LONG-TERM EFFICACY OF ARTIFICIAL CAVITIES FOR RED-COCKADED WOODPECKERS: LESSONS LEARNED FROM HURRICANE HUGO

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Abstract: Between 1990 and 1992 an extensive artificial cavity installation program was conducted on the Francis Marion National Forest (FMNF) in coastal South Carolina where Hurricane Hugo had caused vast devastation. Four artificial cavity types were installed: drilled starts, drilled cavities, modified drilled cavities, and inserts. In 1998, we examined 443 of the artificial cavities (average age 8.5 years). Our objective was to determine the relative effectiveness of the 4 types of artificial cavities by comparing their use and durability as well as host tree mortality and reproductive success of red-cockaded woodpeckers (*Picoides borealis*) using the various types of artificial cavities. Per annum mortality rates for longleaf pines with drilled starts, drilled cavities, and modified drilled cavities did not vary, but the mortality rate of loblolly pines with inserts was 2.4 times greater than for longleaf pines with inserts. Drilled cavities had the highest usability of all cavity types whereas modified drilled cavities and inserts in loblolly pines had the lowest. Modified drilled cavities were more prone to structural damage than drilled cavities, and inserts and modified drilled cavities were more prone to flooding and enlargement than were drilled cavities. Each type was used successfully for nesting and the number of young fledged from artificial cavities did not differ significantly from the number of young fledged from natural cavities. However, red-cockaded woodpecker use of artificial cavities for nesting declined over time, and the long-term usability of drilled starts and drilled cavities for nesting was greater than that of modified drilled cavities and inserts. Although red-cockaded woodpeckers used all cavity types, drilled cavities and drilled starts tended to be the most effective over time. However, managers must weigh training time, tree characteristics, and long-term usability when deciding what types of artificial cavity to install.

Key words: artificial cavities, loblolly pine, longleaf pine, *Picoides borealis*, *Pinus palustris*, *Pinus taeda*, red-cockaded woodpecker, reproductive success.

In September 1989, Hurricane Hugo, a Category IV hurricane, hit South Carolina causing severe damage to people, buildings, and natural resources (Marsinko et al. 1993). The strongest winds passed through the center of the FMNF. Although the winds' force decreased as the storm passed over land, hurricane-force winds affected the entire forest (Hooper and McAdie 1995). At the time of the storm, the FMNF supported the second largest and only naturally increasing population of the endangered red-cockaded woodpecker (Hooper et al. 1991*a*). Damage from Hugo resulted in the loss of 87% of active cavity trees (Hooper et al. 1990). Further, all cavity trees were lost in 47% of the clusters, and all active trees were lost in 57% of the clusters. Although at least 1 bird survived the storm in 344 clusters, 117 of those clusters had no remaining cavity trees (Watson et al. 1995). Surveys conducted immediately after the storm showed that 63% of the birds were lost as a direct result of the storm, and that 18% of the remaining birds did not survive the winter. The result was an overall loss of 70% of the pre-Hugo population (Hooper et al. 1990). Overwinter mortality was likely due to severe weather coupled with an extremely limited supply of cavities (Watson et al. 1995).

Because the FMNF red-cockaded woodpecker population was critical to the species' overall recovery (U.S. Fish and Wildlife Service 1985), efforts to mitigate the storm's impact were begun immediately (Watson et al. 1995). Prior to September 1989, 3 techniques for constructing artificial cavities had been developed, but only had been tested on a limited basis (Copeyon 1990, Allen 1991). Due to the extreme need for cavities to prevent the FMNF red-cockaded woodpecker population from declining further and to begin the process of restoration, it was decided to install artificial cavities on a wide scale (Watson et al. 1995). The

first priority was to ensure that each cluster with at least 1 bird had ≥2 functional cavities. The long-term goal was to ensure that each cluster had ≥4 functional cavities. Without the artificial cavity program, it is estimated that by 1992, the population would have dropped to 100-125 groups. Instead, the number of groups with ≥2 birds increased from 249 in 1990 to 332 in 1992.

The massive cavity installation program begun on the FMNF in the wake of Hurricane Hugo is an excellent example of adaptive management (Loeb et al. 1998), a process whereby an experimental management plan is initiated followed by continuous monitoring, feedback, and adjustments based on the system's reaction to management activities (Walters and Holling 1990). For example, the first artificial cavity inserts were 20.3 cm deep. Based on observations during the first post-Hugo nesting season, the depth was increased to 25.4 cm to reduce use by other cavity nesters (Watson et al. 1995). The method for constructing drilled cavities was also modified reducing the learning time from 6 to 2 weeks and almost eliminating the possibility for mistakes (Taylor and Hooper 1991).

Although the cavity installation program on the FMNF in response to Hurricane Hugo may be viewed as a large-scale experiment, an experimental design was not used to guide the number, placement, or types of cavities installed. Despite the lack of experimental design (e.g., random placement of cavity types), the artificial cavity program on the FMNF represents one of the first and largest artificial cavity programs, and provides an excellent opportunity to evaluate the 4 types of artificial cavities in 1 area over a long period of time (up to 9 years). Our objective was to examine the relative effectiveness of the various artificial cavities by comparing their use and durability, as well as host tree mortality and the reproductive success of red-cockaded woodpeckers using the various types of artificial cavities. Further, after 5 years of steady increase, the red-cockaded woodpecker population began to decline. A possible cause of this decline is the aging of artificial cavities. Thus, a further objective was to examine this hypothesis.

STUDY AREA

The study was conducted on the FMNF on the lower Coastal Plain of South Carolina. Prior to Hurricane Hugo, there were approximately 97,000 ha of forested area, comprised of 51% loblolly pine (*Pinus taeda*), 19% longleaf pine (*P. palustris*), 2% pond pine (*P. serotina*), 25% hardwood, and 3% mixed pine-hardwood forest types (Hooper et al. 1991*a*). Much of the area that had been used by red-cockaded woodpeckers was severely damaged. Hurricane Hugo destroyed approximately 70% of the trees >25.4 cm diameter at breast height (dbh) resulting in the need to regenerate approximately 24,000 ha of loblolly pine and 7,300 ha of longleaf pine (U.S. Forest Service 1989).

METHODS

Artificial Cavity Installation

The artificial cavities we examined were installed between 1990 and 1992. Artificial cavities were installed into the bole of live longleaf pines (*Pinus palustris*) and loblolly pines (*P. taeda*) at either 3.7 m or 6.7 m above ground. Critical details of artificial cavity construction and installation may be found in Copeyon (1990), Allen (1991), and Taylor and Hooper (1991). A brief description of each cavity type follows.

Drilled starts.—A 5.1-cm diameter entrance tunnel was drilled at a slightly upward angle through sapwood and at least 6.5 cm into the heartwood. A 4.0-cm bit was used to enlarge the heartwood portion of the entrance tunnel about 2.5 cm in all directions. The interior of the entrance tunnel was coated with a thin layer of a non-toxic wood filler to inhibit resin flow into the tunnel. Loose bark was scraped from the bole 1.5 m above and below the entrance. Artificial resin wells were made with a chisel, and white wood filler was spread over the bark to simulate resin flow. Although red-cockaded woodpeckers were able to roost in some drilled starts without additional excavation by the birds, nesting would require considerably more excavation by the bird.

Drilled cavities.—A 5.1-cm entrance tunnel was drilled through the sapwood and about 7.5 cm into the heartwood. Then a 5.1-cm diameter access tunnel was drilled about 7 cm above the entrance tunnel and about 4.5 cm into the sapwood. A 4.0-cm bit was used to drill downward at a sharp angle via the access tunnel and intersect the entrance tunnel. This hole was continued downward below the entrance tunnel as the bit was moved from side to side to cut out an interior chamber 7.5-9.0 cm in diameter. The access tunnel was closed with wooden plugs and wood filler. The exterior of the tree was treated to simulate resin wells and resin flow. With relatively little work, woodpeckers could

expand the interior chamber and use it for nesting.

Modified drilled cavities.—Construction of drilled cavities was modified to reduce the time it took to learn the installation process. By using a larger access hole, the worker could more easily prevent breaching the sapwood when drilling the interior chamber. An 8.9-cm access tunnel was drilled first, then extended downward as far as 36 cm with a 7.6-cm diameter bit. The access tunnel was closed with wooden plugs and wood filler. A 5.1-cm entrance tunnel was drilled to provide access to the interior chamber. The outside of the tree was treated to simulate resin wells and resin flow as described above.

Inserts.—A block of western redcedar (*Thuja plicata*) 10.1 x 25.4 x 15.2 cm was drilled with a 7.6-cm diameter bit to a depth of 20.3 cm. A 4.5-cm entrance hole was then drilled 2.9 cm from the top of the block. The insert was completed by gluing a thin plywood lid to cover the end of the block through which the 7.6-cm diameter hole had been drilled. Finally, the entire insert was coated with a nontoxic waterproof sealant to prevent resin leakage through small, sometimes imperceptible, cracks in the cavity chamber. A modified chainsaw and chisel were used to remove a block of the host tree slightly larger than the insert. The insert was fitted into the tree with wooden shims and wood filler so that it was flush with the cambium. The outside of the tree was treated to simulate resin wells and resin flow. A metal restrictor was placed over the exposed face of the insert to protect it from enlargement by other woodpeckers.

Follow-up Examination

During March-June 1998, we examined 443 artificial cavities of the different types that had been installed 6.7-9.3 years earlier (Table 1). We climbed each living cavity tree and examined the cavity interior using a light and mirror. For safety reasons we did not climb dead trees but examined each to determine the cause of death. We recorded the condition of the host trees and the structural integrity of each artificial cavity. Artificial cavities that were structurally sound and in a live tree were considered usable. A cavity could be usable but not display evidence of current use. We used the condition of resin wells and plates pecked by red-cockaded woodpeckers to expose the sapwood around the cavity's perimeter to determine current use (Jackson 1977*a*, Hooper al. 1980). Between 1990 and 1998, we determined the outcome of 393 nesting attempts in artificial cavities and an additional 284 nesting attempts in natural cavities. The presence of at least 1 red-cockaded woodpecker egg was considered a nesting attempt. Tree age and dbh were recorded at the time of cavity installation.

Statistical Analyses

We used chi-square tests of independence to test the following null hypotheses: (1) tree mortality was independent of artificial cavity type, (2) tree mortality was independent of tree species, (3) activity status was independent of artificial cavity type, (4) usability of artificial cavities was independent of cavity type, and (5) damage (e.g., leakage, enlargement) was independent of cavity type. We conducted a series of 2 x 2 chi-square tests to determine significant differences in usability among cavity types. We used the Bonferonni (α) = 0.005 (0.05/10) to adjust for the 10 tests. Two-way analysis of variance (ANOVA) was used to test that the number of young fledged did not differ by cavity type and year. We used 1-way ANOVA to test whether trees that received the 4 types of artificial cavities differed in age and dbh. We used Tukey's Studentized Range Test (α = 0.5) to make comparisons among individual cavity types and years.

Table 1. Status of artificial cavities and cavity trees on the Francis Marion National Forest and their mean (± 1 standard deviation) age and diameter at breast height (DBH). Cavities were installed in 1990-1992 and re-examined in 1998. Means within a column followed by different letters are significantly different ($P < 0.05$).

Cavity Type	Total Trees	Number Alive	Number Dead	Number Usable	Tree Age	DBH (cm)
Drilled Starts	98	79	19	48	109.0 ± 23.1^{A}	42.1 ± 4.6^{A}
Drilled Cavities	90	70	20	57	106.9 ± 20.5^{A}	41.9 ± 4.1^{A}
Modified Drilled Cavities	87	76	11	27	108.9 ± 20.5^{A}	43.3 ± 3.9^{A}
Inserts – Longleaf	103	82	21	48	121.1 ± 33.0^{B}	47.3 ± 4.4^{B}
Inserts – Loblolly	65	32	33	16	77.1 ± 23.6^{C}	50.3 ± 5.3^{C}
Total	443	339	104	195		

RESULTS

The age and dbh of trees with artificial cavities varied significantly among species and cavity types ($F_{4,352}$ = 27.84, P = < 0.0001 and $F_{4,387}$ = 50.17, P < 0.0001). Loblolly pines with inserts were significantly younger but also significantly larger than longleaf pines with inserts and other types of artificial cavities (Table 1). Longleaf pines with inserts were older and larger than longleaf pines with other types of artificial cavities.

Tree Mortality Rates

One hundred four (23.5%) of the trees with artificial cavities died between installation and 1998. We rarely could determine the cause of mortality. Lightning killed 8 of the trees, and 2 loblolly pines died from southern pine beetle infestation. Lightning and southern pine beetles probably killed other cavity trees, but the cause could not be confirmed because of decayed sapwood. Three trees broke 4-6 m above the cavity at cracks caused by Hurricane Hugo. Six trees broke at the site of the artificial cavity: 2 drilled cavities, 1 drilled start, and 3 inserts. None of the modified drilled cavities broke at the cavity, and none of the other cavity trees for which the cause of death was uncertain died as a result of breaking at the cavity. Thus, after 6.7-9.3 years of exposure, only 1.4% of the 443 trees with artificial cavities died from structural failure of the bole at the site of artificial cavity installation.

Average age of drilled starts, drilled cavities, and inserts was 8.5 years. The average age of modified drilled cavities was 7.3 years. Per annum mortality rates for longleaf pines with drilled starts, drilled cavities, and inserts were 0.0228, 0.0261, and 0.0242, respectively. Mortality did not vary among these 3 cavity types (X^2_2 = 0.23, P = 0.89). The annual mortality rate for longleaf pines with modified drilled cavities was 0.0173. Mortality adjusted for time since cavity installation did not differ among all 4 cavity types (X^2_3 = 1.63, P = 0.65).

Mortality of trees with inserts varied significantly by species (X^2_1 = 15.89, P = 0.001). The per annum mortality rate in loblolly pines with inserts was 0.0579, which was 2.4 times greater than in longleaf pines with inserts of the same age (8.5 years).

Woodpecker Mortality

Between 1990-1998, 4 red-cockaded woodpeckers became stuck in resin and died while trying to use artificial cavities. One bird was killed in an insert that leaked resin through a crack that apparently occurred during installation. Two of the 4 birds were killed in the entrance tunnel of drilled starts. The birds had partially pecked away the wood filler barrier that lined the entrance tunnel, allowing resin to leak into the tunnel. One bird died while stuck inside of an improperly installed, modified drilled cavity that had leaked resin. The junction of the entrance tunnel and access tunnel

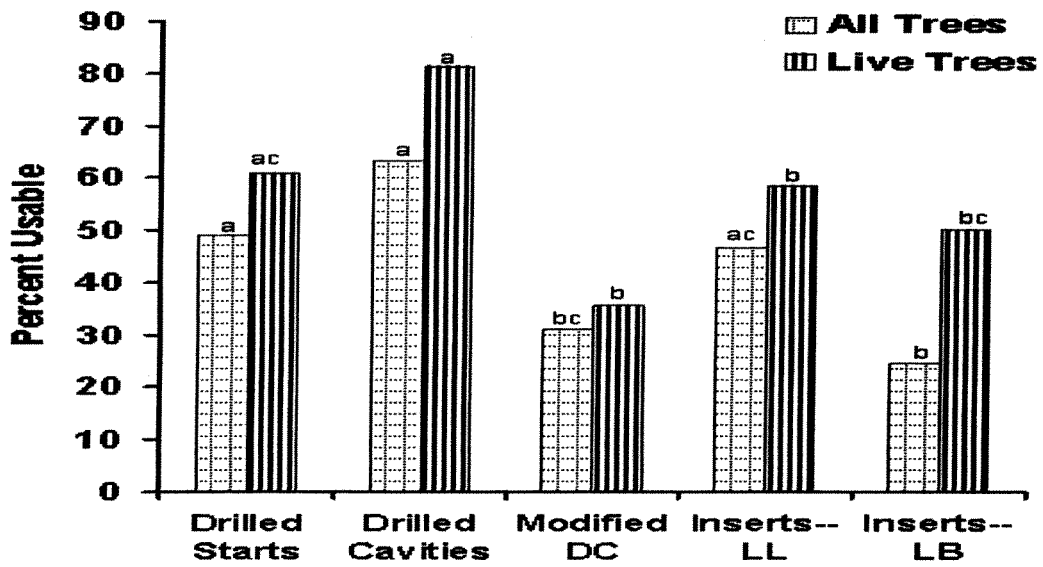

Figure 1. Percent of artificial cavities installed on the Francis Marion National Forest 1990-1992 that were usable in 1998. Bars of the same color with different letters indicate a significant difference (α = 0.005) in usability between cavity types. DC = drilled cavity, LL = longleaf pine, LB = loblolly pine.

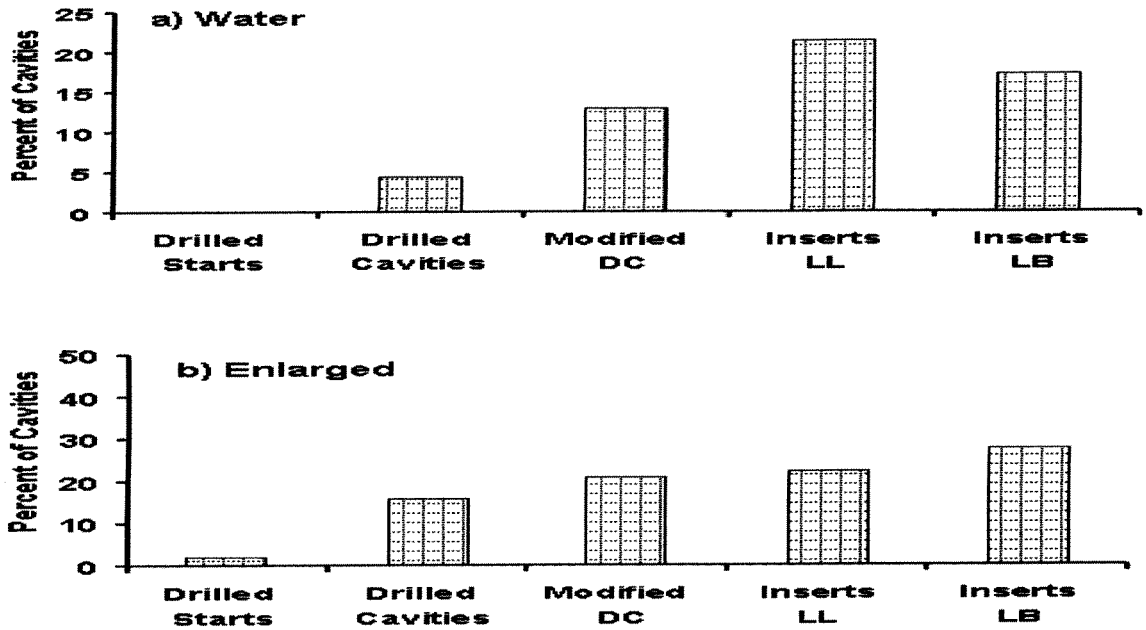

Figure 2. a) Percent of artificial cavities installed on the Francis Marion National Forest 1990-1992 that had water in them in 1998. b) Percent of artificial cavities installed on the Francis Marion National Forest 1990-1992 whose entrances had been enlarged when examined in 1998.

was not entirely in heartwood, a fact not detected until discovery of the dead bird.

Long-term Usability of Artificial Cavities

Usability of artificial cavities that averaged 8.5 years old (7.3 years for modified drilled cavities) was dependent upon cavity type ($X^2_4 = 30.72$, $P < 0.001$). Drilled cavities had the highest usability; modified drilled cavities and inserts in loblolly pines had the lowest (Figure 1).

Among all drilled starts (n = 98), only 48.0% were usable (Figure 1). Among live trees (n = 79), 60.1% had been excavated into a completed cavity. Of completed drilled starts in living trees, 97.9% were

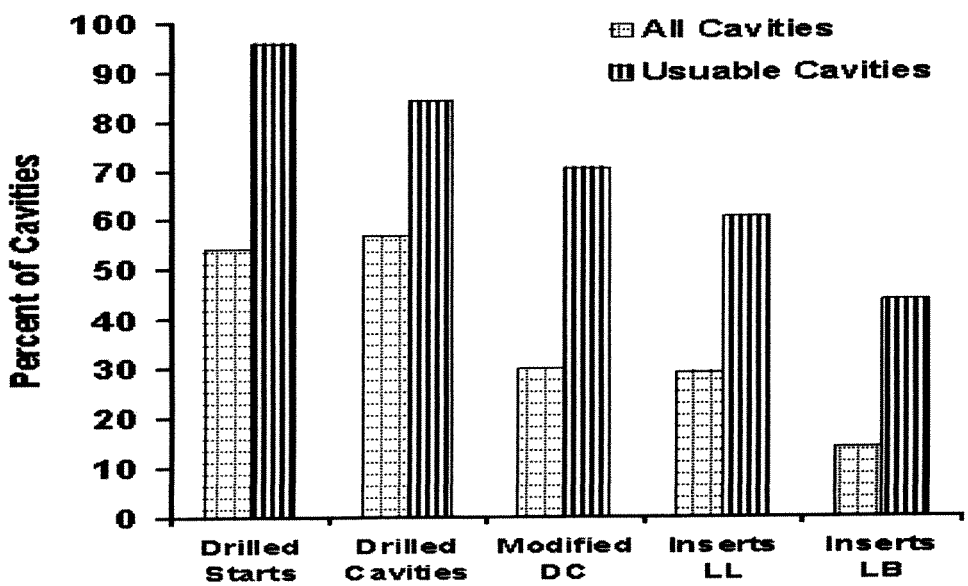

Figure 3. Percent of all artificial cavities and usable artificial cavities installed on the Francis Marion National Forest 1990-1992 that were active in 1998.

usable. Among starts that had not been completed (n = 31), 41.9% were partially completed. Of the partially completed drilled starts (n = 13), 5 had active resin wells, which suggests that woodpeckers were trying to complete them.

The usability of inserts that averaged 8.5 years old (n = 168) was dependent upon tree species. Forty-seven percent of the inserts in longleaf pines were usable, compared to 24.6% in loblolly pines (X^2_1 = 8.17, P = 0.004). Much of the difference was attributable to species mortality. Usability of inserts in living longleaf and loblolly pines was similar (Figure 1; X^2_1 = 0.96, P = 0.33).

Modified drilled cavities were more prone to structural damage than drilled cavities. Access plugs in 33.3% of the modified drilled cavities were rotted, compared to 1.4% of the drilled cavities (X^2_1 = 23.50, P = 0.001). The septum between the access plug and the cavity entrance was severely altered by decay or other woodpeckers in 60.4% of the modified drilled cavities, compared to 35.7% of the drilled cavities (X^2_1 = 7.00, P = 0.008).

The vulnerability of cavities to flooding by water varied among cavity types (X^2_4 = 22.02, P < 0.001). Inserts were most likely to flood, and completed drilled starts were least likely (Figure 2a). Greater structural damage made modified drilled cavities more prone to flooding than drilled cavities (Figure 2a).

Enlargement of 17.3% of cavity entrances (n = 327) by pileated woodpeckers (*Dryocopus pileatus)* and red-bellied woodpeckers (*Melanerpes carolinus)* also rendered artificial cavities unusable for red-cockaded woodpeckers. Enlargement to a size no longer suitable for red-cockaded woodpeckers was dependent upon type of artificial cavity (X^2_4 = 11.69, P = 0.02). Inserts and modified drilled cavities were the most prone to enlargement followed by drilled cavities and drilled starts (Figure 2b).

Long-term Activity Status of Artificial Cavities

The frequency of artificial cavity use after 6.7-9.3 years (mostly roosting and to an unknown extent in this comparison, nesting) by red-cockaded woodpeckers was dependent upon cavity type for all cavities (X^2_4 = 45.96, P < 0.001) and for usable cavities (X^2_4 = 28.46, P = 0.001). Among usable cavities, almost all drilled starts and a majority of drilled cavities were active (Figure 3).

Red-cockaded woodpeckers often expanded the interior of inserts to the extent that the walls and floor were breached. In some cases, expansion led to sap leakage or flooding. We found 43.2% of inserts in longleaf pines and 48.3% of inserts in loblolly pines had their interior walls or floor breached to the point where the tree was exposed. However, the activity status of inserts was independent of interior expansion for longleaf pines (X^2_1 = 0.000, P = 0.94) and loblolly pines (X^2_1 = 1.77, P = 0.18); 40.6% of the insert cavities in longleaf pines that had been expanded were active and 43.9% of the insert cavities in loblolly pines that had been expanded were active.

Use of Artificial Cavities for Nests

Red-cockaded woodpeckers successfully used each of the 4 types of artificial cavities as nesting cavities (Table 2). The number of young fledged varied significantly among cavity types ($F_{4,657}$ = 2.66, P = 0.0013) but not among years ($F_{8,657}$ = 1.71, P = 0.09) or the interaction ($F_{30,657}$ = 1.35, P = 0.10). However, the number of young fledged from artificial cavities did not differ significantly from the number of young fledged from natural cavities (Table 2). The number of young fledged from

Table 2. Mean and standard deviation of fledglings produced from nests in artificial and natural cavities on the Francis Marion National Forest 1990-1998. *N* denotes the number of nests. Means for all years followed by different letters are significantly different (Tukey's Studentized Range Test, α = 0.05).

Year	Drilled Starts			Drilled Cavities			Modified Drilled Cavities			Insert Cavities			Natural Cavities		
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
1990				18	1.44	0.86				13	1.46	0.78	29	1.62	0.90
1991	12	1.42	1.08	19	1.79	0.92	5	1.60	0.55	30	1.37	1.00	29	1.55	0.78
1992	16	1.50	0.63	18	2.00	0.48	7	1.57	0.53	23	1.26	0.75	32	1.69	0.86
1993	11	1.54	0.82	15	1.47	0.99	8	1.88	0.64	13	1.46	1.05	28	1.89	0.92
1994	15	1.47	0.92	13	1.92	0.86	10	2.40	0.52	16	1.62	0.81	24	1.83	0.76
1995	19	1.26	0.80	11	2.00	0.77	10	2.40	0.52	10	1.70	1.06	28	2.00	0.86
1996	23	1.43	0.90	5	2.20	1.30	9	2.11	1.05	7	1.57	1.13	36	1.61	0.80
1997	14	1.86	0.53	5	1.60	0.55	5	1.40	0.55	6	0.83	0.98	42	1.57	0.91
1998	13	1.92	0.86	5	2.00	0.71	5	1.00	1.22	3	2.00	1.00	40	1.45	0.88
All Years	123	1.53^{AC}	0.83	109	1.78^{AB}	0.84	59	1.91^{B}	0.82	121	1.43^{C}	0.92	289	1.67^{BC}	0.86

modified drilled cavities was significantly greater than the number of young fledged from drilled starts and inserts. Otherwise, there were no significant differences in the number of young fledged from artificial cavities.

The use of artificial cavities for nesting varied over time (Figure 4). From 1990 to 1993, inserts and drilled cavities were the most commonly used artificial cavities. As drilled starts were excavated their use increased steadily, and they became the most commonly used artificial structure after 1994. However, use of drilled starts for nests began to decrease in 1997. By 1997, most nests were in natural cavities (Figure 4).

The long-term usability of drilled starts and drilled cavities for nests appeared to be greater than of modified drilled cavities and inserts (Figure 5). The average age of cavities used for nests was similar among the 4 types through 1996, although modified drilled cavities were approximately 1 year younger because they were installed later. However, by 1998 the average age of modified drilled cavities and inserts used for nests was 5.1 (range 2.1-6.5) and 4.5 years (range 1.8-5.8), respectively, indicating that red-cockaded woodpeckers primarily were using modified drilled cavities and inserts that had been installed after the initial installation program. By contrast, the average age of drilled starts and drilled cavities used as nests in 1998 was 6.6 years (range 4.3-8.6) and 8.4 (range 8.3-8.6), respectively.

DISCUSSION

Early in the development of artificial cavity technology, there was concern that the invasive nature of these techniques would seriously weaken the structure of host trees. Our study dispels that concern. On average, less than 0.2 % of trees with artificial cavities broke at the cavity in any one year. Between 1990 and 1998, winds were severe enough to break or blow down more than 100,000 pine trees in the FMNF. Most had been damaged by Hurricane Hugo. During installation of artificial cavities we followed guidelines for minimum tree size suggested by developers of the techniques (Copeyon 1990, Allen 1991, Taylor and Hooper 1991), which appear to be effective for winds up to gale force.

Per annum mortality rates of trees with artificial cavities ranged from 0.02 to 0.06. It appears that artificial cavities cause no more tree mortality than natural cavities. In east Texas, annual mortality rates for longleaf and loblolly pines with natural cavities are 0.01 and 0.06 respectively (Conner et al. 1991). Although mortality rates of loblolly pines with artificial cavities in our study were similar to mortality rates of loblolly pines in Texas, the mortality rate for longleaf pines with artificial cavities on the FMNF was almost twice the rate observed in Texas. Partial loss of crowns and root damage from Hurricane Hugo may have contributed to the higher rates. Although we did not compare mortality

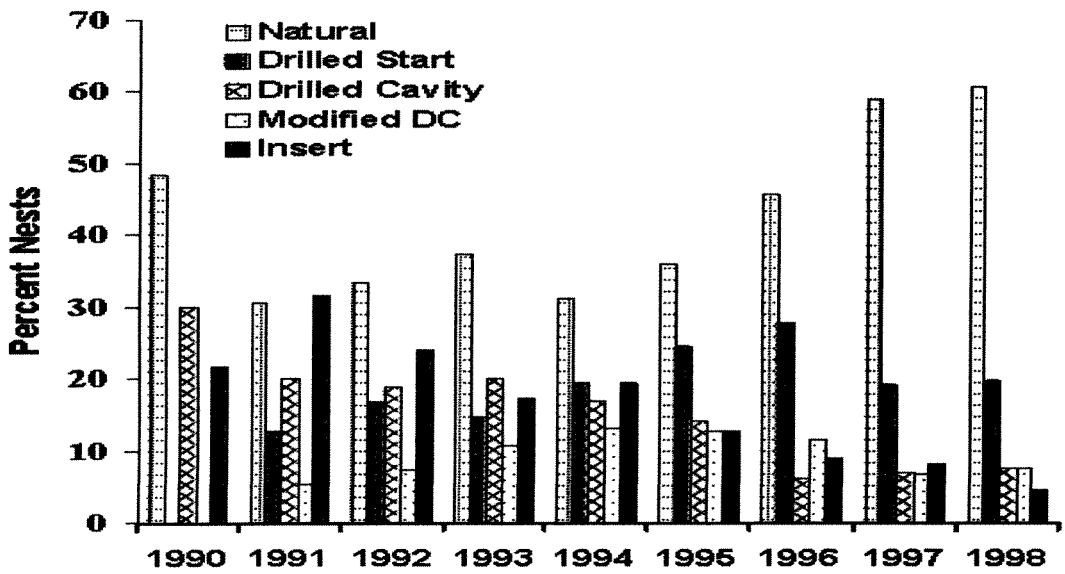

Figure 4. Percent of red-cockaded woodpecker nests in natural cavities and each of 4 artificial cavity types with at least one egg on the Francis Marion National Forest.

rates of trees with artificial cavities and natural cavities, Conner et al. (1998*a*) found no significant difference in the mortality rate of pines with inserts and those with natural cavities.

Mortality of red-cockaded woodpeckers resulting from artificial cavity use was low. Careful installation, screening of cavity entrances until the possibility of resin leakage is unlikely, and a diligent inspection process help keep mortality rates low (Copeyon 1990, Allen 1991, Taylor and Hooper 1991). Although any mortality is unfortunate, more than 2,400 young were fledged from artificial cavities between 1990-1998. The overall benefit to the FMNF red-cockaded woodpecker population more than compensated for 4 birds that died in artificial cavities.

Long-term usability was greater for drilled starts and drilled cavities than for modified drilled cavities and inserts. Inserts and modified drilled cavities were more likely to be enlarged and fill with water, which accounted for their shorter term of usability. Modified drilled cavities suffered from greater structural damage from decay and from pileated woodpeckers than did drilled cavities. Unlike the drilled cavity, where the access plug is covered by resin flow, the modified drilled cavity's access plug typically remains exposed, subjecting it to decay. Also, the larger access hole of modified drilled cavities resulted in a larger septum of wood between the entrance tunnel and the access hole. The larger septum tended to rot and encourage pileated woodpecker activity. However, when damaged modified drilled cavities were repaired with restrictor plates they were frequently used again by red-cockaded woodpeckers. Placement of restrictor plates during installation would greatly enhance the useful life of modified drilled cavities. Such restrictors should cover the plug for the access hole and septum, as well as protect the entrance tunnel from enlargement. Use of restrictor plates on inserts has become a common practice (U.S. Fish and Wildlife Service 2003).

It was necessary for red-cockaded woodpeckers to finish excavating drilled starts before they could use them for nesting or completely functional roosting. Only 62% of drilled starts had been completed after 9 nesting seasons but most (>75%) drilled starts that were completed, were completed prior to the second nesting season. This short completion time suggests some factors besides elapsed time had a bearing on their completion. The most likely factor was the presence of heartwood fungus (*Phellinus pini*), which makes the final stages of cavity excavation easier (Conner and Rudolph 1995*a*). We were unable to test for the presence of heart rot, but it is safe to assume that the fungus played some role in completion of the drilled starts. It would be desirable to increase the frequency that drilled starts are completed, although it is not clear how to do that. Making drilled starts in trees infected

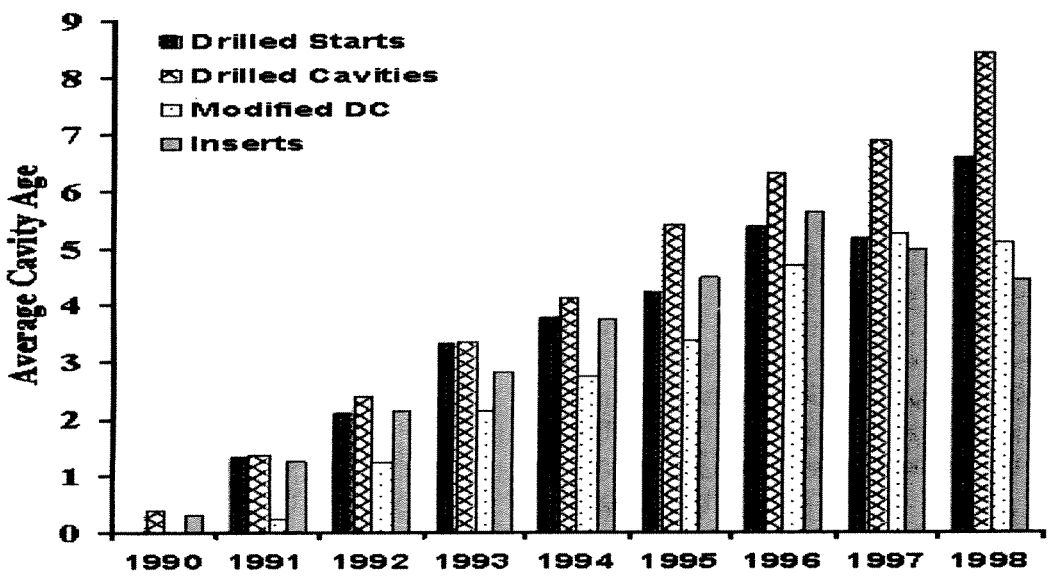

Figure 5. Mean age of artificial cavities used for nesting on the Francis Marion National Forest.

with heart rot would probably help, but this may not be practical. We typically installed 2 drilled starts in each cluster, which increased the chance of hitting heart rot. Generally, red-cockaded woodpeckers completed only 1 of the 2 drilled starts in a cluster.

All 4 types of artificial cavities were successfully used as nest cavities, and reproductive success of red-cockaded woodpeckers using artificial cavities did not differ significantly from the success of those using natural cavities. The mean number of young fledged from artificial cavities fell within the range commonly found in northern populations of red-cockaded woodpeckers (Lennartz et al. 1987, LaBranche and Walters 1994, Laves and Loeb 1999). Although the number of young fledged from modified drilled cavities was significantly greater than from drilled starts and inserts, there was a great deal of annual variation in reproductive success (Table 2). Further, it appears that older modified drilled cavities and inserts were not used for nesting. By contrast, drilled starts and drilled cavities were stilled being used for nesting in their 9th nesting season post installation. In Texas, red-cockaded woodpeckers select the newest cavities in a cluster, perhaps because of the greater resin production (Conner et al. 1998*b*). The mean age of natural cavities used for nesting in Texas was 2.48 yrs in loblolly/shortleaf trees and 3.68 years in longleaf pines. All types of artificial cavities we studied were used at least as long, on average, as the natural cavities in the Texas study. The lack of a steady supply of new cavities may explain the extended use of artificial cavities in our study.

MANAGEMENT IMPLICATIONS

Managers of red-cockaded woodpeckers can choose from 4 types of artificial cavities that are effective as both roosting and nesting cavities. Each type of artificial cavity has some advantages over the others, allowing the manager to tailor application to specific circumstances.

Overall, drilled cavities tended to be the most effective. However, installation of drilled cavities requires the most skill to construct, the most training (several weeks), and the most heartwood. Nonetheless, in many cases, none of these limitations is prohibitive.

For the first 3 years, inserts were highly effective as nesting cavities. Over time though, they did not endure as well as drilled cavities. However, a deteriorated insert can be removed and replaced. Importantly, inserts are the only choice when there are few older trees with sufficient heartwood for drilled cavities and starts. Also, installation of inserts can be learned in about 2 days with proper instruction.

When installing modified drilled cavities, we recommend the installation of a restrictor plate that covers the access hole and septum, as well as the area around the cavity entrance. This addition should greatly reduce the loss of modified drilled cavities to structural damage. Training time for installing modified drilled cavities is less than for drilled cavities, but more than for inserts. For 3-5 years after construction, modified drilled cavities performed better than inserts or drilled cavities.

Drilled starts older than 1 year are nearly as effective as drilled cavities and inserts, and could be used to supplement established clusters where a new usable cavity is not needed immediately. Drilled starts are cheaper than drilled cavities, and much less time is required to learn the construction technique. On average, drilled starts are usable longer than the other types. Generally, because not all drilled starts are made into cavities by the woodpecker, more than 1 start per cluster should be made for each desired new cavity.

Depending upon type of cavity, usefulness declines rapidly 3-6 years after construction. Consequently, managers should plan for replacement of artificial cavities after initial construction.

ACKNOWLEDGMENTS

We thank D. H. Allen, R.N. Conner, D. L. Krusac, and S. M. Lohr for helpful comments on earlier drafts of this manuscript.

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