conner and Rudolph (1991) speculate that the presence of an extensive hardwood midstory may increase the number of nest competitors, reduce the quality of foraging habitat near the nest trees so that feeding young becomes more difficult, or be counter to what the bird has become accustomed to through its evolutionary history. The cavity trees that are occupied by a given group are referred to as a "cluster," and cavities are used nightly throughout the year. From 1985–1996, a total of 2,182 ha ($\bar{x}$ = 181.8 ha/yr) of active clusters, inactive clusters, and recruitment stands (a recruitment stand is an area that does not contain a Red-cockaded Woodpecker group but that has been treated for midstory control and has been fitted with artificial cavities; see below) at the site were treated with some form of midstory control (W. Jarvis, pers. comm.). Intermediate and co-dominant pines in the overstory were treated mainly with commercial thinning to reduce the remaining pine basal area to 13.8-18.3 m^2 per ha. These treatments continue to be employed as a method to improve foraging and nesting habitat.

ARTIFICIAL CAVITY INSERTS

Red-cockaded Woodpeckers prefer older, live pine trees for constructing their cavities (Steirly 1957, Jackson et al. 1979, Conner and O'Hallaron 1987, Rudolph and Conner 1991). The limited availability of live pine trees of sufficient age to provide cavity trees was a major concern in the management of the population, as it precluded population expansion. After considerable time and effort, an artificial cavity insert was developed by David Allen at the SRS that could be installed inside the trunk of younger pine trees and was accepted by the birds (see Allen 1991 for details on the design, construction, and installation). A drilled cavity technique (Copeyon 1990) was developed, but was not suitable for use at the SRS because the majority of available pine trees were too young for this procedure. Cavity restrictors, consisting of metal plates that are fitted over the cavity entrances (Carter et al. 1989), have been effective in preventing other species, especially Red-bellied (*Melanerpes carolinus*) and Pileated (*Dryocopus pileatus*) woodpeckers, from enlarging cavity entrances and usurping the cavities. From 1986-1996, 305 artificial cavities were installed by Forest Service personnel at the SRS, of which 292 are still usable for roosting and nesting. Red-cockaded Woodpeckers readily accepted the artificial cavities and successfully reproduced in them.

CONTROL OF SOUTHERN FLYING SQUIRRELS AND SQUIRREL EXCLUDER DEVICES

Southern flying squirrels are known to use Red-cockaded Woodpecker cavities extensively at the Savannah River Site. To minimize the potential adverse effects of squirrel cavity use on the Red-cockaded Woodpecker population, a squirrel monitoring program was initiated and any flying squirrels encountered during the routine checks were destroyed. Active clusters, inactive clusters, and recruitment stands were included in the squirrel monitoring program.

Cavity inspections varied from a low of 282 in 1986 to a high of 4,594 in 1995 and resulted in 2,304 southern flying squirrels being removed and destroyed from artificial cavities, natural cavities, and nest boxes (Table 1). Most of the squirrels were taken from artificial cavities (1,511 squirrels from artificial cavities, 652 from natural cavities, and 141 from nest boxes).

To determine the necessity of continuing the labor intensive squirrel removal program, an evaluation was made to assess the possible impact of squirrel removal on Red-cockaded

TABLE 1. SOUTHERN FLYING SQUIRREL REMOVAL PROGRAM AT THE SAVANNAH RIVER SITE, SOUTH CAROLINA (1986–1996; FRANZREB 1997)

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	Totals
No. of cavity or box inspections	282	515	640	588	900	1300	1500	1600	1449	4594	4992	17860
No. of artificial cavities available	NA[a]	17	28	28	33	48	101	151	195	245	292	292
No. of squirrels removed from artificial cavities	NA	3	43	47	49	54	70	97	135	430	583	1511
No. of squirrels removed from natural cavities	69	24	83	49	58	35	34	38	32	82	148	652
No. of squirrels removed from nest boxes	14	35	22	4	3	5	16	7	20	15	NA	141
No. of flying squirrels removed during inspections	83	62	148	100	110	94	120	142	187	527	731	2304
No. squirrels removed per inspection	0.29	0.12	0.23	0.17	0.12	0.07	0.08	0.09	0.13	0.12	0.16	0.13

[a] NA = not applicable.

Woodpecker reproductive success. Such testing could not be conducted at the SRS because of the small Red-cockaded Woodpecker population size. A controlled experiment was undertaken at the Carolina Sandhills National Wildlife Refuge, South Carolina, to assess whether southern flying squirrels adversely affected reproductive success of Red-cockaded Woodpeckers. The refuge provides habitat that is similar to the Savannah River Site (e.g., Upper Coastal Plain). Red-cockaded Woodpecker groups that nested in areas in which flying squirrels had been removed by ground trapping and during cavity checks produced significantly more fledglings than control clusters during both years of this study (1994 and 1995; Laves and Loeb 1996, Laves 1996). Reproductive rates at the Savannah River Site (2.5 fledglings/breeding pair in 1994 and 2.1 in 1995) were similar to those in the Sandhills study for clusters in which flying squirrels had been removed.

A squirrel excluder device, or SQED, was developed by Montague et al. (1995) in Arkansas as a means to control flying squirrels less laboriously. It consists of paired strips of aluminum flashing stapled tightly to the bark above and below the cavity entrance. During testing of the new device in Arkansas, Montague et al. (1995) found that squirrels abandoned 6 of 10 cavities that had been treated by installing excluder devices, and Red-cockaded Woodpeckers reoccupied 10 of the 11 cavities (one treated cavity was not occupied previously by squirrels). Recently SQEDs were tested at the Savannah River Site in unoccupied Red-cockaded Woodpecker clusters and results indicated that the devices were effective in impeding cavity use by flying squirrels (S. C. Loeb, in press). None of these SQED-treated cavity trees has been occupied by Red-cockaded Woodpeckers as of yet (S. C. Loeb, pers. comm.). At the SRS, a study is underway to evaluate whether Red-cockaded Woodpeckers will continue to use cavities after SQEDs have been installed.

MONITORING, POPULATION STATUS, AND TRENDS

As part of the intensive monitoring program for the Red-cockaded Woodpecker at the Savannah River Site, all cavities, whether natural (e.g., constructed by the Red-cockaded Woodpecker) or artificial, are monitored to determine cavity use. Cavities are checked from a ladder using a dentist's mirror and flashlight to furnish information on the number of eggs, number of nestlings, laying and hatching dates, and sex of nestlings. Fledging success rate is determined by counting the number of fledglings in the cluster soon after the anticipated fledging date.

Every adult on the site is banded with a U.S.

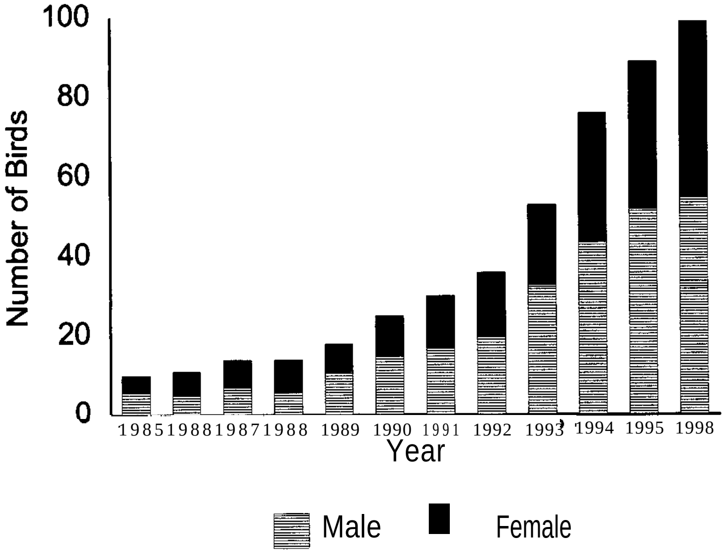

FIGURE 1. Sex ratio and population growth in response to intensive management of Red-cockaded Woodpeckers at the Savannah River Site, South Carolina (198551996; Franzreb 1997).

Fish and Wildlife Service aluminum leg band and with a unique color plastic leg band combination to allow individual identification in the field. Birds were banded either as nestlings, when first captured on the site, or when relocated to the site from elsewhere.

Group and cavity monitoring data indicate population status, reproductive success, spatial distribution, and group composition. Survivorship and mortality rates are determined during monthly observations of groups throughout the year. During the breeding season (April-July) monitoring efforts are intensified and each group is observed weekly. Red-cockaded Woodpeckers return each night to roost singly in cavities. By checking the last known nightly roost, the status of individual Red-cockaded Woodpeckers usually can be determined. Data are obtained routinely for each group on survival, sex ratio, number of helpers, number of active/inactive pairs, location of nests, identity of breeding adults, fledging dates, number and sex of fledglings, and reproductive success. These data have been instrumental in monitoring the status of the population and our management efforts.

From the late 1985 population level of four birds, the population at the SRS has grown to 21 active groups and a total of 99 individuals by the end of the breeding season in 1996 (Fig. 1). Of these 21 groups, there were 19 breeding pairs of which 16 were reproductively successful, producing 43 fledglings (Franzreb 1997).

For all years but 1988, the number of fledglings produced has increased every year and has varied from 3 to 43 (Fig. 2). Generally, male fledglings outnumber females; however, in 1988 all fledglings were female. From 1985-1996, the mean fledging success defined as the number of fledglings/successful nesting attempt, was 2.3. The low was 1.6 in 1991 (N = 8 nesting attempts) and the high was 3.0 in 1985 (N = 1 nesting attempt).

POPULATION VIABILITY ANALYSIS AND GENETIC CONSIDERATIONS

Haig et al. (1993) performed a series of population and pedigree analyzes on the birds on the SRS to determine the prospects for long-term population viability at the site. They used OGENES gene-drop pedigree analysis, a technique to measure genetic diversity in the current population relative to allelic diversity of its founders. Population viability, evaluated as the probability of persistence over the next 200 years, was estimated using VORTEX, a Monte Carlo simulation of demographic events. Using these procedures, Haig et al. (1993) concluded that during the next 200 years, the population has a 68-100% chance of extinction, with outcome depending on stochastic environmental events and the extent of inbreeding depression. By annually translocating at least three females and two males to the SRS from donor populations for a period of 10 years, the likelihood of survival of the population for the next 200 years is 96% (Haig et al. 1993). Based upon an assessment of genetic similarities of Red-cockaded Woodpecker populations, the Francis Marion

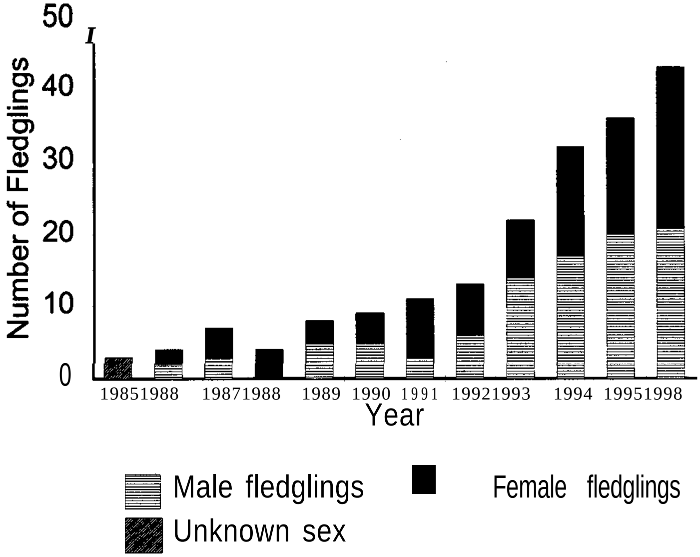

FIGURE 2. Number and sex ratio of Red-cockaded Woodpecker fledglings produced at the Savannah River Site, South Carolina (1985-1996; Franzreb 1997).

National Forest and Sandhills populations in South Carolina are genetically close to the birds at the SRS (Stangel et al. 1991). For this reason, and because both these populations are relatively large, Haig et al. (1993) recommended that these two areas serve as donor populations.

TRANSLOCATIONS AND THE EXPERIMENTAL USE OF A MOBILE AVIARY

In an effort to increase the population size and to increase the genetic diversity of the population, 54 Red-cockaded Woodpeckers were translocated from either off-site populations (N = 21) or within the Savannah River Site (N = 33) from 1986-1996 (Franzreb 1999). Birds were moved into clusters that had been provisioned with artificial cavity inserts if no vacant natural Red-cockaded Woodpecker cavities were available. The goal of these translocations was to provide a mate to an established breeding bird who had lost its partner, or to form a new pair in unoccupied territory. Allen et al. (1993) report on the results of the initial 16 translocations, and the outcome of all 54 translocations is summarized by Franzreb (1999). Success was defined subjectively as the bird remaining at the release site or close by for at least 30 days after being released. Thirty-one of 49 translocations (63.2%) involving subadult and adult Red-cockaded Woodpeckers were successful and 51.0% of the translocated birds have reproduced (Franzreb 1999). Of the 54 moves, five were of nestlings, resulting in one success.

In an effort to enhance the translocation success rate, we are testing a mobile aviary at the SRS. The aviary is approximately 5 m high and 5 m in diameter, and consists of a frame with shade cloth and hardware cloth on the outside. It is erected around a living pine tree that contains either a natural or artificial cavity. Birds are captured and transported to the release location at the SRS where they are maintained in the aviary for 10–14 days. It is hoped that during this time period, the bird will develop an affinity for the site and be more inclined to remain after it is released.

FORAGING BEHAVIOR

Providing a sufficient amount of quality foraging habitat is a requisite for the reproductive success and recovery of the Red-cockaded Woodpecker. To accomplish this requires an understanding and appreciation of the habitat characteristics that define suitable foraging habitat. Living pines were the overwhelmingly preferred foraging source for birds in Florida (Ligon 1968, 1970; Nesbitt et al. 1978, DeLotelle et al. 1983, Porter and Labisky 1986) , Louisiana (Morse 1972, Jones and Hunt 1996), South Carolina (Skorupa and McFarlane 1976, Skorupa 1979, Hooper and Lennartz 1981), Mississippi (Ramey 1980), Oklahoma (Wood 1977), Virginia (Miller 1978), and North Carolina (Repasky 1984). Red-cockaded Woodpeckers apparently prefer to forage on large trees (Skorupa 1979, Hooper and Lennartz 1981, DeLotelle et al. 1983). In an earlier foraging study of two groups of Red-cockaded Woodpeckers at the SRS, the birds foraged on trees with the largest diameters (58% utilization vs. 8% availability; Skorupa 1979).

Intersexual differences in foraging behavior have been observed for many woodpecker species, including the Red-cockaded Woodpecker. Most studies found that male Red-cockaded Woodpeckers tended to use the upper trunk area and limbs more than the females (Ligon 1968, Skorupa 1979, Repasky 1984, Hooper and Lennartz 1981; cf. Morse 1972). The mean foraging height was lower for females (8.7 m) than males (14.1 m) on the Francis Marion National Forest, South Carolina (Hooper and Lennartz 1981).

In 1992, a study was initiated at the SRS to assess foraging behavior in relation to quantified forest structural characteristics and to determine if there were any intersexual differences in foraging. The results will interface with the concurrent arthropod prey base research described below. Birds were followed throughout the day all months of the year over a 3-yr period. Observations were taken at 15-min intervals and included band identification number, sex, method (peck, probe, glean, etc.), substrate (trunk vs. limbs), location in relation to the trunk/crown, foraging height, tree height, tree species, diameter at breast height (dbh), and tree condition (alive vs. dead). Preliminary analysis of the 1992-1993 data indicates that male and female Red-cockaded Woodpeckers are segregating not by species of tree selected or by using trees of different heights, but mainly by foraging on different components of the same trees, with males using the upper strata of the tree trunks and limbs significantly more than females (K. E. Franzreb, unpubl. data). Such habitat partitioning provides a mechanism to use the available resources more efficiently, thereby, presumably enhancing survival and reproductive success. An analysis covering the entire 3-yr period is underway.

ARTHROPOD PREY BASE AND PREY USE BY THE RED-COCKADED WOODPECKER

The diet of the Red-cockaded Woodpecker is composed almost exclusively of arthropods. Red-cockaded Woodpeckers spend most of their foraging time capturing arthropods on live pine trees (Ligon 1968, Morse 1972, Wood 1977, Miller 1978, Nesbitt et al. 1978, Skorupa 1979, Ramey 1980, Hooper and Lennartz 198 1, Patterson and Robertson 1981, DeLotelle et al. 1983, Repasky 1984, Porter and Labisky 1986).

To better provide for the foraging needs of this species, information is needed on the arthropod prey base and how the birds use it. Providing for the dietary requirements of the young as well as adult woodpeckers also is important. To determine the diet of nestling Red-cockaded Woodpeckers at the SRS, four nest cavities were monitored using automatic cameras and infrared tripping devices (Hanula and Franzreb 1995, Franzreb and Hanula 1995). In 65% of the 3,000 photographs of nest site visits by the adults, prey were identifiable and the majority (69.4%) were wood roaches (*Parcoblatta* spp.). Prey fed to the young were primarily a few common arthropods. Other common prey items were wood borer larvae (Cerambycidae or Buprestidae, 5.4%), Lepidoptera larvae (4.5%), spiders (Araneae, 3.6%), and ants (Formicidae, 3.1%; Hanula and Franzreb 1995).

Hooper (1996) examined the relationship of arthropod biomass on longleaf pine trees 22-127 yrs old in winter on the Francis Marion National Forest in the coastal plain of South Carolina. He found that total arthropod biomass for the entire tree increased with tree age up to 86 yrs and then declined as the tree aged further. Arthropod biomass on the bole declined with increasing tree age, but increased with tree age on the dead and live limbs for trees up to 80 yrs-old.

At the SRS, the diversity, abundance, and biomass of arthropods on 50-70 yr-old longleaf pine trunks was investigated to assess seasonal variability of prey and to determine if prey originated on the tree bole or moved there from elsewhere (Hanula and Franzreb 1998). Crawl, flight, and pitfall traps were monitored continuously for 12 months at the SRS. Results indicated that over 400 genera of arthropods were represented on the bark. In trees with barriers to arthropod movement up the tree, the arthropod biomass was reduced by 40–70%. Arthropod biomass was distributed relatively evenly along the tree bole and was highest in the fall of the year. Little of the arthropod biomass found on the trunk was comprised of organisms that resided exclusively in that area. Moreover, a large proportion of biomass on the trunk originated either in the soil/litter layer or was the result of a diverse fauna that flew onto the bark surface.

Hess and James (unpubl. ms cited in James et al. 1997) found that arboreal ants were the main component of adult Red-cockaded Woodpecker diets in the Apalachicola National Forest, Florida. James and co-workers (1997) hypothesized that fire may indirectly enhance the availability and quantity of ants because it influences how nutrients are cycled through the plant community, which is reflected in the ground cover composition. Hanula and Franzreb (1998) demonstrated that the arthropod prey base of the Red-cockaded Woodpecker that is found on the boles is an open system whereby arthropods move between the litter/soil layer and the tree boles. Therefore, it appears that an appropriate fire management schedule would control not just encroaching mid-story vegetation, but also would have a beneficial effect on the prey base.

As Red-cockaded Woodpeckers do not migrate, the availability of suitable prey throughout the year is important. Skorupa and McFarlane (1976) speculated that prey was readily available to the Red-cockaded Woodpecker at the SRS in the summer but was limited in winter. However, results of the extensive arthropod study conducted recently at the SRS described above suggest that Red-cockaded Woodpeckers do not experience periods of low arthropod availability on the bole portion of the trees (Hanula and Franzreb 1998). In fact, Hanula and Franzreb (1998) found that arthropod biomass was highest in the fall and winter.

To manage foraging habitat of the Red-cockaded Woodpecker effectively, it is essential to understand the habitat needs of the arthropods on the bark that constitute the major prey items for the woodpecker. Because arthropods now are known to move readily between the bark surface and the forest floor or understory vegetation, the habitat requirements of the prey species in these areas as well as on the bark surface should be considered in the interest of providing adequate Red-cockaded Woodpecker foraging habitat.

Home Range

During a 5-month study in 1976-1977 of two groups of Red-cockaded Woodpeckers at the SRS, Skorupa (1979) found that territory size (the defended area) was smaller in the summer than winter, with a minimum size of 15.8 ha in the summer and 16.0 ha in the winter. Skorupa (1979) speculated that the younger forest at the SRS provides lower quality foraging habitat than older habitat available elsewhere and that the effects of habitat quality are significant in the winter. The mean home range size (defined as the area used by the group, but not necessarily defended) of the Red-cockaded Woodpecker is variable (129 ha in Florida, Porter and Labisky 1986; 70.3 ha in coastal South Carolina, Hooper et al. 1982; and 148.1 ha for Florida; DeLotelle et al. 1983). One must be cautious when comparing home range sizes obtained by different estimators as not all estimation techniques provide similar results,

Home ranges were delineated for 7 groups of Red-cockaded Woodpeckers at the SRS to determine size, configuration, and temporal (annual and seasonal) changes. Data were collected from May 1992 through May 1995 by following the birds and recording locations every 15 minutes using a Pathfinder Professional Global Positioning System unit. Locations were differentially corrected and interfaced with GIS using ARC/INFO (for details see Franzreb and Barnhill 1995). Preliminary home range analyses using the minimum convex polygon and bivariate normal ellipse home range estimators as described in the computer program HOME RANGE (Ackerman et al. 1990) indicate that home range sizes vary from 46.5 to 128.6 ha (K. E. Franzreb, unpubl. data). Selection of a home range estimator for each group was determined using the HOME RANGE program, which evaluates each data set to assess which, if any, of the included estimators are appropriate for a particular data set. In depth analysis of the home range data is underway.

INTEGRATION OF RED-COCKADED WOODPECKER RESEARCH AND MANAGEMENT ACTIVITIES

The Southern Research Station has been responsible for the monitoring, translocation, and overall research endeavor for the Red-cockaded Woodpecker at the SRS since 1985. As part of this effort, the research staff prepared reports on an annual basis that thoroughly summarized all Red-cockaded Woodpecker related activities that had been undertaken on the site that year, and provided a current estimate of the overall population size, sex ratio, number of active groups, number of southern flying squirrels removed, and information on reproduction and mortality. Throughout the years there have been numerous meetings held to address the status of the Red-cockaded Woodpecker on the site, discuss research findings, review the outcomes of ongoing management actions, and plan for future activities. This successful partnership is chronicled in Gaines and co-workers (1995).

In 1991-1992, when SRI staff prepared the management plan for the Red-cockaded Woodpecker on the site (G. D. Gaines, Savannah River Site Red-cockaded Woodpecker Management Plan, unpubl. report), research staff provided input into its development and extensive technical review. This management plan is in the process of being revised. The draft results of the foraging behavior and home range studies of the Red-cockaded Woodpecker on the site were provided to SRI for consideration in reformulating the management plan.

The U.S. Fish and Wildlife Service guidelines (USFWS 1989) for managing Red-cockaded Woodpeckers include providing foraging habitat within 800 m of an active Red-cockaded Woodpecker cluster that contains a minimum of 6,350 live pine stems with a dbh $\geq$ 25.4 cm and a pine basal area of at least 804 m^2. Anything less than this would require data to substantiate that the birds would not be adversely affected under Section 7 of the Endangered Species Act of 1973, as amended. SRI envisions using the foraging data that research has provided to propose including some of the live pine stems that are 20.3-24.4 cm dbh within 800 m of active clusters to meet the overall requirement of 6,350 live pine stems (J. Blake, pers. comm.). Moreover, the U.S. Fish and Wildlife Service is now working on revising the Red-cockaded Woodpecker Recovery Plan (USFWS 1985), and the guidelines for foraging may be modified pending the completion and approval of this plan.

Regardless of the outcome of the new recovery plan and possible modifications in the existing U.S. Fish and Wildlife Service guidelines, the foraging data, long-term reproductive and population data, and home range information obtained at the SRS will be instrumental in helping define a more appropriate conservation strategy for this species at the site. Moreover, the model described below relies on site-specific information in its development. Although some of this information, such as that on foraging ecology, home range size, and population dynamics, is available from elsewhere in the range, it is rare to find all these data from one site and obtained over such a prolonged period of time. Use of such information should strengthen the reliability of the model.

A GIS-BASED MODEL FOR RED-COCKADED WOODPECKER HABITAT AT THE SAVANNAH RIVER SITE

Our discussion to this point has focused on research designed either to understand Red-cockaded Woodpecker biology or to develop management options that can be used in a population recovery strategy. A major obstacle to the application of these research results is a lack of analytical tools to evaluate and to track over time the spatial interconnectedness of Red-cockaded Woodpecker recovery strategies, forest stand management actions (in the form of thinning and regeneration harvests), and forest growth dynamics. In response to this need, we initiated a research project designed to link Red-cockaded Woodpecker demographics and habitat needs with a spatially referenced model of forest structure. Forest structure is defined here as the within-stand, unit-area distribution of tree diameter classes based on measurements at breast height. Change in forest structure is modeled by tracking harvesting actions over time as to type, location, amounts removed, and/or residual densities, and by modeling the growth of the trees that remain.

A primary product of the research is a spatial simulator of forest structure that integrates existing and planned geographic databases, Red-cockaded Woodpecker demographics, and forecasting of forest growth. The simulator allows a resource manager to choose specific stands for thinning or clearcutting at given times over multi-year planning cycles and then simulate the effects on the Red-cockaded Woodpecker population. Alternatively, the resource manager may permit the simulator to select stands for thinning or clearcutting using target harvest volume goals, harvest decision rules (such as the residual basal area left in thinned stands), and constraints arising because of Red-cockaded Woodpecker needs. The simulator has the capacity to evaluate the interacting impacts of Red-cockaded Woodpecker habitat requirements and the harvesting of trees. This is accomplished by running the simulator in two modes. One mode specifies a given amount of harvesting activity, the level of which is set by a harvesting target, and then evaluates over time the maximum number of Red-cockaded Woodpecker foraging areas that the resulting forest structure can support. A second mode identifies a desired number of Red-cockaded Woodpecker breeding groups, and then simulates harvesting actions (over time) that will not compromise the Red-cockaded Woodpecker population goal.

CONCEPTUAL APPROACH USING SRS DATABASES

Present stand inventory data for the SRS consists of spatial information in the form of a GIS layer of stand boundaries, with associated data on the stand's forest type, age, and merchantability class (e.g., sapling, pole, mature, or saw timber). A major shortcoming of this data set is that it lacks complete information on productivity and stocking (the amount of basal area per unit-area). For example, many stands lack the basic measure of productivity (referred to as site index), only a few have basal area stocking estimates, and none have diameter distributions per unit area (our selected measure of forest structure).

The scope of the simulation is constrained to the pine and mixed pine-hardwood forest types on the SRS because this is where the harvesting activity occurs and where the Red-cockaded Woodpeckers nest and forage. Because the diameter distributions are the basic data needed to drive the forest growth simulation, we developed a way to generate unbiased estimates of tree diameter distributions ("tree lists") for each stand. To approximate the diameter distributions for the pine and mixed pine-hardwood forest types, we used an approach that approximates diameter distributions from a network of permanently located and periodically remeasured forest inventory plots established on the SRS land base. These data were obtained under contract by the Forest Inventory and Analysis (FIA) unit of the USDA Southern Research Station.

Approximately 800 inventory plots are distributed uniformly across the SRS land base. There are 2,225 stands within the area covered by the model. Therefore, even with this very dense set of inventory plots, not every one of the 2,225 stand polygons has an inventory plot associated with it. We developed the tree list assignments for each stand by relating the empirical diameter distributions from the permanent plots to the variables of forest type and stand age.

The estimated species-specific tree diameter list is used as input to a distance-independent, individual-tree growth simulator. Bolton and Meldahl (1990) used this kind of model form in developing SETWIGS for southern forest types using growth measurements from permanent-plot forest inventory data located throughout the South. Furthermore, SETWIGS has been incorporated into a growth model delivery system maintained by the USDA Forest Service called FVS (Forest Vegetation System). We decided to use FVS because it has a permanent technical support and development staff who provide help with fitting, maintaining, and/or modifying the models in the system.

Although the simulator is for pine dominated stands, may of these stands still have hardwood mid-stories that need to be included in the forest structure description because they can be present in significant enough quantities to negatively affect the suitability of the habitat for Red-cockaded Woodpecker nesting and foraging. Two data sources are being used to estimate the quantity and location of this mid-story component. One source is GIS-based orthoimagery (Sumerall and Lloyd 1995) developed from 195 1 panchromatic aerial photography taken when the SRS was acquired by the Federal government. The value of these data lies in the spatial identification of two broad land use conditions (forested and agriculture) present at the time the area was purchased and replanted. It turns out that these two land use conditions are related to current mid-story structure differences. The quantity of hardwood mid-story is being estimated from the FIA permanent plot inventory data, and the location of the mid-story over the entire landscape is being determined using the orthoimage land use classification.

Since the model simulates a dynamic forest, the simulator needs a way to mimic change in the location and aerial extent of management and Red-cockaded Woodpecker usage areas. Mimicking change is accomplished by breaking the GIS-depicted land base into small, contiguous, hexagonally shaped land units (polygons). These land units are small enough to be relatively uniform as to topography and soil type, and when aggregated, are capable of accurately approximating the larger forest stand polygons from which they are derived. Spatial objects such as Red-cockaded Woodpecker foraging areas, stand boundaries, burned areas, and treatment locations (for examples, areas that have been thinned) are represented in GIS data bases as closed polygons. In the real world these boundaries are not static over time. For example, only a portion of a stand might be burned, or a Red-cockaded Woodpecker foraging area can change over time as the result of harvesting activity or from competition for foraging habitat needed by newly established Red-cockaded Woodpecker groups. Our approach to providing this dynamic quality to our simulator is to approximate stands by aggregating these small, hexagonal polygons. By modeling the effects of silvicultural activities and Red-cockaded Woodpecker usage, we gain the dynamic quality we seek. As we decrease the size of these small, uniform, hexagonal polygons, the accuracy of using contiguous aggregations to approximate stands, foraging areas, etc., increases. However, at the same time, computation time and data storage needs increase.

To determine the most appropriate size for the new, hexagonal units, we experimented using a number of possible cell sizes. We did this by overlaying grids of different cell sizes on the stand boundary GIS data layer. When any particular hexagonal polygon encompassed more than one stand, it was assigned the attributes of the stand with the most area within it. After testing a range of cell sizes, we selected a 3-ha unit. Only a few small, linearly shaped stands were lost in this conversion process. Our analysis suggested that a 3-ha sub-area was an appropriate compromise between computation time and minimizing the loss of stands in the conversion. We also chose to use a hexagonal polygon rather than the usual square shape implied by the normal grid process built into GIS software because all polygon center points are equally distant to their neighbors, and it allows the demographics model to simulate fledgling dispersal in six directions instead of only the four that would have been accommodated by a square polygon.

The bird dispersal model is not yet developed, but it will be probability-based and will use habitat information from the forest structure simulator to predict availability of Red-cockaded Woodpecker foraging areas. All foraging areas will be formed around "seed" cells that contain trees suitable for natural cavity construction or installation of artificial cavity inserts. New groups will be formed either by artificial cavity creation (with or without translocation of birds into the new nesting sites), or by natural dispersal from established breeding pairs into neighboring or distant areas using a probabilistic prediction. New foraging areas will be created by aggregating hexagonal cells into areas that meet minimum foraging requirements. Red-cockaded Woodpecker research on foraging requirements will be used to delimit foraging areas. Foraging area associated with a given group is changed by the model over time as the population grows and adjusts to the changing competition from nearby groups and the accumulated effects of timber harvesting.

A management scenario builder will be developed that either accepts user-supplied actions and translates policies and user-supplied goals (e.g., a fixed annual harvest target, burning targets, or artificial cavity installation rates) into year-by-year events occurring in specific stands. This module uses standards and guidelines that deal with the full array of management actions. It allows unconstrained implementation, that is, ignoring standards and guidelines, or constrained implementation. Priority can be given to either the harvesting goal or the Red-cockaded Woodpecker population goal. When the simulator selects stands for harvesting as opposed to user-selection, the scenario management builder will only harvest in compliance with guidelines.

SIGNIFICANCE OF THE SIMULATOR

Some elementary examples of applications can help illustrate the significance of this research. The resource manager can evaluate the effect of a user-supplied, time-sequenced set of harvesting actions on the Red-cockaded Woodpecker population expansion. In this case, the management scenario builder is instructed to give priority to the harvesting activities. A second example could use the same simulations to track effects of the harvesting plan on the total number of potential (as opposed to actual) nesting/roosting sites for the Red-cockaded Woodpecker over time. A third application example could switch the priority for actions from harvesting to establishment of new breeding groups at specific places. In this case, the potential nesting sites identified could be used to develop a time-sequenced plan of artificial cavity creation by identifying suitable locations for new nesting sites. Using the location of new groups as input, a follow-up simulation would allow only harvesting that does not compromise the location-specific Red-cockaded Woodpecker objective.

The general significance of this simulator is its value as ,a decision aid that uses spatial data as the vehicle for capturing the interconnected effects of multiple resource management actions on outputs from the same land base. It will more fully and effectively use the foraging behavior, home range, and population demographics research results for the Red-cockaded Woodpecker that have been developed for the SRS. The simulator has application potential beyond the SRS and provides a major step in developing decision tools that will evaluate more than the two resource goals considered here.

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