Analysis of the Southern Pine Beetle Suppression Program on the National Forests in Texas in the 1990s

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ABSTRACT: *Infestations of the southern pine beetle (SPB) (*Dendroctonus frontalis *Zimmermann) affected 7,929 ac of managed forest and 13,346 ac of wilderness on the National Forests in Texas (NFT) during the 1990s. Direct control treatments were applied to two-thirds of the 8,486 infestations on managed forest; the average size of treated spots was 1.3 ac. Inactive infestations averaged only 0.25 ac. Cut-and-remove was the preferred treatment; and only one application per infestation was required for over 97% of infestations treated by this method. Cut-and-leave was applied to 27% of infestations requiring treatment; and a single application was effective for 90% of treated infestations. In wilderness, where SPB suppression was limited due to legal constraints, large infestations developed, killing over 40% of the susceptible host type. In contrast, less than 2% of the susceptible host type was killed in nonwilderness areas of the NFT. Economic analyses indicate the SPB suppression program was cost-effective, with an estimated benefit/cost ratio of 3.55:1. South. J. Appl. For. 27(2):122–129.*

Key Words: *Dendroctonus frontalis*, wilderness, direct control, insect suppression, economic analysis.

The National Forests in Texas (NFT), located in east Texas, comprise the Angelina, Davy Crockett, Sabine, and Sam Houston National Forests. These forests cover 637,472 ac, much of which is occupied by southern yellow pine. The USDA Forest Service Continuous Inventory of Stand Conditions (CISC) data show that the age classes of pine forests are skewed toward older stands; the dominant trees in 65% of the stands are over 60 yr old.

The southern pine beetle (SPB), *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae), is an important insect pest in pine forests of the southern United States. In east Texas, loblolly (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.) stands of high basal area (>120 ft^2/ac) and slow radial growth are considered high hazard for SPB attack (Hicks 1980, Mason et al. 1985). The predominance of pine stands and their senescent age classes make the NFT very susceptible to the SPB. The CISC records listed approximately 450,000 ac of susceptible host type in the managed (general) forest areas of the NFT in the early 1990s.

To minimize resource loss to SPB, the NFT practices an integrated pest management (IPM) program with four main components: prevention, detection, evaluation, and suppression. Prevention, incorporating silvicultural tools such as thinning and adjusting the species composition or age classes to reduce hazard (Belanger and Malac 1980), cannot always be used where needed on the NFT due to environmental, management, or legal constraints; accordingly, susceptible pine stands are usually present.

When SPB infestations occur, detection, evaluation, and suppression are implemented. From spring through early fall, SPB populations are aggregated in expanding infestations called "spots." Spot expansion occurs as additional trees come under attack in a localized area known as the "spot head," and expansion is generally unidirectional when spots are small. Aerial detection flights are conducted to locate the expanding infestations. Survey frequency varies, ranging from one or two annually during endemic years to once every 2 wk during outbreaks. All suspected SPB infestations are plotted on maps or aerial photographs, then located and evaluated on the ground. The field crew recommends what suppression treatment, if any, should be applied. In general, infestations are candidates for suppression if they are expanding, have more than ten currently-infested trees, have freshly attacked trees present, and have additional host type available (Hedden and Billings 1979, Billings 1980).

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Given that spot expansion is localized at the spot heads, direct control measures may be applied to prevent spot growth. SPB suppression has been shown to be effective in halting the expansion of individual infestations and reducing resource loss (Billings and Varner 1986, Redmond and Nettleton 1990). Four suppression techniques are currently approved for use on the NFT by the Final Environmental Impact Statement (FEIS) for the Suppression of the SPB (USDA Forest Service 1987): cut-and-remove, cut-and-leave, cut-and-hand-spray, and pile-and-burn. The selection of a suppression method depends on time of year, accessibility, management area considerations, timber markets, and spot size. Cut-and-remove is applied when environmental conditions allow logging access and markets for beetle-killed timber are available. All currently infested trees and a buffer strip of uninfested trees around the spot head are felled and removed. This is the preferred method of spot treatment because the beetles are removed from the site, and the federal treasury receives a monetary return from the sale of the trees. The cut-and-leave treatment is similar to cut-and-remove, except the trees are felled toward the center of the spot and left on the ground (Billings 1980). This tactic is usually recommended only from May through October when SPB initiate few infestations, and for infestations <100 trees (USDA Forest Service 1987). Beetles that survive and emerge from felled trees are forced to disperse because of the absence of pheromones from SPB in freshly attacked trees. Mortality of SPB dispersing in the summer is believed to be high (Billings and Pase 1979).

For cut-and-hand-spray, the currently infested trees are felled, bucked into sections, and the entire bark surface sprayed with a registered insecticide. Pile-and-burn, in which the currently infested trees are felled, pushed into a pile, then burned, is seldom used.

The NFT requests and receives federal suppression funds as needed for aerial detection surveys, ground-checking, infestation monitoring, approved suppression treatments, and database management. These monies fund cut-and-remove treatments to the point of marking the trees for removal. Salvage sale funds must be used to complete these treatments.

Five wildernesses have been established on the NFT: Indian Mounds, Little Lake Creek, Upland Island, Turkey Hill, and Big Slough. The first four had large acreages of susceptible pine type prior to their wilderness designation in 1984 (USDA Forest Service 1987), and 1600 ac of wilderness on the NFT were affected by SPB in the 1980s. Initially, SPB suppression within wilderness was permitted and implemented, but subsequent judicial rulings on legal challenges and the enactment of the Final Environmental Impact Statement for the Suppression of the SPB in 1987 limited direct control. SPB suppression in wilderness is now allowed only to protect threatened tree resources on adjacent private or high-value federal lands, or to protect essential endangered species habitat, such as clusters and limited foraging area of the red-cockaded woodpecker (RCW), *Picoides borealis*.

Several criteria must be met before direct control can be implemented in the wilderness to protect adjacent private land. First, the infestation must be within one-quarter mile of susceptible trees on the private land. Second, a site-specific evaluation of the infestation by a professional entomologist must conclude that the infestation has the potential to expand directly onto the private property. Third, the Forest Service must conclude that any control measures applied have a "reasonable prospect" of success in preventing spot expansion to private land. Finally, the private landowner has to indicate a willingness to suppress SPB infestations on his or her property. Suppression in wilderness to protect endangered species habitat may proceed only after a professional entomologist predicts the expanding infestation will infest the susceptible hosts within the essential habitat within 30 days.

SPB activity is cyclic. Historical records of the Texas Forest Service reveal outbreaks in Texas in 1882–1885, 1910–1912, 1919, 1926, 1938–1939, 1944–1947, 1949–1951, 1962–1968, 1972–1977, and 1984–1986. From 1960–1989, SPB killed an estimated 1,211,689 cords and 1,368,937 mbf of pine in east Texas (Price et al. 1998). The economic value of the resource lost was calculated at $142,228,104. Each successive outbreak increased in severity during this period, with losses in 1985 alone accounting for approximately 35% of the total sawtimber volume lost during the three decades. Following the SPB outbreak from 1984–1986, SPB activity declined to low-moderate levels in Texas for the next 2 yr (Price et al. 1998). Populations increased dramatically in 1989, with over 2,000 infestations detected in that year (Clarke et al. 1994).

The objectives of this article are to: (1) chronicle SPB activity and suppression actions on the NFT during the 1990s; (2) assess the effectiveness of SPB suppression by comparing resource losses on the managed forest area, where suppression is allowed, with those in wilderness, where suppression is severely restricted; (3) gauge the efficacy of the individual treatment methods applied; and (4) evaluate the benefits of the SPB suppression program.

Materials and Methods

Data Analysis

The finalized USDA Forest Service Southern Pine Beetle Information System (SPBIS) database was used to compile numbers of SPB spots on the NFT from 1990–1999. SPBIS is an operational database allowing the National Forests in the Southern Region to track SPB infestations. All SPB infestations with 10 or more infested trees are assigned a spot number in SPBIS. Smaller infestations may be included if they occur in a high-value area such as a cluster of the endangered RCW. Data fields in SPBIS include National Forest, spot number, detection date, ground-check date, numbers of infested trees, acres affected, and suppression date, among others. Each spot is assigned a primary treatment: cut-and-remove, cut-and-leave, cut-and-hand-spray, pile-and-burn, inactive, or monitor. This primary treatment can be changed when the database is updated based on subsequent management of the spot. Most monitored spots are subsequently reclassified as inactive, because they typically contain very few or no freshly attacked trees at the initial ground check and the emerging SPB disperse (Hedden and Billings 1979). Sawtimber and pulpwood volumes are included for spots treated by cut-and-remove. Numbers of trees treated are recorded for cut-and-leave and cut-and-hand-spray treatments. Treatment breakouts (reinfestations) are tracked by adding a letter to the end of the spot number, starting with *A*. Infestations with trees treated by cut-and-leave that are subsequently salvaged are designated with an *R*, and the recovered volumes are tallied.

The NFT monitors SPB activity by federal fiscal year (October 1–September 30) for budgetary reasons; however, the spot data were compiled by calendar year for this study. SPB activity diminishes in the winter, so the calendar year provides a cleaner analysis of the data and is biologically more appropriate. The date the spot was initially detected was used to assign the year. For example, if a spot was detected in 1990 but not treated until 1991, the treatment data would be included in the 1990 totals. The database was carefully checked for any obvious errors or duplication.

Wilderness SPB spots are recorded separately in SPBIS. It is difficult to track individual infestations because they may keep expanding for several years, but acreages are only attributed to the year the spot is finally declared inactive or controlled. Wilderness spots often merge or split. Sometimes the inactive portion of an infestation is closed out at the end of a fiscal year, and the active portion is renumbered and tracked through the new fiscal year. Therefore this report does not include the number of infestations within wilderness, but uses total acres infested as a measure of SPB impact.

SPBIS status reports were used to estimate the wilderness acreage affected by SPB per year. These reports update the acres infested every 2 wk. At the beginning of the fiscal year, the inactive acres are subtracted from the total acres, and only the active acres of infestation are carried over into the new fiscal year. Adding the acreage infested from January through September to the acreage infested from October through December in the new fiscal year provided an estimate of impact for the calendar year that did not rely on the detection or suppression date.

Suppression activities within wilderness were grouped as sites treated rather than spots treated. For large infestations, only the spot head threatening adjacent private land or endangered species habitat was treated in many cases, rather than all currently-infested trees.

Acres of susceptible host type were obtained from CISC. All stands of predominately pine type with adequate stocking that were not classified in regeneration or seedling-sapling age classes were included.

Economic Analysis

The Southern Pine Beetle Economic Evaluation Program (SPBEEP) [Unpublished SPEEP User's Manual on file at the USDA Forest Service, Forest Health Protection office, Pineville, LA], developed by the USDA Forest Service, was used to estimate the economic benefits of the SPB suppression projects on the NFT. Data were collected annually from ten active infestations per Ranger District or Forest in outbreak areas, including the number of infested trees, stand age, primary pine species, pine and total basal area, and average pine diameter at breast height (dbh). The program used these data, the number of infestations on the Ranger District, and the anticipated percentage of infestations treated to calculate timber volume killed and volume salvaged, both with and without a suppression project. Any volume not salvaged was considered volume lost. The volume lost was multiplied by a spot spread factor generated internally by the program from a spot spread model developed by Hedden and Billings (1979) to calculate volume threatened. The difference between the volumes threatened with and without a suppression project was volume protected. The projected volume at harvest was then generated from the volume threatened and user inputs of site index, tree age, and tree species composition. Current prices for green and salvaged timber were input to calculate the difference in the combined value of timber lost (present and at harvest) under each scenario. This monetary difference and the suppression and salvage sale funds expended for SPB detection, control, and monitoring were used to compute the expected project benefits and the benefit/cost ratio of the suppression project.

A more accurate estimate of volume protected was obtained using the ratio of volume removed/volume protected estimated by SPBEEP and the actual volume removed during SPB suppression reported by the NFT:

$$\text{revised vol. protected} = \frac{\text{actual vol. removed} \times \text{est. vol. protected}}{\text{est. vol. removed}}$$

Results

Managed Forest

There were 7,929 ac affected by SPB on the NFT during the 1990s (excluding wilderness), or roughly 1.8% of the susceptible host type (Table 1). A majority of the infestations in the NFT were detected in June and July (Figure 1), reflecting the fact that most new SPB infestations in east Texas are initiated in the spring (Hedden and Billings 1979) and then detected 4-8 weeks later when the foliage fades in color (Billings and Kibbe 1978). The Sam Houston and Davy Crockett NFs had significant levels of SPB infestation

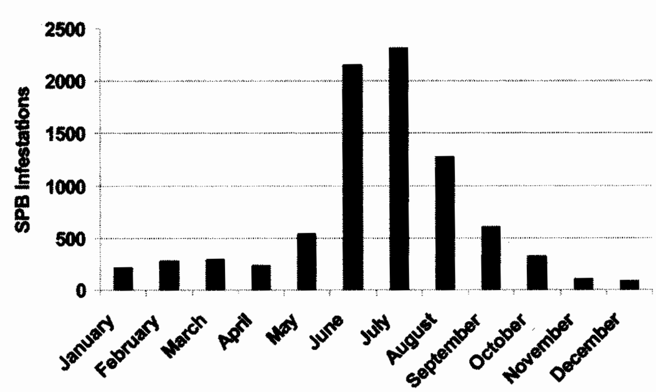

Figure 1. Southern pine beetle infestations on the National Forests in Texas by month of detection, 1990–1998.

Table 1. Number and acreage of southern pine beetle infestations on managed forestland on the National Forests in Texas, 1990–1999.

	New spots		Spots requiring treatment			Inactive spots		
Year	No.	Acres	No.	Acres	Ac/spot	No.	Acres	Ac/spot
1990	1,252	832.5	767	740.1	0.97	485	92.4	0.19
1991	1,494	1,153.9	1,048	1,078.9	1.03	446	75.0	0.17
1992	2,777	2,806.5	1,956	2,633.8	1.35	821	172.7	0.21
1993	1,958	2,075.2	1,355	1,933.2	1.43	603	142.0	0.24
1994	299	139.7	133	87.7	0.66	166	52.0	0.31
1995	136	55.6	55	38.7	0.70	81	16.9	0.21
1996	102	32.4	11	3.8	0.35	91	28.6	0.31
1997	440	821.4	234	679.2	2.90	206	142.2	0.69
1998	28	11.8	13	5.4	0.41	15	6.4	0.43
1999	0	0	0	0		0	0	
Total	8,486	7,929.0	5,572	7,200.8	1.29	2,914	728.2	0.25

in 1990, and an outbreak occurred throughout the NFT in 1991–1993. The Angelina NF had 1398 new infestations detected from 1992 through 1993, while the Sabine NF had 1,815 infestations during the same time period. These two NFs had not experienced significant SPB activity since 1986. SPB populations declined in 1994, and remained low throughout 1995–1996. A resurgence of SPB activity occurred in the late summer and fall of 1997, but did not continue into 1998. In 1999, no SPB infestations were reported throughout east Texas.

Two-thirds of SPB infestations on the NFT required treatment (Table 1). The average size of treated spots was 1.5 ac, except on the Davy Crockett NF, where the average treated spot size was 0.68 ac. Infestations were more likely to receive treatment in years when populations were high (>100 infestations/NF). Spots classified as inactive at ground-check averaged only one-fifth the size of treated spots.

Cut-and-remove was applied to approximately 50% of the spots requiring control on the Angelina and Sam Houston NFs, while it was implemented over 80% of the time on the other two NFs. Total volume removed from the NFT was approximately 76.8 mmbf of sawtimber and 1.1 mmcf of pulpwood (Tables 2 and 3). A small amount of this volume was from cut-and-leave treatments that were later salvaged. The average volume per treated infestation was lower for the two forests with the highest percentage of spots cut and removed.

Cut-and-leave was applied to 27% of infestations requir-

Table 2. Number, acreage, and removal volumes of southern pine beetle infestations treated by cut-and-remove (C&R) on managed forestland on the National Forests in Texas, 1990–1999.

Year	Spots	Breakouts	Acres	Ac/spot	Sawtimber (MBF)	Pulpwood (CCF)
1990	554	13	535.0	0.97	5,757.7	414.9
1991	805	15	879.0	1.09	12,373.8	1,813.6
1992	1,382	72	2,051.4	1.48	27,039.7	4,216.6
1993	994	15	1,541.2	1.55	16,701.6	2,629.7
1994	63	1	48.8	0.77	559.1	72.0
1995	42	2	31.3	0.74	382.0	7.5
1996	11	1	3.8	0.35	91.8	1.3
1997	130	0	493.8	3.80	10,747.1	1,369.2
1998	11	0	4.8	0.43	99.0	0.9
1999	0	0	0		0	0
Total	3,992	119	5,589.1	1.40	73,751.8	10,525.7

Table 3. Number, acreage, and salvaged volumes of southern pine beetle infestations treated by cut-and-leave (C&L) on managed forestland on the National Forests in Texas, 1990–1999.

Year	Spots	Breakouts	Acres	Ac/spot	Trees	Spots salvaged*	Volume (MBF)*	Volume (CCF)*
1990	188	18	193.5	1.03	34,841	31	567.0	48.0
1991	241	23	199.9	0.83	44,489	1	19.0	
1992	559	72	578.5	1.03	132,514	105	1,707.5	252.9
1993	354	46	389.0	1.10	95,919	24	265.3	19.4
1994	70	1	39.0	0.56	8,183	4	62.0	2.0
1995	12	0	7.2	0.60	1,126	0	0	0
1996	0	0	0		0	0	0	0
1997	104	1	185.4	1.78	24,168	4	414.0	53.0
1998	2	0	0.6	0.30	156	0	0	0
1999	0	0	0		0	0	0	0
Total	1,530	161	1,593.1	1.04	341,396	169	3,034.8	375.3

* Spots or volumes from cut-and-leave treatments that were subsequently salvaged for marketable timber.

Table 4. Number and acreage of southern pine beetle infestations treated by cut-and-hand spray (C&HS) or pile-and-burn (P&B) on managed forestland on the National Forests in Texas, 1990–1999.

	C&HS				P&B		
Year	Spots	Breakouts	Acres	Trees	Spots	Acres	Trees
1990	25	8	11.7	1,949	0	0	0
1991	0	0	0	0	2	0.5	187
1992	10	4	3.9	780	5	2.4	648
1993	7	1	2.9	269	0	0	0
1994	0	0	0	0	0	0	0
1995	1	0	0.2	0	0	0	0
1996	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0
Total	43	13	18.7	2,998	7	2.9	835

ing treatment (Table 3). Almost 95% of cut-and-leave treatments were applied between May and October, with 71% of treatments applied in June, July, and August. The average spot size was just over an acre, smaller than the average size for salvaged spots (1.4 ac). An average of 223 trees were felled per treatment, including noninfested trees felled in the buffer. This average of approximately 223 trees/ac per treated spot indicates that the acreage was often not updated after treatment and/or reflects the fact that cut-and-leave is applied in stands with lower pine mean dbh and larger mean number of trees/ac.

Cut-and-hand-spray and pile-and-burn were rarely used in the 1990s to suppress SPB infestations (Table 4). Most infestations treated by these tactics were small, averaging less than 0.5 ac.

Retreatment was required for less than 3% of infestations treated by cut-and-remove and for just over 10% of cut-and-leave treatments (Tables 2 and 3). Breakouts occurred for 30% of the cut-and-hand-spray treatments (Table 4). The exact percentages were difficult to compute from SPBIS data, as some treated spots may have concurrent breakouts, or a breakout may occur after a retreatment. Breakouts were more likely to occur in years when area-wide SPB populations were high.

Wilderness

Constraints on direct control of SPB in wilderness allowed infestations to grow unimpeded, resulting in large acreages of SPB-killed pines (Table 5), especially in 1993. Overall, over 40% of the 31,656 ac of susceptible host type in wilderness was killed by SPB in the 1990s. The acres of susceptible host type used in the calculation were determined from CISC records at the initial designation of the wildernesses in 1984, and include acres lost to SPB in the latter half of the 1980s. Indian Mounds Wilderness sustained the most impact in the 1990s, with 76% of the acres of susceptible host type affected. The east and south sections of Turkey Hill containing dense stands of loblolly pine were decimated by SPB, but mature longleaf pine (*Pinus palustris* Mill.) stands in the northwest section were not affected. Though Upland Island lost over 1,700 ac, large areas of mature loblolly pine remain. Big Slough had very little susceptible host type, and impacts were minor. Little Lake Creek also was beset by several large infestations, and about 44% of the susceptible host type was killed.

Suppression occurred in 103 cases to prevent the loss of RCW cluster trees and/or limited foraging habitat in Little Lake Creek (Table 6). There were six active and six inactive clusters located within or partially within the wilderness (USDA Forest Service 1996). Cut-and-leave was the primary treatment used, although cut-and-hand-spray using Dursban® 4E was occasionally applied when treatment areas were small.

Suppression was undertaken in three other wildernesses to protect trees on adjacent private land (Table 6). Cut-and-leave was usually the treatment of choice. Expanded buffers were often necessary due to the large size of the spot or spot head being treated. In some instances, the goal of treatment

Table 5. Estimated acreage infested by southern pine beetle per year in wilderness on the National Forests in Texas, 1990–1999.

Year	Upland Island	Turkey Hill	Big Slough	Indian Mounds	Little Lake Creek	Total
1990	72.0	5.0	46.0	374.0	301.0	798.0
1991	4.0	3.0	1.0	66.0	42.0	116.0
1992	557.0	200.0	50.0	1,472.5	872.5	3,152.0
1993	1,066.6	1,868.0	32.0	5,987.8	207.5	9,161.9
1994	38.4	44.0	0	7.0	0	89.4
1995	0.3	1.4	0.5	12.0	0.2	14.4
1996	0.5	0	0	0	1.8	2.3
1997	6.8	5.0	0	0	0	11.8
1998	0	0	0	0	0	0
1999	0	0	0	0	0	0
Total	1,745.6	2,126.4	129.5	7,919.3	1,425.0	13,345.8

Table 6. Southern pine beetle suppression treatments in wilderness on the National Forests in Texas, 1990–1993.

	Cut-and leave			Cut-and-hand spray		
Year	Sites	Trees	Acres	Sites	Trees	Acres
Upland Island						
1990	0	0	0	0	0	0
1991	0	0	0	0	0	0
1992	0	0	0	1	329	4.0
1993	1	29	1.0	0	0	0
Turkey Hill						
1990	0	0	0	0	0	0
191	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	20	4,446	60.1	0	0	0
Indian Mounds						
1990	0	0	0	0	0	0
1991	0	0	0	0	0	0
1992	3	3,408	31.0	1	392	4.0
1993	9	1,624	11.9	12	1,078	14.4
Little Lake Creek						
1990	47	11,507	184.8	11	2,111	49.2
1991	4	585	6.1	1	121	0.8
1992	28	3,674	12.5	4	340	2.5
1993	12	1,565	18.3	2	157	1.7
Grand total	124	26,838	325.7	32	4,528	81.6

was to divert the infestation away from the boundary, allowing it to expand back into the wilderness. Cut-and-hand-spray was used when infestations were close to the boundary, and the buffer required for cut-and-leave could not be felled. Overall, only 3% of the acres affected by SPB in wilderness were treated by direct control, compared to 91% of the infested acres on NF land outside wilderness.

Economic Analysis

The suppression funds received by the NFT are given in Table 7. Just over $7.5 million were spent in the 1990s for SPB detection, evaluation, and suppression. As calculated by SPBEEP, suppression project funding provided an estimated benefit of $26.7 million, with an overall benefit/cost ratio of 3.55:1.

The annual volumes protected were based on actual volumes removed reported by the NFT, rather than on the predicted removal generated by SPBEEP. Thus in Table 7 there is not a clearcut correlation between the volume protected annually and the estimated project benefits computed by the economic analyses. Using the revised total volume protected and a conservative price of $200 per mbf of green timber for the 1990s, the benefit of the SPB suppression project was $6 million more than the estimate given in Table 7.

Discussion

Suppression Program Efficacy

Prompt detection and suppression of expanding SPB infestations were efficacious in reducing tree loss on the NFT in the 1990s. The managed forest acreage affected for the entire NFT was equivalent to the acreage killed solely within Indian Mounds Wilderness. Our data are similar to those given in previous reports compiled from the SPBIS biweekly reports (Billings 1995, 1998). Though some differences in

Table 7. Economic costs and benefits of the southern pine beetle (SPB) suppression program for the National Forests in Texas (NFT). Benefits and volume protected calculated using the Southern Pine Beetle Economic Evaluation Program (SPBEEP).

Fiscal year	Suppression dollars[1]	Salvage sale funds[2]	Benefit/cost	Project benefits ($)	Volume protected (mbf)[3]
	($)				
1990	670,000	45,000	1.82	1,303,679	28,503
1991	275,000	100,000	9.26	3,472,473	25,522
1992	1,112,500	404,000	6.01	9,121,017	51,560
1993	1,135,000	1,200,000	4.29	10,021,528	32,460
1994	636,000	900,000	1.42	906,928	739
1995	300,000	198,000	3.02	906,928	431
1996	85,000	150,000	2.70	241,649	60
1997	222,142	95,000	3.26	724,795	24,808
Grand total	4,435,642	3,092,000	3.55	26,698,997	164,083

[1] Dollars appropriated for the NFT for the SPB suppression program.
[2] Estimated dollars available for removal of infested trees.
[3] Estimates based on actual volumes removed reported by the NFT and the volume protected/removed ratio generated by SPBEEP.

stand conditions existed between managed forest and wilderness, the differences were not significant because little management was conducted on much of the managed forest area in the years following wilderness designation due to court-mandated restrictions. The disparate impacts of SPB in stands of susceptible host type within and outside of wilderness on the NFT in the 1990s clearly demonstrate the value of a SPB suppression program.

Treatment Efficacy

Cut-and-remove and cut-and-leave were generally effective in suppressing infestations with only one treatment. Cut-and-hand-spray was not as effective. Cut-and-hand-spray does not require a buffer, so trees just coming under attack may be missed, resulting in breakouts. The SPB in felled trees that were recently attacked may still produce aggregation pheromone. Without a buffer strip, these pheromones may induce emerging SPB to attack the residual standing trees adjacent to the old spot head. Cut-and-hand-spray treatments are likely to be more effective when area populations are low or when applied with a small buffer.

Area-Wide Efficacy

Direct control treatments are designed only to suppress an individual, expanding SPB infestation. These tactics are not intended to reduce area-wide SPB populations. However, the comparison presented above of infested acreage between areas with and without direct control provides evidence that a suppression program can significantly lower the area-wide impacts of SPB.

There also has been concern that spot disruption tactics, in particular cut-and-leave, may exacerbate area-wide SPB problems (Turchin and Thoeny 1993). Based on our analysis of the SPB suppression program on the NFT, we consider these concerns unfounded. Cut-and-leave is recommended only when cut-and remove cannot be implemented, and it was applied to only slightly more than one-quarter of the infestations on the NFT requiring treatment during the 1990s. Cut-and-leave is recommended for use from May to October, and the seasonal implementation of cut-and-leave on the NFT verifies that this pattern is followed. Most new infestations are initiated in the spring (Hedden and Billings 1979) or in the fall (Thatcher and Pickard 1967), so the chance that SPB dispersing from cut-and-leave treatments will result in new infestations is slight. In independent studies in Texas, Billings, and Pase (1979) and Fitzgerald et al. (1994) found that beetles emigrating from suppression treatments did not cause an increase in numbers of new spots initiated locally. In contrast, Billings and Pase (1979) found that new infestations were more common near uncontrolled infestations than near cut-and-leave treatments applied in the summer (see also USDA 1987, Appendix B). The low incidence of breakouts for cut-and-leave treatments observed on the NFT also suggests that beetles dispersing from spot disruption treatments are unlikely to initiate new infestations.

Though cut-and-leave does not lead to increased spot proliferation, beetles dispersing from these treatments could participate in attacks in established spots. However, SPB dispersing from cut-and-leave treatments will have farther to fly to find a source of aggregation pheromone, and in the summer, SPB cannot survive for long periods outside of a pine (Coulson 1980).

The NFT data suggest that cut-and-leave is an effective component of an SPB suppression program. Delaying action until cut-and-remove can be applied or failure to treat an active infestation will result in higher tree mortality than the application of cut-and-leave. On average, untreated infestations more than doubled in size in 2–6 wk in the summer (Clarke et al. 1999, Cronin et al. 1999), and beetles also disperse from untreated infestations (Cronin et al. 1999).

Outbreak Initiation and Collapse

The SPB suppression program on the NFT was effective in reducing resource loss, but did not prevent the onset of an outbreak. Suppression is but one part of an integrated pest management program for SPB, and silvicultural activities to reduce forest-wide susceptibility to SPB are necessary. The effects of SPB suppression on the collapse of the outbreak are unclear, though as stated above, spot proliferation is greater around untreated spots. Lack of susceptible host resource did not appear to be a factor in the SPB population collapse in 1994, as only 1.8% of the susceptible host type was lost. In wilderness, infestation expansion in 1994 slowed and then ceased, even when suitable hosts were present. It is possible that environmental conditions may have increased host resistance, but it is doubtful that this factor alone would lead to the dramatic decline observed.

It has been suggested that the chief predator of SPB, the clerid beetle *Thanasimus dubius* (Coleoptera: Cleridae), is involved in SPB population fluctuations (Reeve 1997). This predator can have an extended diapause, and it is hypothesized that a delayed density-dependent response by *T. dubius* to SPB populations serves to bring their populations back to endemic levels (see also Turchin et al. 1991). Clerids were abundant on pines under attack throughout the epidemic. *Thanasimus dubius* is attracted by frontalin, the primary aggregation pheromone produced by SPB (Vité and Williamson 1970); also Billings (1988) demonstrated a relationship between SPB population trends and the ratio of clerids and SPB captured in pheromone traps in the spring. However, the true relationship between clerid numbers and SPB outbreaks remains to be determined.

An increase in competition for resource utilization under the bark was observed, particularly in large wilderness infestations. Populations of *Ips* bark beetles and borers (*Monochamus* spp., Coleoptera: Cerambycidae) appeared to increase dramatically near the collapse of the outbreak. The impacts of interspecific competition in the reduction SPB populations need to be quantified.

Economic Benefits

Our economic analysis indicates that SPB suppression is cost-effective. De Steiguer et al. (1987) estimated a benefit/cost of 6.61:1 or 9.68:1 for SPB suppression on federal lands in Texas, depending on the discount rate used (10% or 4%). These levels were 2–3 times higher than the ratio given by the SPBEEP used in this study. The project benefits listed in Table 7 were calculated using only timber values, as was the analysis by de Steiguer et al. (1987). If impacts on recreation, endangered species habitat, scenic, and other values were included, the benefits of SPB suppression would be much higher. Also, based on the impact in wilderness, where close to half of the susceptible host type was lost, the estimates of volume protected used in the calculations are probably low. It is clear that the SPB suppression program in Texas was well justified.

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