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Direct Control of Western Pine Beetle (*Dendroctonus brevicomis* LeConte): Review and Assessment

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Nearly 70 years of research and application are reviewed and assessed. Results of direct control projects can be characterized as generally effective, temporary, quite variable, and unpredictable in reducing subsequent tree mortality. Some causes of this characterization are variable and difficult stand conditions and logistics, lack of good beetle population measurements and prediction, unknown attributes of tree and stand dynamics and of beetle population dynamics, and unforeseen post-application factors. The control method used did not appreciably change this characterization: fell-peel-bum, salvage logging, penetrating oil, residual toxic sprays, or attractive pheromones. Use of attractive pheromones was never thoroughly analyzed, and use of baited toxic trap trees was never adequately tested; both should be done.

Retrieval Terms: ponderosa pine, western pine beetle, Coulter pine, mountain pine beetle, direct control, salvage logging, fell-peel-burn, toxic sprays, attractive pheromones, baited toxic trap trees

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INTRODUCTION

Western pine beetle (*Dendroctonus brevicomis* LeConte) was, for several decades, considered one of the most damaging, if not the most damaging, forest insect in the West and in the United States. Virtually all losses have been in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws). Coulter pine (*Pinus coulteri* D. Don) is a host, but losses have been very small compared to ponderosa pine. Miller and Keen (1960) estimated that from 1910 to 1960 western pine beetle killed about 50 billion board feet of timber. The annual loss ranged widely from 200 to 300 million board feet to more than 3 billion. Since 1960, loss records have not been obtained regularly, but experienced observers estimate that losses have not been as severe from 1960 to 1985 as they were from 1910 to 1960. Nevertheless, for certain periods in the past 25 years losses have been high, with estimates at over 2 billion board feet per year for 1- to 3-year periods. One or more of the following factors could have caused this apparent improvement: more intensive forest management, use of risk rating and sanitation salvage, decrease in area of old-growth stands, more favorable weather conditions for tree growth and, lack of reliable loss data.

Direct control, in simplest terms, is action taken to kill beetles directly, with a variety of procedures, in order to reduce their numbers and subsequent beetle activity as measured by a reduction in tree mortality in the defined area. Direct control of bark beetles is difficult and complex because of the many gaps in our knowledge about them, the complexity of forest stands, and the interaction of beetle population dynamics with tree and stand conditions and dynamics. Difficulties in assessment are further compounded by uncontrollable events during the period of control action and evaluation, such as fire, logging, winter storms, the activities of other related insects, and extreme weather such as flood, drought, and low temperatures. Improvement in procedures can only come through the benefits of experience and by review and analysis of both successful and unsuccessful programs.

It should be stressed that this paper will not compare the merits of direct and indirect control. Most resource managers recognize that indirect control methods, such as sanitation logging, sanitation salvage, regulation of stand density and composition, and other stand management procedures which can improve stand vigor should be used whenever possible. But from their long experience, they also recognize conditions--ecological, economical, biological--under which direct action is required--even though all the best indirect methods have been used.

I know of no comprehensive review of the direct control of western pine beetle since the report by Miller and Keen (1960). General reviews of bark beetles have been published, but these contain little or nothing about direct control. There have been efforts to present information on bark beetle control in the form of concepts or models, but these are of little value for actual review of control programs and procedures, and in the improvements of direct control methods.

The predilection and justification for direct control of bark beetles in the West may have actually started in the East. A.D. Hopkins (1909) reported the successful control of eastern spruce beetle (then *D. piceaperda,* now *D. rufepennis* Kirby) in Maine in 1900-1901 by salvaging infested trees and burning the slabs at the mill. Success was based on the total absence of infested trees in the area the following year. Hopkins also reported successful control of the Black Hills beetle *(D. ponderosae* Hopkins) by timber salvage in 1905. Again, no formal study was made and success was based on an estimate of reduction in attacked trees the next year. In 1906 Hopkins reported the salvaging of ponderosa pines infested with Black Hills beetle in southern Colorado; in 1908 he was unable to find any newly infested trees in the area.

Perhaps the first closely observed direct control project was with the Black Hills beetle near Idaho Springs, Colorado, in 1907, when 63,000 board feet of timber were infested. In 1908 the area had 250,000 board feet of timber in about 1,000 trees. These 1,000 trees were salvaged in early 1908, and in late 1908 only three newly infested trees could be found. Hopkins (1909) reported on other cases with similar results. These early successes may have been the impetus for the direct control of western pine beetle, and this impetus lasted about 20 years until considerable experience had been gained from extensive field operations. It is important to note that mountain pine beetle usually has one generation per year, but western pine beetle usually has two to three generations per year.

In the early years of bark beetle control in western United States, from about 1910 to 1925, the efficacy of direct control of *Dendroctonus* was not doubted. Then, starting about 1925 some doubt about the efficacy of the direct control of western pine beetle began to be expressed, and the issue has remained to this date. Since 1925, forest conditions have changed, forest entomologists have changed, methods and materials have changed, our understanding of beetles and trees has changed, and the beetle itself may have changed. But differences of opinion about the efficacy, ecology, and economy of the direct control of bark beetles persist.

Direct control captured the imagination of nearly all the early forest entomologists who looked at it as a challenge and almost analogous to warfare. In fact, terms of warfare were often used in their reports. They seemed to be so engrossed in control projects, and the related survey, that research effort suffered. However, the trend soon changed and after 1925 an increasing amount of effort was directed to research. Since 1960 there has been limited use of direct control and most forest management plans were to absorb the losses or salvage dead and dying trees without attempting direct control.

This paper describes but does not discuss methods of direct control. Direct control methods can be divided into three classes, based on the biology of the beetle: pre-emergence, at-emergence, and post-emergence.

Pre-emergence procedures are those which destroy the developing brood under or in the bark before the brood is fully developed and emerges. The most commonly used of these procedures are: (a) fell-peel-burn of infested bark either on logs or stripped from logs, (b) salvage logging of infested trees with the subsequent destruction of the brood at the mill, (c) submersion of infested logs in water, sometimes in conjunction with salvage logging, (d) use of solar heat by exposing infested logs to direct sunlight with frequent turning of logs to expose the full circumference to direct sunlight, and (e) application of oils such as ethylene dibromide or orthodichlorobenzene which penetrate the bark and kill the brood in place.

At-emergence procedures are those designed to kill or incapacitate the beetles as they bore out through the bark. Residual insecticides are the only materials that have been used. These materials are applied to the bark of standing or felled trees before the beetles emerge. The most effective of these insecticides are lindane--or the gamma isomer of benzene hexachloride--and carbaryl. In very early testing DDT did not prove to be effective enough and it was not used operationally. Other insecticides that have proven to be effective in early research but have not been fully tested are Dursban, permethrin, and deltamethrin. The last two look particularly promising because of safety and the efficacy of the very low concentrations which can be used.

Post-emergence methods are those designed to kill the beetles after they have emerged from the infested brood tree or log and before they can reach and attack another tree. The two methods used are (a) trapping beetles on baited sticky traps and (b) killing beetles attracted to baited toxic trap trees. Pheromones of the western pine beetle have been the attractive material for both methods. The toxicants for the toxic trap trees are the same as those for at-emergence treatments.

Throughout this report, beetle population will usually be expressed as the number of trees currently killed by the beetle within a specified time and area, and beetle-caused mortality will usually be expressed as board feet of timber. The work that has been done to measure the actual beetle population suggests that there may not be a strong association between numbers of beetles in currently killed trees and the numbers of trees attacked and killed by the next generation of beetles. Recent efforts have been made to develop a beetle population sampling procedure by a combination of aerial survey of dying trees and ground sampling of numbers of beetles in these trees. But these procedures have not been thoroughly tested. Likewise, a reliable predictive mechanism does not exist.

This review of direct control work is divided into four time periods: 1910-1925, 1926-1940, 1941-1965, 1966-1986. Attitudes or procedures, or conditions shifted significantly during each period. Many operational programs had some research characteristics, and many research programs had some control characteristics. Therefore, both kinds will be treated together.

1910-1925

During the period from 1910 to 1925 many large scale direct control projects of western pine beetle were conducted in California and southern Oregon. Much of this early work was done in winter and early spring by the fell-peel-burn procedure to kill the over-wintering brood; some salvage logging was used at times. The areas to be controlled were delineated by line surveys conducted the previous fall. The actual control work was a total coverage of the area. Efficacy was often based on the change in the level of tree loss between the survey before and after treatment, but sometimes efficacy determinations also included comparisons with results of simultaneous surveys in an untreated area. Tests were rarely replicated. Stand and site conditions almost always varied widely, even within a single project. Weather conditions--snow, rain, low temperatures--were often not the best. Sometimes the control action carried on into warmer weather, or short periods of warm weather occurred during the treatment period. The work was done without airplane, aerial photos, chain saw, good road systems, heavy powered vehicles, and other modern equipment. During the period from 1910 to 1925 much of the value of the dead and dying trees was lost; rapid logging procedures and equipment were not fully developed or widely used to salvage the scattered trees killed by western pine beetle.

Results of 38 larger projects conducted during this period were summarized by Miller and Keen (1960). These projects ranged in size from just a few thousand acres to nearly 70,000 acres. The 38 projects totaled 560,000 acres and 25,000 treated trees with a volume of 29 million board feet. The details of many of these programs are found in "California Region Insect Control Projects, 1913-1935" (Anon.).

Of the 38 projects, 18 could be evaluated on pre- and post-treatment surveys. The change in the volume of timber killed the year following control ranged widely from a reduction of nearly 90 percent in one project to an increase of nearly 40 percent in another. The average reduction in volume killed was about 65 percent. Eight other projects were not evaluated on the basis of pre- and post-treatment survey but were simply judged as satisfactory. The term "satisfactory" was usually applied to situations in which the benefits were simply estimated to exceed the costs. The remaining 12 projects were not adequately evaluated or judged. Miller and Keen (1960) concluded that, "substantial reductions of losses can be obtained by control work the first year following the work." However, the factors that produced the best results cannot be readily determined from the available data.

One direct control project (not included in the 38) that Miller and Keen (1960) noted in particular was the 1922-1924 project in southern Oregon. They considered this the largest and best planned and executed of any direct control program up to that time. The total area of the project was more than a million acres with actual control confined to about 400,000 acres. Nearly 32,000 trees were treated, or nearly 0.1 trees per acre. The results were similar to those of earlier projects with about 30 percent reduction in subsequent tree mortality. The reduction calculation was based on before- and after-treatment surveys of 30 treated and 30 untreated plots of approximately a section each. Miller and Keen (1960) concluded that control was proportional to trees treated (with about a 10 to 6 relationship between the number of treated trees and the number saved the following year), that fall treatment gave better results than spring treatment, and that the best results were obtained with more intense infestations.

In assessing many of these projects, the researchers were unable to determine the factors which reduced tree mortality by 90 percent in one project and those which increased it by 40 percent in another project. On the basis of early but limited work on other beetle species they were expecting 90 percent reduction or more. Two factors that they considered responsible for this variation were failure to locate all brood trees and failure to thoroughly treat all those located. In the earliest projects the thoroughness of the work was not too serious a concern because Hopkins (1909) had formulated his 75 percent rule, which states that if 75 percent of the brood is killed, the remaining 25 percent will probably be taken care of by natural factors. Also, Hopkins estimated that about 75 percent of the brood trees could be reached easily and at a reasonable cost, but that the remaining 25 percent would be much more difficult and costly to locate and treat. Thus, Hopkins' 75 percent rule was attained more by the nature of the field conditions than by the design of the project. The early results with western pine beetle cast serious doubt about the 75 percent rule, and it was not followed for long. Instead, those early workers tried diligently to locate all trees and to be thorough in the treatment of them. But the results were not greatly changed.

A small study conducted during this period may have been the basis for what is now called maintenance control--continued direct control in the same area for two or more years--in Southern California. From 1918 to 1921 the annual losses on a small area were 34, 23, 79, 65 trees. In 1922 direct control was carried out and the losses dropped to 13 trees in 1923. These 13 trees were treated and the 1924 loss was down to one tree. No work was done in 1924 and 1925, but by 1926 the losses were back up to 50 trees. The contention was, of course, that had work been continued in 1924 and 1925, the losses in 1926 would not have been so high.

Three articles were written toward the end of the period--the mid-1920's --about progress of bark beetle control and problems in the western United States. These three articles (Craighead 1925, Craighead and others 1931, Miller 1926) sum up the findings and the attitude at that time. Collectively, these three articles concluded that:

- Results were quite variable, though usually of an economic benefit;
- Results were usually temporary, often lasting only one or two seasons;
- Locating all brood trees was difficult and uncertain;
- If forest conditions were favorable for the beetle, the brood from untreated trees could sustain or even increase the pretreatment level of loss;
- Control work was best--or at least demonstrated to be best--against an increasing population than against a decreasing one;
- Some factor or group of factors other than the numbers of beetles was highly important in beetle population dynamics.

The authors of these three articles made no effort to hide their problems or their failures.

The attitude during this period progressed from one of optimism that highly favorable results could be achieved by simply applying Hopkins' 75 percent rule, to one of determination to exceed Hopkins' rule and try to get every beetle, to one of frustration at failure to achieve desirable results with their best effort, to one of puzzlement about variation and temporary characteristics of the effects.

Though digressing from the assigned topic, this paragraph illustrates how they handled their problems and how the course of forest insect research was changed. In frustration they directed their efforts to "another factor," host condition. They turned what they considered their failure into success because they questioned their work and, as a result, research on host relationship of bark beetles was started around 1924. It was clearly expressed by J.M. Miller in a letter of 1924: "The only answer [to variable and temporary effects] seems to be through methods of stand management which will reduce or eliminate in the stand these trees [as yet unidentified] which are especially susceptible to [western pine beetle] attack." These early workers were aware of host resistance but they did not express it as a significant factor in beetle dynamics. This new search for host susceptibility also directed more effort into research. For more than 15 years before 1925 most forest entomologists in the West were heavily committed to bark beetle survey and control efforts. And in the search for susceptibility they were eventually successful in developing the California pine risk rating system (Salman and Bongberg 1942), the Keen vigor classification, and the various related systems. They also obtained much biological and ecological data about western pine beetle. Many of the forest entomologists of the 1920's and 1930's became involved in these studies of host relationships (see Acknowledgment). The history, development, and use of the risk concept is reviewed by Smith and others (1981).

Actually, if one looks closely at the procedures and results of the early control programs, it can be concluded that they usually did a commendable job; results were generally quite favorable and somewhat proportional to their ability to locate and treat brood trees. But Craighead (1925) noted that, if a stand was unusually susceptible to attack, it would not take many beetles to increase the population level very quickly. All these early direct control projects were directed against what might be called epidemics. No projects were designed to prevent very scattered, endemic losses from developing into an epidemic. Such action was ruled out by the great difficulty, costs, and uncertainty of locating and treating widely scattered brood trees.

The period from 1910-1925 seemed to start with great expectations and end with a significant shift toward more research, particularly ecological research on host relationship.

1926-1940

Large direct control programs continued after 1925, despite variable and temporary results, simply because that was a period of general increase in beetle activity which apparently demanded action. Again results were variable and temporary. Program managers tended to concentrate efforts on areas with the most severe loss where they could "get more for their money." Precipitation in many of these years was considered nearly normal or subnormal, with some years well below normal. Many areas had much greater tree-killing during this period than in the previous period. As one example, an area on the Modoc National Forest, which was closely watched, had 60 trees killed per section in 1923 and 1200 per section in 1927. Another example of greater tree-killing is a comparison of the control projects. From 1912 to 1922 in 29 projects covering 960,000 acres and 25,000 treated trees, there was an average of 0.03 trees killed per acre. From 1932 to 1935 the respective values for 28 projects were 287,000 acres, 30,000 trees, and 0.10 trees per acre. The estimated reduction in subsequent losses was much better for 1912-1922 than for 1932-1935 *(table 1).* Thus overall, better results were obtained with the less severe infestations, even though Miller and Keen (1960) contend that the best results were obtained with the more severe infestations.

An interesting study can be made of variability of results for the years 1932-1935 in California *(table 2).* All four projects in 1932 were considered highly successful because the next year's reduction ranged from 50 percent to 70 percent. Results on seven projects in 1933 were not quite as good as in 1932 with reduction ranging from 40 percent to 60 percent. But in 1934 results were poor in all projects with reduction in losses the next year ranging from 0 percent to 30 percent. In all 3 years the severity of the infestation was about the same. One might wonder if there was some overall phenomenon during the 1934 period. K.A. Salman, who supervised most of these projects, speculated that influx of beetles from outside the projects and unusually heavy activity by flathead borers could have caused the failures. Then, in 1935 the loss reduction attributable to the control efforts was back at the 40 percent to 80 percent level.

Fell-peel-burn was often replaced by salvage logging or by the use of penetrating oil or both during the latter part of this period. Both salvage logging and use of penetrating oils reduced the fire hazard associated with fell-peel-burn.

A cursory study of four unsuccessful projects, i.e., where tree mortality actually increased the year after control action, from 1910-1935 revealed no striking similarities among them nor any striking differences between them and projects that were successful. Attributes such as infestation rates, size of area, and thoroughness of work were comparable between successful and unsuccessful projects. However, many other attributes were not fully known such as prior winter weather, local stand characteristics, activity of other insects, and the very large imponderable of beetle in-flight mortality.

In summary, from 1925 to 1940, when salvage logging and penetrating oil were frequently used, results were no better, in general, than during the previous period when fell-peel-burn was used. Temporary and large, unexplained variable effects still characterized direct control results. Probably most importantly, research on host susceptibility was being experimentally applied, and the early results of the application of risk-rating and hazard-rating systems were excellent.

1941-1965

The number and size of direct control programs declined sharply during this period, and the emphasis shifted quickly to the application of the risk-rating principle (Salman and Bongberg 1942) in the form of sanitation cuttings in uninfested or lightly infested old-growth stands and to sanitation/salvage logging in infested areas of old growth. When direct control was undertaken, residual toxic sprays, salvage logging, or penetrating oil sprays were often used in place of fell-peel-burn. In heavily used forest areas where values were considered high, such as southern California, maintenance control was installed and direct control was done annually in the same general area.

Two small studies of direct control are worth noting. Bongberg (1947) set up a small study in Shasta County to compare the results of three methods of control *(table 3).* It is quite clear that sanitation/salvage, which combines indirect (sanitation) and direct (salvage) control, was the most effective. Fell-peel-burn was essentially ineffective. Bongberg gives no rationale for the failure of fell-peel-burn, but two reasons come to mind: sanita-

Table 1--*Comparison of results of direct control programs against western pine beetle in two different periods*[1]

Years	Projects	Percent reduction in tree mortality by projects the year following control application				
		>60 pct	60 pct-50 pct	<50 pct	Success-full	Unsuccessful[2]
	Number	*Number of projects*				
1912-1922	29	15	4	3	6	1
1932-1935	28	9	5	2	10	2

[1]Source: Anon. (1913-1935).
[2]Estimated only as successful or unsuccessful.

Table 2--*Summary of direct control programs for western pine beetle from 1932-1935 in California*[1]

Year	Programs	Area	Treated trees	Results[2]	Approximate brood trees per acre
	Number	*Acres*	*Number*	*Percent*	*Number*
1932	4	55,000	6,526	50 to 70	0.1
1933	7	61,000	6,798	40 to 60	0.1
1934	9	120,500	13,313	0 to 30	0.1
1935	7	51,000	6,763	40 to 80	0.1

[1]Source: Anon. (1913-1935).
[2]Percent reduction in tree mortality the following season or when compared to that in untreated areas.

tion logging was not used with fell-peel-burn, or it was one of those areas in which--as noted by Craighead (1925)--the stand was in a particularly susceptible state. Furniss (1954) also conducted a direct control study using salvage logging. The study included treated and untreated plots over an 11,000-acre area. The results show that the change in board foot loss per acre for the year before treatment to the year after treatment went from 166 to 9 on treated plots and from 148 to 127 in untreated plots, a reduction in loss in the treated plots of more than 90 percent. Thus, in two tests with direct control very different results were obtained. The first, using fell-peel-burn, showed a net reduction of about 33 percent; the second, using salvage logging, showed a net reduction of about 90 percent. The tests were in different years and different forest locations. But they still illustrate the great variation in results, even when a strong effort was made to apply the method and to measure the results carefully and adequately.

One of the early tests with residual toxic sprays was conducted during this period against mountain pine beetle in lodgepole pine on the Plum as National Forest (Wickman and Lyon 1962). A 74 percent reduction in the number of killed trees was obtained the year following treatment. However, some brood trees were missed, and portions of some infested trees were found to be untreated. When these misses were considered, the degree of control obtained was calculated to be about equal to the percent of the brood killed, i.e., about 75 percent of the brood was killed and subsequent tree mortality was reduced by 75 percent. However, they were working with mountain pine beetle and not western pine beetle.

1966-1986

This period can be characterized by the first use of pheromones, by the first use of a combination of pheromones and insecticides, by attempts to measure the beetle population by both number of brood trees and by the actual beetle population in these trees, and by continued doubt in some circles about the efficacy, ecology, and economy of direct control..

The most noteworthy change was the use of pheromones. Their use opened the possibility of not having to locate and treat brood trees. Throughout all the years of direct control, locating brood trees was considered the most expensive, the most difficult, and the most uncertain of all the tasks. The pheromone used for western pine beetle was the triplet of exo-brevicomin, frontalin, and myrcene. These three together are much more potent than any of the three singly or in pairs. Brevicomin is largely a product of the female beetle, frontalin of the male beetle, and myrcene of ponderosa pine (Browne and others 1979).

The first extensive field use of pheromones was an experimental project in the Bass Lake Basin of the Sierra National Forest from 1969 to 1971 (Bedard and Wood 1974). The total area of the study was about 25 mi^2 with tree mortality at about ten trees per square mile. Within this large area there were two treated and two untreated plots, each of about 0.5 mi^2. The method of control was by pheromone-baited sticky traps (Browne 1978). Each suppression trap had a surface area of about 72 ft^2 and was held upright on a pole about seven feet above the ground. Each treated plot had 66 of these suppression traps evenly spaced at about ten chain intervals. To monitor the beetle population, the entire area of 25 mi^2 was covered by an 0.5-mi, grid of survey traps of the same size as the suppression trap but with one-tenth the elution rate of the pheromone. The attractant was the western pine beetle triplet (Bedard and Wood 1974). The suppression traps were left in place for only the spring flight of the beetle; the survey traps were left in place for the full season. Logistically and biologically, this procedure (except for the survey traps) was similar to the older direct control procedures which sought to kill the over-wintering population.

The results (DeMars and others 1980) show that during the year of treatment, 1970, the loss was much higher in the treated plots than in the untreated or remaining area. However, the year after treatment all types of areas show 77 percent to 88 percent reduction in the losses when compared with before treatment. Three observations can be made: (1) the treatment might have concentrated the beetle population in the treated area and, therefore, gave the appearance of little reduction the first year; (2) the population for the whole area, however, was very sharply reduced; (3) the survey traps may have acted like suppression traps.

Over 400,000 beetles were caught on the 264 suppression traps for the short period they were operational. Nearly 200,000

Table 3--*Average loss in board feet per acre caused by western pine beetle in plots for each of three control methods and an untreated check set*[1]

Control method	Loss in board feet per acre					
	One year before treatment	One year after treatment				
	Average	---------------------Plot-----------------				
		1	2	3	4	5
	Bd. ft.	*Bd. ft.*				
Fell-peel-bum	54	69	25	41	70	43
Sanitation/salvage	72	29	16	22	51	28
Sanitation/salvage plus (extra thoroughness)	102	29	8	23	47	19
Untreated	38	61	43	42	68	23

[1]Taken from: Bongberg (1947).

beetles were caught in about 120 survey traps. Therefore, the survey traps may have been *defacto* suppression traps to further reduce the beetle population. Based on the old criterion of projecting loss before treatment to loss the year after treatment for the whole basin, the treatment resulted in an 87 percent reduction in tree mortality. It was observed that trees near the baited traps were sometimes attacked and killed and these became part of the overall mortality. Such trees also could have detracted from the attractiveness of the baited sticky traps. Hopkins (1910) observed this tendency of western pine beetle to attack nearby trees in experiments with trap logs. This characteristic of attacking trees adjacent to trap logs was one of the main reasons why the use of trap logs was discontinued by Hopkins and others in the early years. One might speculate that by leaving the survey traps in place for full seasons, the experiment may have shown that this constant drain on the population might be a better way to use pheromones. In general the study could be called successful.

In 1971, another pheromone trap-out experiment, with both similarities to and differences from the Bass Lake study, was initiated at McCloud Flat on the Shasta-Trinity National Forest. To date, the results of these experiments have not been published, although other publications have alluded to analyses (Wood 1980, Wood and others 1985). Roettgering (1973) prepared a report on the progress of the experiments but states that some of the data in the report had not been carefully verified. However, the study will be reviewed here to the extent that a general understanding of the experiment can be achieved and the tentative results displayed.

The project at McCloud Flat used the same trap, the same triplet, and treated and untreated plots of the same size as those used at Bass Lake. The experimental design at McCloud Flat used a total of six plots within the large infested area: two plots were treated both years, two were untreated both years, and two were switched from treated and untreated in 1971 to untreated and treated in 1972.

At McCloud Flat, suppression traps were left in place for the 1971 and 1972 full flight period. Survey traps were reduced to a cylindrical mesh trap of about 1 ft^2 and were placed on a 0.5-mi grid. The area, at about 50 mi^2, was much larger than that at Bass Lake; and the incidence of brood trees was much greater; the year before the experiment there had been about 35 trees per mil for the entire 50 mi^2. Therefore the population density was about four times greater than at Bass Lake. However, the population, as judged by the location of brood trees, was heavily concentrated in the three treated and three untreated plots.

Table 4--*Number of infested trees one year after treatment with baited sticky traps on 3 types of area at McCloud Flat; number of trees the previous year were there at time of treatment*[1]

Year of treatment	Types of area: Three treated plots	untreated Three plots	Remaining area
	----------Number of infested trees -----------		
1970[2]	469	307	1,004
1971	754	599	2,130
1972	1,116	724	2,545

[1]Compiled from Roettgering (1973).
[2]No treatment in 1970.

A summary of the tree mortality data, listed in Roettgering's report as fully verified, in the sets of treated and untreated plots and in the remaining area shows that tree mortality increased considerably in all areas--treated plots, untreated plots, and the large remaining area--both years while the treatment was in place *(table 4).* However, in the first year of treatment the percent of increase of tree mortality was somewhat less in the three treated plots than in the three untreated plots and in the remaining area. In the second year there was practically no difference in the size of the increase between the three types of areas; tree mortality increased noticeably.

The McCloud Flat experiment also included a substantial study of the change in beetle population level both in tree and in trap during the whole period of the experiment. I believe an analysis of these data is still forthcoming; so again, I will deal only with summary data. The total survey trap catch was about 229,000 in 1971 and 335,000 in 1972. However, even with such a substantial increase in beetle catch, about one-fifth of the traps showed a decrease, but there was no pattern which could firmly associate the increase or decrease with population shifts because of the location of the three treated plots. The overall catch of beetles on the suppression traps also increased from about 2.39 million in 1971 to 3.90 million in 1972. Thus, the survey traps were a reasonable gauge of the beetle population. Although large numbers of beetles were caught in suppression and survey traps, the numbers not trapped were sufficient to cause an increase in tree mortality.

A comparison of the two trap-out experiments (Bass Lake judged successful and McCloud Flat judged unsuccessful) does not seem justified because of difference in stand structure, treatment duration, survey trap logistics, and in the basic level and dynamics of the beetle population. However, one might speculate that the greater population density at McCloud Flat may have exceeded the capacity of the traps.

Another procedure which utilized the western pine beetle pheromone was the baited toxic trap tree. The procedure combines recent advances in the use of insecticides with pheromones, i.e., the tree trunk is sprayed with a proven insecticide and baited with the pheromone. In comparison to the sticky trap, a baited toxic trap tree provides much greater trapping surface area, has the trapping surface higher above the ground, has the important natural tree silhouette, and can be used on low grade trees. Pitman (1971) had made an early attempt to trap out mountain pine beetle in western white pine using lindane as the toxicant and trans-verbenol plus a-pinene as the attractant mixture. Trans-verbenol was considered the attractant of mountain pine beetle at that time. The results were not successful, apparently because the lindane was not sufficiently effective. Since then other researchers have found that the attractant used was found to lack some important chemicals (Borden and others 1983).

After Pitman's experiment a small test was conducted on mountain pine beetle in lodgepole pine in the Sierra Nevada (Smith 1976). Freshly attacked logs were the attractant, and the trap was the baited tree sprayed with 0.3 percent lindane aqueous emulsion applied to the basal 25 feet. The nine nearest trees, all within 12 feet, were sprayed with 1.0 percent lindane aqueous emulsion to protect them from beetle attack. From prior exploratory work it was found that the 0.3 percent lindane did not fully protect the tree but did kill large numbers of beetles and made it more difficult for the attacking beetles to successfully colonize the tree. Thus, the rationale was that the baited tree would be killed very slowly and the pheromone produced by the attacking beetles would add to the attractiveness of the tree. At the same time the 1.0 percent lindane would protect the adjacent trees. Large numbers of beetles were killed by the baited toxic trap tree, though it was eventually killed, and there was a sharp reduction in the number of attacked trees in the 60 acres around the trap site. Many beetles were also killed by the adjacent trees sprayed with the 1.0 percent lindane.

The use of baited toxic trap trees was then carried to ponderosa pine and the western pine beetle (Smith 1986). An exploratory test in 1977 showed that beetles will almost always attack trees adjacent to the baited toxic tree; therefore, adjacent trees had to be protected. In subsequent experiments, these adjacent trees either were given a protective spray before the test was started or were sprayed as soon as possible after beetle attack was noticed. The tests were largely designed to test insecticides and concentrations, to test the need for protecting adjacent trees, and to measure the numbers of western pine beetle and its associates arriving at the baited tree and the adjacent trees. The four insecticides used were lindane, sevin, permethrin, deltamethrin, and all were effective in killing large numbers of beetles on the baited tree and in protecting the adjacent trees. Only general observations were made of the incidence of tree mortality in the vicinity of the trap trees, and these observations suggest that very few, if any, trees were attacked within the observable distance of the trap trees. It was very clear in those baited toxic trap tree experiments that protection of trees adjacent to trap trees was absolutely essential. In the 1978 series of tests, the average trap tree killed about 34,000 beetles--in contrast to about 21,700 killed by the average sticky trap at McCloud Flat in 1972. Further testing was done in 1979 and 1980 (Smith 1986) with results comparable to the previous work, but there was no opportunity to accurately assess pre- and post-treatment tree mortality in these two tests.

In 1980-1981 a large baited toxic trap experiment was established in California and southern Oregon in ponderosa pine for western pine beetle. The basic purpose was population restraint, i.e., to apply the treatment against low populations to prevent population increase and thereby reduce the incidence and severity of epidemics. Such a procedure could be effective in times of anticipated drought conditions, in areas where western pine beetle seems to be a chronic problem, and in high use areas. The basic experimental design was 65 pairs of treated and untreated plots, each plot about 0.5 mile in diameter. Plots were at least one mile apart. Each plot had two trap trees which were to be baited; the nearest five trees, or those within 12 feet, were given a protective spray. Unfortunately, the scope of the experiment exceeded the available funds and the study had to be dropped after establishment. Baited toxic trap trees, or logs, have been used against the mountain pine beetle (Borden and others 1983).

Two additional points are worth noting about the effectiveness of direct control of western pine beetle. Several years ago a court, in effect, ruled in favor of direct control by ruling for the Klamath Indians in a lawsuit. The Klamath Indians claimed that they had lost much timber because the U.S. Department of Interior had failed to use direct control measures against western pine beetle on Indian lands in the 1920's and 1930's. More recently the California Department of Forestry reviewed their program of maintenance control in southern California. The review was discussed at the 1987 meeting of the California Forest Pest Council. The Department decided to continue maintenance control.

DISCUSSION

Many different experiments and decades of control programs have satisfactorily shown that direct control of western pine beetle is feasible, effective, and economical. Nevertheless, there are still some who question efficacy and economics. But even when direct control is effective, the results are still variable, uncertain, usually temporary, and no less so now than 40 to 50 years ago. However, an infrequent and unexplained failure has occurred throughout the years. Therefore, there appears to be critical ecological and biological factors which are not yet understood or are misunderstood. The problem is far more complex and difficult than anticipated. The introduction of new concepts and models has done little or nothing to improve our understanding of the problem. The use of models actually may have deceived us into thinking that models were the answers and not the questions and that the problem could be clearly understood and solved by simply applying models and simulated data.

The most persistent criticisms of direct control have been the lack of permanency and doubts about the economic benefits. I know of few insect pests for which control is permanent. If "control" were permanent, economic research on insects and control would not exist. Thus, lack of permanency does not seem to be a valid criticism. Economics is more difficult to assess. Forests are not row crops, they require decades until harvest, and related--and important--values such as water, recreation, wildlife, and environmental enhancement are almost impossible to assess. In many of the early control programs the cost of the operation was compared to the value of the timber saved. In nearly all cases, the costs of control were much less than the value of the timber saved. However, costs and benefits of direct control operations over the years before harvest have not been analyzed. Until such analyses are made, it appears that neither criticism--economics, temporary effect--necessarily precludes the use of direct control.

In hindsight, the early, large-scale programs generally using the fell-peel-burn method were surprisingly successful when all difficulties and uncertainties are now considered. The questioning of the variable and temporary effects of these programs led directly to the strengthening of forest insect research on the western pine beetle and to the initiation of research on host relationships. This research directly led to the development of risk, vigor, hazard classifications, and their forest management derivatives such as sanitation logging and sanitation/salvage logging. The use of penetrating oils, salvage logging, and residual insecticides in place of fell-peel-burn did not appreciably improve results, although they did make the operation safer and more economical. Most recently, the use of pheromone-based trapping systems also did not change results; however, the use of them has not been fully exploited nor are they adequately understood.

One of the more important points about the work reviewed is that all direct control programs, whether research or operational, involved population levels that were judged comparatively high and were generally classed as epidemics; none involved low population levels, or those that could be classed as endemics. Although Miller and Keen (1960) contend that the best results were secured with the higher population levels, strong evidence to support their contention is just not there. It seems more likely that they were forced to work with higher population levels because such situations looked more threatening or because more beetles could be killed easier and more economically. Prevention rather than control of epidemics has always been considered the best procedure, no matter what the causal organism. Yet I have been unable to detect this philosophy in any of the direct control work reviewed. In all cases high population levels were enjoined with the basic objective of reducing subsequent beetle-caused tree mortality. With the development of pheromones and toxicants, it would certainly seem advisable to conduct research on the prevention of epidemics. Some of the best results with direct control programs have been in lightly infested areas in the application of sanitation-salvage. But in such cases there was a double treatment: salvage of lightly scattered infested trees and sanitation by removing high-risk trees. Thus, it would appear that direct control programs should be applied against low population levels--as low as one to two trees per section--to see if population increase can be prevented. To some degree the baited toxic trap trees procedure, when applied to low level populations, is somewhat like prescribed burning which reduces the fuel load in order to reduce the incidence and severity of fires; baited toxic trap trees could reduce the beetle load in order to lower the incidence and severity of epidemics.

It is also important to contrast the situation at the conclusion of the two large trap-out experiments (Bass Lake, McCloud Flat) with that which existed in 1925, just 50 years earlier. In both cases the results were not as good as expected despite careful planning and execution. However, in 1925 those involved in the work voiced their dissatisfaction with results and accepted the challenge to seek answers to several important questions, whereas since 1972 there has been no effort to answer questions about the inability of the pheromone-based trap-out method to give better control.

Several questions might be raised about the two large trap-out experiments using attractants with sticky traps:

- Was the trapping started soon enough in the spring? In some years in the foothills of the Sierra Nevada I have been able to trap western pine beetle at times during the late fall and winter months; sometimes the numbers are low, but sometimes the numbers were quite large. These beetles are, presumably, re-emerging, over-wintering, parents. Are those beetles simply lost from the population or have they some unknown habit, such as quasi-hibernation, which permits them to survive until conditions are suitable for attack in the spring? Englemann spruce beetle does have such a habit. The first catches of western pine beetle after deploying the pheromone in early spring were often quite sizeable, suggesting that many beetles were flying before trap deployment. However, in the two large experiments they were presumably guided in trap deployment by measuring emergence from sample trees;
- Were the traps too low to the ground? The assumption has been that the beetles are guided into the trap by odor trails. Yet it is possible that a beetle, flying at 30-40 feet above the ground, can get a strong enough odor signal to land on a tree rather than continue to follow the odor trail to its origin, in the middle of the sticky trap. Tilden and others (1979) were able to catch large numbers of beetles in traps 3 m off the ground;
- Are there additional components to the pheromone mixture? Most of the elucidation of the pheromone was done with attacks in freshly cut logs and not attacked trees. My work suggests quite strongly that beetle attacks are far more successful in trees than in logs cut from green trees. Some critical changes might take place in an attacked tree which do or do not take place in an attacked log, at least as reflected in the success of brood development;
- Do the sticky traps provide sufficient trapping surface?
- Did the closeness of the suppression traps cause them to compete for effectiveness rather than add to effectiveness, i.e., do we know enough about trap logistics? Do we know enough about beetle behavior to effectively place traps in various types and levels of beetle population?
- Do all beetles respond in the same way? Do re-emerged adults respond like brood adults?
- Did the large number of pheromone sources in early spring modify the ecological conditions of the area in favor of the beetle?

The information on western pine beetle is substantial, yet it is clear that some vital biological and ecological data are lacking--data that will be difficult and costly to obtain. Four of the obvious subjects not adequately understood are beetle flight and attack behavior; relationship of host conditions to the success of beetle attack and reproduction; the causes of these host conditions; and population dynamics as it relates to infestation level, and population distribution.

There are no research programs which address these large problems; and the current climate for funding such research does not appear favorable. Progress may have to come from a number of carefully planned small studies, by frequent and open meetings to exchange information, to honestly discuss problems and results, and by reasonable support by research administrators.

One example will be cited to illustrate just one question to be resolved. One very important factor in the dynamics of western pine beetle is brood production in successfully attacked trees. Brood production varies greatly and may have been one of the causes of variable results of control programs in which population was measured by the number of attacked trees. Actually, little is known about the cause of this great variation except that it has often been attributed to "host condition." I have made many attempts to culture western pine beetle on freshly cut logs of ponderosa pine. Success was always mixed, but generally poor. Success could be varied, at times appreciably, by such factors as moisture, temperature, and age of log. Moisture seemed to be very important. Thus, I conclude that western pine beetle requires rather specific conditions for good brood development. If these conditions are fully met, the beetle is highly successful. But the availability of these conditions seemed to be quite variable and, thus, success of brood development is also very variable. Likewise, the conditions of a freshly cut log do not meet the full requirements of the beetle. The full requirements seem to be met by the beetles quickly attacking and overcoming a living tree.

It is also quite clear that western pine beetle populations vary in number and direction because of the inherent nature of the beetle and its very strong link with the stand and tree dynamics. Therefore, no two control projects or experimental studies are alike and are not comparable, so it is not surprising that results have been unpredictable. Craighead (1925) may also have touched on a critical point when he noted that western pine beetle is less aggressive--and at the same time more selective--than other beetles and that a more aggressive beetle like mountain pine beetle may be more easily controlled by direct action.

The elucidation of the pheromone triplet was a significant achievement which seemed to open up new, more effective, and more economical ways to reduce a population and the attendant tree mortality. The first large-scale trap-out test appeared to be successful; the second one appeared not to be successful, but little effort was made to determine why. Experiments using baited toxic trap trees showed great promise for improvement but were not adequately funded or evaluated. Advances in aerial imagery to monitor and measure loss and stand conditions, and developments in data processing with computers have yet to be fully utilized.

In recent years forest pest managers and research scientists as well seem to have spent more time in pointing out what they considered the disadvantages of direct control than in a renewed searching for answers to many perplexing biological and ecological questions. Maybe it is time to change direction from models and concepts and to see what can be done with well-supported field research on direct control, benefiting from recent experiences and using newer tools and insights and, of course, obtaining administrative support.

One can easily develop a long list of options which may be similar to or different from the one I've developed below. For western pine beetle in general, the following is a list of alternatives for direct control study:

- Rework and rethink carefully the biology and ecology of the beetle in light of recent developments and experimentation, and look for critical characteristics, particularly re-emergence, overlooked flight habits, in-flight mortality, effect of host on brood success;
- Search for a predictive mechanism so that action can be taken to restrain endemic populations and prevent epidemics;
- Establish a research and development program specifically designed for direct control;

For these direct control experiments, the following should be considered:

- First, and foremost, attempts should be made to prevent or lessen the incidence of epidemics by installing and maintaining a trap-out program for several years when beetle populations levels are very low or when drought or other tree stress conditions are anticipated. The aborted baited toxic trap tree experiment of 1980-1981 was just such a program. The scale of that study may have been too large; and a much more modest approach should be considered;
- Continue to refine the baited toxic trap-tree method, considering such factors as number and location of trap-trees, and the size of the study area;
- Try year-round application of baited toxic trap-trees until it is clearly shown that there is no beetle activity outside the presumed flight period;
- Reevaluate the pheromone triplet to see whether there are other components and whether mixture and release ratio can be improved;
- Look for and test newer insecticides, including biologic materials; develop a more efficient procedure for spraying trap trees;
- Consider "artificial trees" that can be treated under laboratory-type conditions and hauled to the forest. This would reduce environmental hazards. The use of low grade host trees growing in the stand is a good option as well;
- Consider the use of non-host species as trap trees. For example, in preliminary studies I was able to attract western pine beetles to Jeffrey pine quite readily, and, not surprisingly, the beetles were not successful in attacking this non-host tree which occurs within parts of the range of western pine beetle. I was not sure of the results in attracting western pine beetle to white fir. In this testing, freshly infested bolts of ponderosa pine were the source of attraction. Mountain pine beetle readily attacked both Jeffrey pine and white fir which had been baited with freshly infested bolts of ponderosa pine.

Even with the most effective direct control procedures, some tree mortality may continue because of the presence of highly susceptible trees which could be equally or more attractive than the triplet pheromone. Therefore, the basic objective should be to lessen the incidence and severity of epidemics. Western pine beetle research may be at a crossroad with two options: convince forest managers that dying trees are a normal event which they will have to accept, or decide to proceed to work on the problem with the new approaches made possible by modern technology.

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