United States
Department of
Agriculture

Forest Service

Expanded
Southern Pine Beetle
Research and Applications
Program

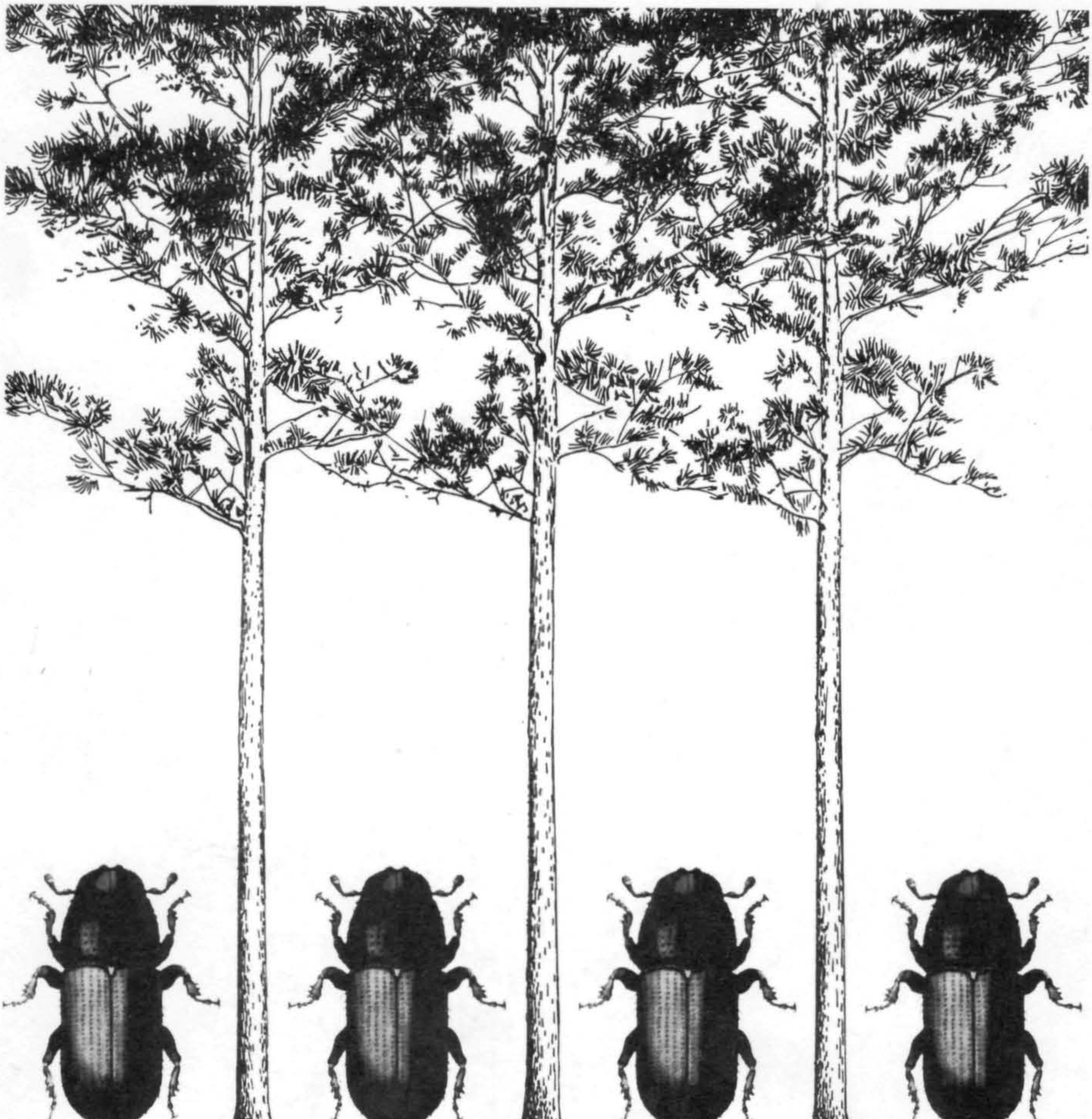
Southeastern Area
State and Private Forestry

Technical Bulletin 1613

Evaluating Control Tactics for the Southern Pine Beetle

Symposium Proceedings

Many, Louisiana
January 30-February 1, 1979



EVALUATING CONTROL TACTICS FOR THE SOUTHERN PINE BEETLE

SYMPOSIUM PROCEEDINGS

January 30--February 1, 1979

Edited by
Jack E. Coster   Janet L. Searcy

Technical Bulletin No.1613
U. S. DEPARTMENT OF AGRICULTURE   FOREST SERVICE

Expanded Southern Pine Beetle Research & Applications Program

Southeastern Area   State and Private Forestry

November 1979

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 001-000-04062-6

FOREWORD

A large number of State and Federal experiment stations, universities and Federal, State and private resource management organizations have participated in the USDA Expanded Southern Pine Beetle Research and Applications Program (ESPBRAP) since its inception in 1975. The objectives of this accelerated effort have been to utilize available knowledge more fully and to develop or improve methods for preventing or reducing losses due to the southern pine beetle.

Nearing the completion of the Program, we thought it appropriate to synthesize some of our results and to determine how they might be used to evaluate control tactics. To accomplish this, about 40 representatives from Federal, State and industry organizations and a number of universities were asked to come together at the Toro Hills Hotel, near Many, Louisiana, to participate in a symposium. The meeting was jointly sponsored by ESPBRAP and the Southeastern Area of State and Private Forestry.

The information presented at the symposium is reproduced here for the benefit of all those interested in what has been learned about evaluating southern pine beetle control tactics.

R. C. Thatcher, Program Manager
J. E. Coster, Applications Coordinator
G. D. Hertel, Research Coordinator

Expanded Southern Pine Beetle Research
and Applications Program

CONTENTS

CONTROL OF THE SOUTHERN PINE BEETLE ON NATIONAL FORESTS

Kenneth M. Swain and Walter Fox[1]

Both kinds of control--direct (suppression) and indirect (prevention)--should be considered inseparable if efforts to reduce timber mortality caused by southern pine beetles (SPB), *Dendroctonus frontalis* Zimm., are to be effective. In the past, too much emphasis has been placed on controlling the beetle and not enough emphasis on managing the host stand.

The history of SPB outbreaks in the Southeastern United States is well documented (Price and Doggett 1978). It is the impact of these outbreaks on the management of National Forest resources and the effectiveness of control projects that lack adequate documentation.

Cyclical insect outbreaks and epidemics in the National Forests frequently emulate the impact of wildfire. Attempts to suppress the insect through chemical spraying, salvage operations, or occasionally piling and burning result in manpower and organizational problems. Budget restrictions, personnel ceilings, and congressionally established targets make it extremely difficult to shift priorities at the field level. District Rangers are forced to shift manpower almost daily as beetles are chased from one spot to another. Planning processes that dictate work programs years in advance leave little flexibility for major shifts when a SPB epidemic occurs.

Numerous suppression projects are initiated when the SPB reaches epidemic proportions. Yet it is difficult to obtain quantifiable results on the success or failure of those projects. In Louisiana, a chemical suppression project was done on 31,500 acres of private land (Lorio and Bennett 1974). During a 5-year period, 2959 infestations, including 10,095 trees, were treated. By the end of the period, fewer spots were present and spot size had decreased. In another study (Morris and Copony 1974), salvage removal was intensively applied to a 4606-acre block of the Cumberland State Forest with a 5265-acre block on private land left untreated to serve as a control. Initially, the treated block had more than three times as many spots as the control. At the end of the study, the situation was reversed. The control block had almost twice the number of spots found on the treated block.

The Texas Forest Service evaluated the operational effectiveness of various control methods used in east Texas. Changes in the expected frequency of new spot proliferation following control action were used as the basis to measure the control effectiveness. Treatment results from 1974 (Billings and Pase 1977) showed that numbers of new spots detected around both cut-and-leave and salvaged spots were lower than those found around active uncontrolled spots.

A successful suppression project was completed on the Apalachicola National Forest in 1977. SPB spots were first detected in November 1976. A biological evaluation (Ward 1977) made in February 1977 indicated there were 12 spots on 5000 acres containing approximately 415 MBF. In ground checking these spots, investigators found healthy SPB populations infesting an overstocked mature stand of loblolly pine. The checked spots had an average basal area of 190 ft^2. The District initiated an aggressive suppression project and treated 39 spots on 206 acres by July 1977. This program resulted in the salvage of 1625 MBF and 1057 cords of infested timber. A postsuppression survey made in October 1977 revealed no further SPB activity. The Texas experience is an excellent example of a suppression project preventing a serious SPB outbreak from expanding further.

The most recent SPB outbreak to become a Southwide epidemic on National Forest land began in 1972 and largely subsided by 1978. During this 7-year period an estimated 301,150 cords, and 311,725 MBF of timber were killed by the beetle. Of these losses, 180,690 cords and 187,035 MBF were salvaged from the National Forests. In recent years chemi-

---

[1] Staff Entomologist, USDA Forest Service, State and Private Forestry, Southeastern Area; and Forester, USDA Forest Service, Southern Region, Atlanta, Ga.

cal treatment (lindane) has been used on a limited basis, primarily on infested trees that could not be logged because of wet soil conditions. Such trees were salvaged when soil conditions became favorable. Until November 1978, it was thought the SPB was confined to a subsiding population in Mississippi. Suddenly, in January 1979, an increasing population was found on the National Forests in Mississippi and a new outbreak was discovered in the Oconee National Forest, in Georgia.

The traditional first reaction to SPB outbreaks is to rush out and combat the dreaded enemy. First, however, a biological evaluation of the SPB problem has to be conducted. Entomologists utilize sketch mapping or aerial photography, with subsequent ground checking, as the first step in obtaining data for the biological evaluation. This evaluation is an appraisal of the current and potential significance of the SPB outbreak, culminating with control recommendations. Entomologists usually recommend two alternatives: control, or do nothing. The final decision is up to the land manager.

Just considering control starts in motion a whole new array of documents--a project control plan, an environmental assessment report (or in some instances an environmental statement), an economic evaluation (with a benefit/cost ratio), and the proposed accomplishments, "targets." These documents form the project proposal package, which is sent to the Forest Service Washington Office for approval and funding. After internal review, the proposal is often sent to OMB for release of money from the Forest Service reserve suppression contingency fund. This procedure often results in a considerable time lag before the funding reaches the National Forests. Eventually, the National Forests receive funds to accomplish their projects and the unofficial goal of the suppression project proposal is met. Apparently, all too often this scenario is followed. Procedures have become mechanical because methodologies for collecting adequate data needed by land managers and entomologists are not available. Consequently, sound decisions cannot be made.

With the current state of technology, perhaps it was the best effort that could be expected. The land manager has no well-defined objectives of what losses to expect without control, or how much loss can be prevented with control. The basic question of what is acceptable control needs to be answered. How much infested timber does the land manager need to remove to obtain an acceptable control level--100 percent of the spots? --10 percent of the spots?--all the spots with more than 10 trees?--all the spots with more than 50 trees? Uncertainty about this fundamental objective presents the land manager with a perplexing situation. Likewise the entomologists are faced with an even greater dilemma. In addition to providing assistance to the land manager, they must predict the consequences of the infestation with and without a project. Many entomologists agonize over this situation, wanting to accomplish the best job possible, but having inadequate tools to do the job. Ultimately they are forced to use historical data, experience, and professional judgment in reaching a final decision.

To be more effective, the land manager and pest control specialist must coordinate their efforts. What new information is needed to effectively manage pine stands for controlling (suppression and prevention) the southern pine beetle?

(1) Economic loss thresholds based on land management objectives

(2) Methodologies for measuring effectiveness of treatments

(3) Methodologies for identifying hazardous stands and probability of attack

(4) Damage prediction techniques
--on a spot basis for setting control priorities
--on an area-wide basis for planning and control strategies and requesting funds
--on an area-wide basis for 5 years and over, for planning prevention programs

(5) New integrated pest management treatment strategies.

Hopefully, in the near future a better job of making control decisions can be based on land management objectives. The objectives of maintaining a stand for wilderness or recreation are obviously different than for timber production. However, there are often different management objectives for timber production based on site, rotation age, accessibility, etc., which must be recognized. Specific suppression recommendations should be geared toward these management objectives while we recognize that suppression is only a short-term holding action.

The Forest Service is utilizing new technology as it becomes available; this often means new techniques are tried before they are published. A SPB information system we developed was recently implemented on a trial basis. This has provided (1) accountability of accomplishments, (2) more reliable data for biological evaluations and benefit/cost analysis, (3) data for postsuppression evaluations, and (4) SPB data on problem areas for forest management planning.

The latest biological and benefit/cost evaluation of the SPB outbreak on the National Forests in Mississippi reflects Forest Insect and Disease Management's best effort to date. What made this possible? First, the new information system made it feasible to monitor SPB timber mortality by age class as each spot was identified by compartment and stand number. Stand age is obtained from the Forest Service's continuous inventory of stand conditions (CISC). Second, application of the attack:emergence ratio prediction technique (Moore et al. 1979) gave an estimate of expected trend. Third, the spot growth algorithm (Hedden and Billings [in press]) was used to determine the volume protected. Certainly it must be realized that these procedures were used on a trial basis. The results will be monitored closely, since modifications will be needed.

The SPB attack:emergence ratio for predicting spot trend is a new tool which could be used for setting control priorities on an operational basis. For example, on the Chickamauga-Chattanooga National Battlefield, if the spots classified as "increase" had been removed, 80 percent of the subsequent loss would have been prevented. If the spots classified as "increase" and "static-increase" had been removed, 96 percent of the subsequent losses would have been prevented (Moore and Hertel 1979).

The key to long-term suppression of the southern pine beetle is in preventing outbreaks through silvicultural management (indirect control). This is not a new concept. But with new technology being generated by ESPBRAP; State, university, and Forest Service research; and Forest Insect and Disease Management studies, it is apparent that implementation is just around the corner.

In the South, thousands of acres of forest type are in similar age classes and stand densities. The recommendation that District Rangers thin or harvest all stands above a certain basal area or age class to prevent SPB attack is not very useful. We must establish priority rankings for susceptible stands if stand hazard ratings are to be meaningful; then after considering other management constraints, District Rangers can assign treatment priorities.

The development of an operational procedure for implementing a SPB stand hazard rating into the National Forest compartment prescription process is underway. The Forest Service uses the compartment prescription as the primary silviculture planning document; consequently, SPB considerations must fit into this procedure. When this is accomplished, SPB prevention will become a part of the decisionmaking process for land managers. High-hazard stands can be identified and treated silviculturally to reduce future SPB timber mortality.

Although the future of managing our stands appears encouraging, a word of caution is in order. As hazardous stands are identified and scheduled for thinning or harvest, one factor is extremely critical--adequate markets must be available, both in time and quantity, to handle the timber. A positive benefit/cost analysis depends upon using monetary values, and this will be applicable only where adequate markets exist.

In closing, it bears repeating that suppression and prevention should not be separated. In fact, this paper should be entitled "Managing the National Forests to Reduce Southern Pine Beetle Timber Mortality."

LITERATURE CITED

Billings, R. F., and H. A. Pase, III. 1977. Developing improved techniques for evaluating the operational effectiveness of southern pine beetle control tactics. 75 p. Final Report to the Expanded Southern Pine Beetle Program. [Unpublished but available from ESPBRAP, 2500 Shreveport Highway, Pineville, La.]

Hedden, R. L., and R. F. Billings. 1979. Southern pine beetle: Factors influencing the growth and decline of summer infestations in east Texas. For. Sci. [In press.]

Lorio, P. L., Jr., and W. H. Bennett. 1974. Recurring southern pine beetle infestations near Oakdale, Louisiana. 6 p. USDA For. Serv. Res. Pap. SO-95. So. For. Exp. Stn., New Orleans, La.

Moore, G. D., G. D. Hertel, and Helen Bhattacharyya. 1979. Southern pine beetle attack:emergence ratio and stand factors for predicting spot growth and subsequent damage. Final Report to the Expanded Southern Pine

Beetle Program. 20 p. [Unpublished but available from ESPBRAP, 2500 Shreveport Highway, Pineville, La.]

Morris, C. L., and J. A. Copony. 1974. Effectiveness of intensive salvage in reducing southern pine beetles in Virginia. J. For. 72:512.

Price, T. S., and C. Doggett. 1978. A history of southern pine beetle outbreaks in the southeastern United States. 31 p. Georgia For. Comm.

Ward, J. D. 1977. Evaluation of southern pine beetle infestations on the Apalachicola Ranger District, Apalachicola National Forest, Florida. USDA For. Serv. Unpub. Report No. 77-3-8. Southeastern Area, State and Private Forestry, Atlanta, Ga.

SOUTHERN PINE BEETLE CONTROL:
NEEDS AND EXPECTATIONS
OF THE SMALL FOREST LANDOWNER

C. L. Morris[1]

The small forest landowner has been accused of raising less wood than he is capable of producing and thereby contributing to the shortage anticipated by the end of this century. More recently, this too-oft-repeated accusation has been seriously challenged by Clawson (1977) and a study of nonindustrial private forests sponsored by the Society of American Foresters and Resources for the Future (Sedjo and Ostermeier 1978).

The small forest landowner has been and will certainly continue to be a key figure in future wood production. Realizing that fact, we have attempted to educate him, cajole him, embarrass him, and "incentify" him in an effort to convince him of the value of adopting certain management practices on his woodland acreage. In a disturbing majority of cases, we have failed. Why?

1. We have failed to establish initial contact with the vast majority of this group.

2. Our message may be inapplicable because the small size of so many holdings makes them uneconomical to manage.

3. We have often failed to gear our message to the *multiple* objectives of many small forest landowners.

4. And we face the economic realities of raising timber, which may involve lack of available markets or investment capital, unfavorable monetary return on such an investment, the long-term aspect of such an investment (subject to the uncontrolled vagaries of climate, fire, insects, disease, etc.), and unfavorable tax laws in some areas.

One thing has become increasingly clear: the small forest landowner of today often has much different objectives than owners had just 20 years earlier. Income is no longer considered to be derived primarily from wood and fiber production but often includes what one author terms "psychic income"--primarily the satisfaction of owning the land and the timber, with management for wood production low on the owner's list of objectives.

With more and more landowners high on psychic satisfaction, how do we take advantage of that "high"? It seems to me that this is the major challenge we face: We must convince the landowner that many of the silvicultural practices we espouse will *protect* his psychic income investment--often providing both a profit and a no-cost assurance that his pine woodland will remain fundamentally the same 5, 10, even 20 years from now.

Such a program would require a wider commitment to a new clientele, and most likely more personnel, possibly within the framework of the urban forestry program.

One of the questions asked me in response to my request for input for the paper from pest managers in the Southeast was, "Do we really have any 'new' technology or methodology to sell?" As far as the small landowner is concerned, the answer is essentially "No." But we do have a wealth of data which support observations that stand density, vigor, growth rate, degree of maturity, and certain disturbances all influence stand susceptibility to beetle attack. How do we get that story across and how do we manage to institute the practices we know can help?

Getting the word to the people who need it is not so tough (the U.S. Postal Service does a creditable job), it's getting them to read and *heed* that word. And we have another audience that needs to be reached--our own people. That is, the foresters--industrial, Federal, State, and private--who tell the forest management story. They must understand how southern pine beetles can impact on the resource base and how the forester can better integrate prevention, detection, and salvage into his forest management recommendations. We also need to impress on the industry trade organizations, who are actively supporting the need for a "third forest," the contribution that a

[1] Chief, Forest Insect and Disease Investigations, Virginia Division of Forestry, Charlottesville, Va.

reduction in beetle damage will make to future wood supplies.

Who influences the small landowner the most? Primarily his peers. Special effort should then be made to convince key individual cooperators of the value of applying those practices which will help to beetle-proof their pine woods. I also contend that the research data present a convincing enough argument for better management practices and that the message is important enough to warrant a serious look at how we can enlist the cooperation of industry, trade associations, State foresters, extension agents, and others in a concentrated effort to direct this message to those who would most benefit. The effort must be a cooperative one, for in many areas of the South action by a true believer is often difficult. And here is where industry can play a key role.

The small landowner needs assistance in two areas--first, in decreasing susceptibility of his stands to beetle attack by applying certain "standard" management practices, and second, in speeding salvage when a beetle outbreak develops.

Industry can assist immeasurably by adopting the recommended forest management practices that have been shown to reduce beetle damage--and *heralding* the fact. In this way, industry will serve as leaders, in adopting "new" technology and hopefully convincing many private landowners to follow.

One of the most recent developments--mechanical harvesting systems--has been applauded by the forest industry, which was faced with shrinking numbers of small independent woods crews. These systems, however, are just not economically practical for partial harvests on small woodlots. Adoption of these mechanical har vesting systems has further reduced the number of available woods workers in many areas.

The recommended silvicultural approaches to reduce future SPB damage in unmanaged stands will depend on the availability of markets for partial cuts and the availability of woods labor to carry out the recommended silvicultural practices and salvage operations. Our Cooperative Forest Management program in Virginia has been quite successful in convincing forest landowners of the value of many of their recommendations *if* the forester is willing to (1) find planting and timber stand improvement crews, (2) contract for aerial spraying, and (3) oversee implementation of all the recommended practices. Herein lies the basis for recommendation number one.

If the forest industry in the South is planning to continue to depend on the private sector for a considerable portion of its wood supply, the industry must accept responsibility for more direct assistance to the small forest landowner. Industry can also assist in these additional ways, by (1) identifying hazard stands on their own land, (2) scheduling and carrying out intermediate improvement cuts on their lands, (3) providing attractive long-term management leases to small landowners, (4) purchasing beetle-killed timber by measure rather than by weight when necessary to increase salvage effectiveness, and finally, and probably *most* important, (5) by assisting the small landowner to carry out recommended management practices in providing woods labor to do the work at cost.

Several pulp and paper industries in Virginia are currently looking hard at the economics of longer rotations (rather than planting pine and clear-cutting at ages 20 to 30). Now is a good time to extol the value of the additional stand "assurance" a company can add to its woodlands by its bug-proofing efforts.

If we succeed in convincing industry to take a leadership role in emphasizing the multiple values of timber management, we will have scored at least a small gain.

Do we need more Federal or State monetary incentive programs to speed the adoption of better management practices, as several studies have suggested? Or do we need subsidies to speed salvage? The failure of some States to fully utilize Federal Forestry Incentive Program funds currently available to them and the successful utilization of those funds in a few other States make this question worthy of further evaluation. Certainly the majority of State and Federal incentive funds now available stress only site preparation and planting. More financial assistance in the area of TSI, however, is worthy of consideration as it relates to the SPB problem. As an alternative to more subsidies, certain tax incentives might be a more logical approach. Do we need more State or Federal laws requiring "bug-free" forests? I think not, since many of the Southern States that have such laws invoke them only under special circumstances.

CONCLUSION

One must recognize the impact of economics on the success of selling a forest management program to the small forest landowner. In many areas, where markets do not exist, implementation is impossible without sizable new financial incentives provided by the government, an unlikely occurrence at this time. We must concentrate, then, on those areas where markets do exist. One must also recognize that *only* when the value of the raw material reaches a certain point will most owners consider protection efforts that they currently reject as uneconomical. But we must not permit the economics of timber production to limit our efforts to reach the small landowner; we must change our approach to meet his broadened objectives.

We may spend these two days [of the symposium] earnestly evaluating tactics for SPB control, but we have accomplished little unless we recognize the importance of convincing *all* forest landowners of the value of adopting those tactics. There is an obvious and proven need to institute preventive control before the problem develops. In this regard, the potential use of USDA Forest Pest Control funds to encourage application of preventative control is an exciting prospect.

Increased industry cooperation and assistance is going to be necessary in many areas of the South where woods workers are in short supply.

The management aspect of SPB "control" will have to be sold to many landowners who value other returns above wood production on the basis of forest stand "assurance."

The time may be approaching when a pilot State or National Forest could be selected to test the integrated pest management system now being formulated for the SPB. Such a test would permit the application of all the principles developed under the ESPBRAP and serve to demonstrate their effectiveness. The new 5-year remote sensing project instituted by the Southeastern Area could be of value in monitoring the results of such a program.

There remains a pressing need that has not yet been completely addressed by the ESPBRAP and that would be of considerable *indirect* value to the small landowner: a more effective "detection and early warning system" which anticipates impending beetle outbreaks--one that can be applied with confidence and ease by State and Federal pest managers.

The proposed technology transfer plan (USDA 1978) states "Research results must be communicated to potential users in ways that will motivate them to implement the research findings." Let's get on with that important task!

The author wishes to thank those members of the Southern Forest Pest Control Organization and FI&DM, USFS, and others who offered suggestions, many of which are incorporated in this paper.

LITERATURE CITED

Clawson, M. 1977. Economic timber production characteristics of nonindustrial private forests in the United States. 64 p. Background paper for the workshop on policy alternatives for nonindustrial private forests, sponsored by the Society of American Foresters and Resources for the Future. [Airlie, Virginia, August 30-September 1, 1977.]

Sedjo, R. A., and D. M. Ostermeier. 1978. Policy alternatives for non-industrial private forests. 64 p. Society of American Foresters, Washington, D.C.

USDA, For. Serv. 1978. Southern pine beetle program--A technology transfer plan. 12 p. [Unpublished but available from ESPBRAP, 2500 Shreveport Highway, Pineville, La 71360.]

SOUTHERN PINE BEETLE CONTROL FOR LARGE INDUSTRIAL FOREST LANDS

John R. Wood[1]

Destruction wrought by the southern pine beetle (SPB) is not confined to private or public lands, small or large ownerships, commercial or noncommercial timber. The threat respects no boundaries and conforms to no ownerships.

Public lands are subject to extensive multiple-use considerations, noneconomic variables, and public budget struggles for pest control funds. Small private landowners, on the other hand, encounter problems of motivation, sufficient economic incentives, and inability to execute effective control strategies.

On the other side of the fence, we have the industrial forest lands. In this sector an analysis of control, need, and expectations presents a simpler picture. Aside from certain environmental and multiple-use constraints, the industrial forest is obligated to defined economic and business pricing systems. Industrial ownerships simply do not have the magnitude of intangibles and people problems associated with other types of ownerships.

Typically, in any industry, the primary consideration is expressed in economic terms--what are the costs? Or, is the effort cost effective? Both these questions are followed by long-run as well as short-run considerations.

Most larger industrial ownerships, along with their manufacturing facilities, are set up on a profit-center basis conforming to long-term strategic plans. Performance and control are monitored by means of monthly operating statements, which reflect budget and profit status. Less obvious are the interrelationships of the profit centers to the whole, or, the bottom line.

Briefly let me run through some particulars. The woodlands or resource-group profit center grows, protects, and harvests trees. These trees are sold at a predetermined or market price to a manufacturing plant. The manufacturing group, itself a profit center, determines profitability simply as sales price less cost of manufacturing plus wood costs. Only if a plant is running entirely from purchased stumpage might the plant's profit margin be a "real" number. Fee timber, which has a depleted value foractual profit and tax purposes, is transferred to the manufacturing plant at a value approaching market value. This difference in actual depleted value and transfer price is generally shown as a profit for resources and, eventually, to the company, appearing in its consolidated statement. To a nonindustrial layman, this creation of "double figures" may seem confusing and unnecessary, yet it is the only consistent yardstick by which value added by manufacturing can be fairly measured and alternatives correctly analyzed. Consequently, we can accurately measure budget and profit performance on the various profit centers.

By now readers are probably asking, "What has all this to do with southern pine beetle control?" In the forest industry, the connection is quite real. As I mentioned earlier, trees are "sold" from the resource group to the manufacturing group. These trees are at once a source of profit and cost. It follows that any reduction in sales (in other words, revenue) or increase in manufacturing costs that can be attributed to some outside force will affect budget and profit performance adversely. Damage caused by the SPB has precisely that potential because plant managers will strongly resist the use of beetle-killed timber and salvaged wood.

How does Kirby control for the SPB damage? For the moment, let's talk about the short run. The mill manager is charged for salvaged logs at a reduced rate. First, this motivates him to utilize damaged timber, and second, it mitigates the adverse cost effects of processing beetle-infested timber. On the other side of the coin, the wood re-

---

[1] General Manager, Land and Forest, Kirby Forest Industries, Houston, Tex.

sources group, faced with reduced prices for its stumpage, tries to minimize prospects of lower revenues by (1) increased field coordination, (2) cutting of adjacent green timber to afford economy of size, and (3) swift removal of damaged timber.

Now in the long run--for example, a full-blown epidemic--effects could be more disruptive, especially to logging plans. What's to be done? Put another way, what alternatives do we have to the system outlined in my remarks concerning the short run?

One, fee timber could be cut as planned, ignoring salvage altogether. The effect of this option would be to force inclusion of unsalvaged catastrophic mortality with the normal harvest volumes. The results would be the same as overcutting. Two, we could replace destroyed fee timber through increased purchases of outside wood. This alternative will result in increasing costs above projections and will impact performance goals, as well as lower corporate bottom-line results.

I believe that quick, efficient, and well-coordinated salvage operations are the most cost-effective means for an industrial owner, particularly during epidemics. Kirby's recent experience confirmed this theory. By utilizing expedient salvage operations and effective internal economic and financial control, Kirby in 1976 experienced minimal income-cost consequences due to the southern pine beetle.

As a matter of fact, salvage can be made profitable or, in a bad year, be made to minimize losses as measured by annual profit-and-loss statements. Two questions quickly come to mind. Do the accounting systems described affect control in real terms? And are there any long-run benefits not depicted in operating statements? These are different questions. The only indications I have to answers are reflected in an unpublished administrative study made by the Texas Forest Service in early 1977.

Beginning in 1975, the TFS made periodic aerial surveys of a given area in southeast Texas. In May and September of 1976 and February of 1977, photographs were taken of an area just over 73,000 acres. These surveys effectively recorded all SPB mortality that occurred during calendar year 1976. Table 1 depicts the annual mortality rate for 1000 acres of host type by owner.

Table 1.--Annual SPB mortality in six industrial land ownerships and miscellaneous private ownerships in southeast Texas, 1976-77

Owner[1]	Annual mortality/1000 acres of host type
Kirby	45
A	335
B	107
C	16
D	18
Private owners	67
Average	110

[1] Owners A-D are industrial concerns.

Only Kirby and industrial owner A had better than 10,000 acres of fee ownership in the area covered by the study. In 1976, Kirby very aggressively salvaged mortality; owner A did little or no salvaging. Industrial owners B, C, and D varied in salvage efforts but did not have sufficient acreage to allow for definitive conclusions. Other private owners with a combined total of 7100 acres of host type had lower mortality than the average, but their rate of 67/1000 acres suggests their inability to perform timely salvage. In monetary terms, owner A implicitly had to undertake significant replacement timber purchases--$250,000 per 1000 acres of host type. That company's experience shows what losses effective control could have prevented and what long-term benefits are possible in the industrial forest.

What I have said to this point can be summed up by stating flatly that salvage will predictably be the chief effective control for large industrial forest lands. What other means do we have? To date, we have no responsive chemical means. Ownership patterns make collective cooperative human efforts highly improbable. The belief that pest control laws can overcome ownership patterns and space problems is a naive oversimplification.

Of course, the industrial owner and Kirby in particular will continue to use various ways to control small spots and endemic populations. This is done primarily to protect highly valuable adjacent stands, terminate spot growth, and put into practice our hope that effective action on a small area will have some greater effect.

It is unlikely that the western Gulf region will ever see another sustained epidemic such as occurred during 1960-1976. We helped it along initially by building up our growing stock and cutting only two-thirds of the annual pine growth. We know better today! But those conditions can return on public lands. Again, the specter of ownership patterns and lack of sustained systematic strategies....

At Kirby, we have struggled hard to absorb the income-cost effects of the bug. Our unique system of performance targets subject to the profit center concept has allowed Kirby to control the devastation of the southern pine beetle and at least minimize the effects of its ravenous appetite.

METHODS USED FOR EVALUATING SOUTHERN PINE BEETLE CONTROL TACTICS

Roy L. Hedden[1]

Abstract.--Methods employed for southern pine beetle (SPB) control treatment evaluation in the past have relied heavily on the impact of within-tree brood mortality or individual tree survival. Little attention has been given to control treatment assessment at either the management unit or ownership level. This lack of attention is due to the inadequacy of methods for evaluating treatments on a scale above the individual spot. Resource managers and other decisionmakers will continue to make decisions under uncertainty until meaningful inputs to the control tactic array are developed. Therefore, development of hypotheses concerning control tactics tested by researchers should be guided by the information needs of resource managers.

INTRODUCTION

I have the task today of reviewing methods used for evaluating southern pine beetle control tactics. I will briefly review control tactics employed and methods used to evaluate these treatments. I will also detail the problems of evaluating treatments and present some ideas for consideration in developing methods for treatment evaluation in the future.

CONTROL TACTICS EMPLOYED

I will briefly review tactics employed for southern pine beetle (SPB) control. I will not define "control," but most of the methods have been used either to kill beetles or to prevent subsequent tree mortality including the disruption of spot growth. These remedial methods include (1) salvage of infested trees, (2) cut-and-leave infested trees, (3) cut-and-top infested trees, (4) pheromones to attract beetles to preselected trees (trap trees) then salvage, (5) trap trees treated with cacodylic acid to cause brood mortality, (6) fell and burn infested trees, (7) fell and remove bark of infested trees, (8) insecticide treat felled trees, (9) insecticide treat standing infested trees.

Preventive "control" tactics are methods which attempt to reduce individual stand or tree susceptibility to initial attack and subsequent spot growth or to prevent initial attack. For instance, thinning overstocked pine stands is recommended to increase tree vigor (Hedden 1978), while use of prophylactic insecticide sprays will prevent successful beetle attack.

METHODS USED TO EVALUATE TREATMENTS

Generally, treatment evaluations have involved assessments of beetle mortality, and occasionally, reductions in tree mortality. Assessments have been conducted at the level of the individual tree and spot. Methods employed for evaluation have usually been adequate to accomplish the objective of the study. Methods of assessing within-tree brood survival are well developed and will not be detailed here. For references to selected studies involving within-tree brood survival, see the Literature Cited section of this paper.

Only one published study has addressed treatment effectiveness at a scale above the individual spot. This retrospective study by Lorio and Bennett (1974) employed operationally collected data. The relationship between spot frequency and selected site and stand variables over a 5-year period on a single ownership was investigated using correlation and regression analysis. Although the statistical methods employed were straightforward, the use of operationally generated records in any study presents some difficulties. Obviously, the reliability of the results will be directly related to the quality of the data. Furthermore, the analysis will also be limited by the availability of collateral data on stand, site, climatic, and other variables.

---

[1] Forest Entomologist, Weyerhaeuser Company, Hot Springs, Ark. In July of 1979, Dr. Hedden joined the faculty of Clemson University.

I will not discuss further the use of operational data in retrospective studies for evaluating treatment effectiveness as this topic will be discussed in detail by Dr. R. F. Billings in a paper to be presented later in this symposium.

PROBLEMS OF EVALUATING CONTROL TACTICS

Control can be defined in many ways, but most researchers have defined southern pine beetle control as the ability to kill beetles or to prevent individual tree mortality. As a consequence, treatment evaluation methods have been developed accordingly. However, this definition of control may be of only limited value to resource managers involved in control tactic decisionmaking. Beetle mortality may be of little or no concern, while reduction in tree mortality may be of interest only at a single point in time and space.

For example, an individual landowner may desire to use salvage and/or cut-and-leave to interrupt spot growth. Prevention of tree mortality on adjacent ownerships may be of no interest; the landowner is interested only in reducing his loss with a minimum of current economic impact. The manager may feel that given the cyclic nature of SPB outbreaks, whatever tactic he employs will have little if any impact on overall beetle population level.

What kind of information does this landowner need to make a decision? First, he needs to know the probability of the spot ceasing to expand without treatment. Second, information on the probability of the spot continuing to grow in spite of the treatment is necessary. Third, he would also like to know the probability of another spot occurring on his ownership as related to the control treatment. Last, information on treatment cost, future value of the stand, disruption of current management plans, availability of labor, access to the stand, and so on, is necessary. With this data, the landowner can now employ a benefit-cost analysis to help him make a decision to use either salvage or cut-and-leave, or to do nothing.

This scenario was purposely constructed to illustrate the weaknesses of methods used in the past to evaluate control treatments. The questions answered by researchers in the past have generally addressed the objectives of the studies. However, little attention has been given to information needed by decisionmakers. Only a few studies have provided information on treatment cost, and no studies have provided data on the effects of a treatment above the level of a single spot. Benefits measured in terms of beetle mortality are not easily translated into a form usable by resource managers.

SOME CONSIDERATIONS IN THE EVALUATION OF TREATMENTS

The methodology employed in treatment evaluation should be directly related to the hypothesis being tested. Obviously, the hypothesis can be tested only if suitable methods are available. In general, methods for evaluating SPB within-tree brood survival are well developed. In addition, it is relatively easy to tell whether new tree mortality is occurring within a single spot. However, methods for evaluating mortality of dispersing beetles and tracking of beetles from spot to spot are nonexistent. Therefore, treatment effects on these phenomena must be evaluated indirectly.

I will not address the question of using indirect methods for treatment evaluation as this topic will be adequately covered in following papers. But I will briefly discuss hypothesis development since methods used for treatment evaluation depend to some extent on the questions asked by the researcher.

An indefinite number of hypotheses could be developed, only a few of which would provide useful information to decisionmakers desiring to use a treatment to manage SPB populations. An aid that might prove useful for selecting hypotheses is a conceptual device which I call the *control tactic array*. The control tactic array is merely a logical method for ordering treatment alternatives. Variables included are the control tactic, the scale on which the treatment is directed, and the result desired from the treatment (fig. 1). Control tactics include salvage, cut-and-leave, and so on. Scale is the operational level at which the tactic is directed, that is, the individual tree, spot, management unit, ownership, or geographical region. The desired result might be maximum beetle mortality, minimum tree mortality, or minimum economic loss. Obviously there are other possible results, such as minimizing esthetic damage.

Any method that allows the logical ordering of alternatives will suffice for conceptualization of the system. Ideally, however, each cell in the array should be related to every other, al-

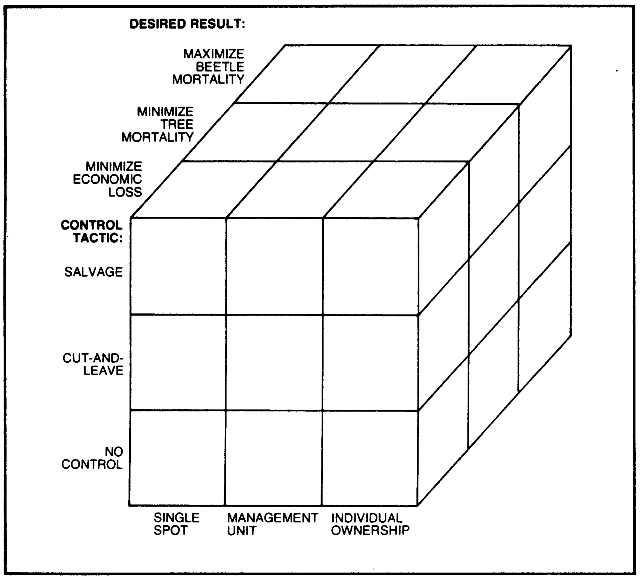


Figure 1.--Geometric representation of a control tactic array. Ideally each cell in the array is related to every other.

though the nature of these relationships may not be perfectly known.

Previously I mentioned a hypothetical landowner considering the employment of three control tactics (salvage, cut-and-leave, or no treatment) on the scale of the individual spot with the goal of minimizing economic loss. The landowner would employ the control tactic or combination of tactics which produces the desired result: minimum economic loss. In order to select meaningful alternatives, the landowner or resource manager needs the appropriate inputs for the control tactic array. Appropriate information will be available only if meaningful hypotheses are tested by researchers. Unfortunately, tests of hypotheses concerning frequently employed treatments above the level of the individual tree await development of acceptable methods of treatment evaluation. Until new and meaningful methods of evaluation are available, resource managers will continue to make decisions under uncertainty. In other words, it is difficult to make 2 × 4's out of dead beetles.

LITERATURE CITED

Copony, J. A., and C. L. Morris. 1972. Southern pine beetle suppression with frontalure and acid treatments. J. Econ. Entomol. 65:754-757.

Hedden, R. L. 1978. The need for intensive forest management to reduce southern pine beetle activity in east Texas. So. J. Appl. For. 1:19-22.

Hodges, J. D., and R. C. Thatcher. 1976. Southern pine beetle survival in trees felled by the cut and top--cut and leave method. 5 p. USDA For. Serv. Res. Note SO-219. South. For. Exp. Stn., New Orleans, La.

Jump, B. J., and C. H. Tsao. 1973. Control of southern pine beetles by spraying standing and felled trees with BHC. J. Ga. Entomol. Soc. 8: 203-209.

Lorio, P. L., Jr., and W. W. Bennett. 1974. Recurring southern pine beetle infestations near Oakdale, Louisiana. 6 p. USDA For. Serv. Res. Pap. SO-95. South. For. Exp. Stn., New Orleans, La.

Ollieu, M. M. 1969. Evaluation of alternative southern pine beetle control techniques. 6 p. Tex. For. Serv. Publ. 104.

POSTTREATMENT TREE MORTALITY IN SOUTHERN PINE BEETLE SPOTS AS A MEASURE OF TREATMENT EFFECTIVENESS[1]

John L. Foltz[2]

Abstract.--Posttreatment tree mortality (PTTM) can be used to evaluate the effectiveness of treatments for controlling spot infestations of the southern pine beetle (SPB), *Dendroctonus frontalis* Zimmerman. Useful statistical tests include χ^2 tests for independence of distributions, regression analysis, *t* tests for comparing means on paired plots, and the nonparametric Wilcoxon rank sum and signed rank tests. This measurement of PTTM on individual spots without the concurrent measurement of insect populations limits the inferences that can be drawn from the experiments. Treatments effective at reducing tree mortality on individual spots may increase or decrease the frequency and severity of SPB spots over larger geographic areas.

INTRODUCTION

The southern pine beetle (SPB), *Dendroctonus frontalis* Zimmerman, attacks and kills large-sized southern pines. Often just one or a few trees will be attacked and then there will be no additional tree mortality for a considerable distance. However, the beetles sometimes kill virtually every pine tree over many acres. Thus, it seems logical to ask if there is some treatment that can be applied to an expanding SPB spot to reduce or stop the tree mortality.

In this paper I will be discussing only tree mortality in individual spots as a measure of treatment effectiveness. Other participants in this symposium will discuss the measurement of other variables on the same or different units of land area.

Specifically I want to deal with the following questions:

(1) What knowledge of the SPB-pine forest system do we have that will help us design valid and efficient experiments for comparing treatments?

(2) What valid inferences can we make if we measure only tree mortality on a series of individual spots?

Let us assume, for purposes of illustrating problems involved in interpreting experimental results, that two forest owners discover SPB infestations in their woodlots. Each owner treats his spot following a treatment prescribed by his county forester. Owner A, 30 days after treating his spot, checks the area and observes no newly infested trees, so he considers the treatment a success. Owner B checks his spot and finds that 10 new trees are infested, so he considers the treatment a failure and doubts its validity as a control tactic.

There are several possible explanations of treatment effectiveness for the results observed in these two examples. In the first example, the absence of further tree mortality may truly indicate that the treatment was effective. However, it is quite possible that naturally occurring factors stopped the infestation so that we have either an effective treatment applied unnecessarily or an ineffective treatment whose success or failure depends solely on other factors affecting spot growth.

The failure of the treatment in the second example may also be due to one of several reasons. Our first reaction is to say that the procedure is ineffective. But perhaps an effective treatment was not properly applied in this case because someone overlooked and failed to treat several infested trees. Another explanation is that some unusual weather, insect, or host condition caused the failure of a normally successful procedure; for example, a new lightning strike may have attracted new beetles to attack trees on the perimeter of the treated spot. Obviously, we need more information than just tree mortality to explain why a treatment succeeds or fails on a particular spot.

---

[1] Florida Agricultural Experiment Station Journal Series No. 1677.

[2] Dept. of Entomology and Nematology, University of Florida, Gainesville, Fla.

EXPERIMENTAL DESIGN

There are three important items we should always consider when designing any experiment to compare treatments (Wadley 1967). First, a clear and concise statement of the objectives is essential. Then we must be sure the experiment is valid and capable of providing evidence on the hypothesis being tested. And third, we should consider the efficiency of the experiment so as to obtain maximum results for the time and expense invested.

The objective of the experiment being considered in this paper is to determine which of several treatments is most effective at reducing posttreatment tree mortality in SPB spots. The experimental unit is the SPB spot and the adjacent uninfested trees. This is also the sample unit. The principal dependent variable will be posttreatment tree mortality (PTTM), the number of trees infested subsequent to the date of treatment. For simplicity we will assume that a tree dies on the date it is is successfully infested by the attacking beetles. Pretreatment covariables such as dominant brood stage in each infested tree, average diameter and height of the pines, basal area per acre, and soil properties will also be recorded to aid in assigning treatments and interpreting results. However, beetle population estimates and tree mortality over larger areas are beyond the scope of this experiment.

Any experimental project with these objectives would probably have the following general procedural steps:

(1) Aerial survey to detect probable SPB infestations
(2) Ground check to determine the status of each infestation and its suitability for treatment
(3) Application of the treatments
(4) Periodic visits to each treated spot to record PTTM
(5) Data analysis, hypothesis testing, inferences, and reports.

The method used to assign a specific treatment to a specific spot is a critical part of this experiment. A nonrandom system is likely to introduce bias that would limit the applicability of the results. The random assignment of treatments to spots as they are detected would be unbiased, but such a system would be an inefficient use of resources and not the most sensitive for detecting small treatment differences. The most efficient and sensitive system would be the formation of groups in which the spots are as similar as possible and then the random assignment of treatments within those groups. Grouping the spots would be largely subjective but based on those factors thought to affect spot growth--factors such as the number of brood trees and site and stand characteristics recorded during the ground checks (Texas Forest Service 1978). In addition, the spots would automatically be grouped in time and geographic area. The objective of the grouping is to minimize the differences due to any variable other than treatments, and thereby to increase the sensitivity of the statistical tests for detecting treatment differences.

Ideally, the time lag between ground checks and application of the treatments would be no more than a few days and there would be no need to remeasure the spot to record the conditions existing on the date of treatment. If there is a substantial time lag, spots should at least be rechecked to determine the number of trees in each brood development class.

The final field step of the general procedures outlined above is to record PTTM at one or more specified times following treatment. An interval of one month would probably be appropriate for summer generations which develop in 25 to 30 days. Longer intervals corresponding to the longer developmental times would be appropriate for other seasons.

ANALYSES

There are a number of statistical tests we can apply to data collected in the manner outlined above in order to determine the significance of differences between treatments. I will discuss four procedures briefly; for simplicity I will talk about the comparison of two treatments. Multiple treatment comparisons will generally be similar. More information can be found in statistical textbooks such as Steel and Torrie (1960), and I recommend that biologists periodically review their favorite book to refresh their memories on the proper and best use of statistics in their work.

χ^2 Tests

When the results of an experiment are recorded as discrete classes of a variable, then the χ^2 test of independence is a simple test to apply. For example, we could classify spots as being active or inactive 30 days after treatment. The hypothesis of independence implies that the proportion found in each activity class is the same for each treatment. Rejection of this hypothesis implies that the observed results are not independent of the treatment category, i.e., there is a significant difference.

The advantage of the χ^2 analysis is that it is relatively easy to classify spots according to some qualitative variable, and χ^2 is an easy statistic to calculate. However, a large number of treated spots are required, to use this test, and it provides no information on the magnitude of the difference in PTTM.

The χ^2 test could be useful for an organization desiring an operational evaluation of several recommended treatments. Say an industrial forestry concern normally treats several hundred spots per year and has the operational flexibility to assign treatments randomly. In this case χ^2 can be used to test the null hypothesis that the treatments are equally successful at stopping additional tree mortality on SPB spots.

Note here the importance of randomization in this and other statistical tests. With random allocation of treatments, a rejection of the null hypothesis implies that the treatments produce different results. But, without random assignment, the difference may be due to some bias rather than the treatment effect!

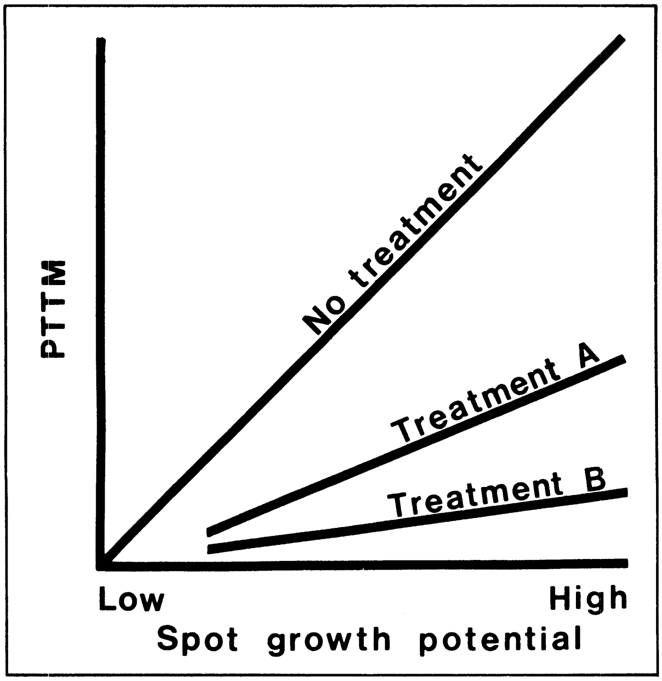


Figure 1.--Regression analyses are useful for comparing experimental results.

Regression Analysis

A regression analysis showing how PTTM changes as a function of treatment and some other variable is another way of comparing or evaluating treatments. Furthermore, the presentation of the results in a graph like figure 1 is useful for helping forest managers decide what treatment would be most appropriate for controlling SPB spots on their lands. Unfortunately, many factors affect spot growth, and we do not yet have a completely satisfactory hazard rating or predictor of tree mortality in the absence of a control treatment.

Multiple regression analysis could help us develop a better predictor if we could identify the important variables and collect data over a sufficient range and combination of the variables. I don't foresee this happening in the near future. Most likely the treatments in any evaluation experiment will be applied to a small number of the high-hazard spots and, thus, one of the following tests will be more appropriate.

t Test

The *t* test is the most frequently used test for comparing two treatment means. We know that when observations from paired plots tend to be positively correlated, the *t* test for paired observations will generally detect a smaller difference between treatments than if the observations were unpaired. We can use insect population levels, site and stand characteristics, and geographical and temporal proximity to pair SPB spots and thus minimize the inherent variability between spots and the variation expected from external factors such as weather.

Nonparametric Tests

Nonparametric statistical tests are useful because they generally have simple computations and require few assumptions about the nature of the population being sampled. Two useful procedures are the Wilcoxon rank sum test (often called the Mann-Whitney test) for unpaired observations and the Wilcoxon signed rank test for paired observations (Wilcoxon and Wilcox 1964). A disadvantage of these tests is that they do not extract as much information from the experiment as do appropriate parametric tests.

DISCUSSION

The preceding material illustrates that we can design experiments to use PTTM as a variable for measuring the effectiveness of treatments applied to control individual SPB spots. However, the lack of additional information severely limits the valid inferences that can be drawn from the experiment. For example, a knowledge of why a normally good treatment failed on specific plots may provide important information for using the treatment in other times and places. Without some measurement of insect population dynamics, we can only speculate on the biological interactions that produced the observed result.

The extrapolation of spot treatments to area-wide control of the pest requires more information than is obtained in the preceding experimental design. A treatment that is effective at reducing PTTM on individual SPB spots will be equally effective on a much larger area only if the treatment does not change the frequency and severity of future spots. It is hard to believe that this would ever be the case. The treatment may increase or decrease the number of spots in the surrounding area depending on its mode of action. Any treatment that reduces PTTM by killing the insects directly ought to reduce spot occurrence and tree mortality through time on the larger area, and thus the benefit would be greater than what occurred on the treated spots. On the other hand, a treatment such as a beetle repellant might merely cause the insects to change the location of the tree mortality. In this case a small reduction in area-wide mortality might not be sufficient to offset the treatment costs. Thus, as other participants in this symposium will surely tell you, the benefits and costs of any treatment need to be calculated for larger areas and longer times than the individual spot.

LITERATURE CITED

Steel, R.G.D., and J. H. Torrie. 1960. Principles and procedures of statistics. 481p. McGraw-Hill, New York.

Texas Forest Service. 1978. Texas forest pest activity 1976-1977 and forest pest control section biennial report. 28 p. Tex. For. Serv. Publ. 117.

Wadley, F. M. 1967. Experimental statistics in entomology. 133 p. USDA Graduate School Press, Washington, D. C.

Wilcoxon, F., and R. A. Wilcox. 1964. Some rapid approximate statistical procedures. 60 p. Lederle Labs, Pearl River, N.Y.

TECHNIQUES FOR EVALUATING THE INFLUENCE OF BEHAVIORAL CHEMICALS ON DISPERSION OF THE SOUTHERN PINE BEETLE WITHIN INFESTATIONS

P. C. Johnson and J. E. Coster[1]

Abstract.--The influence of behavioral chemicals on flying southern pine beetle dispersion can be evaluated by comparing daily estimates of mean crowding (MC) and mean quadrat density (M) from a trapping grid to 95 percent prediction limits about the characteristic regression of MC on M, while daily dispersion patterns can be quantified using the index of patchiness (MC/M). The size and placement of the trapping grid relative to the size and direction of spread of the infestation, the range of infestation size included in the characteristic regression data base, and the cost of maintaining the trapping grid are important considerations.

When control tactics are applied to an insect pest population, the aim is to affect the population's abundance and, implicitly, its distribution in the habitat. Lloyd (1967) points out that the distribution of a population through the available habitat may result in differing degrees of "crowding" (i.e., the local density as perceived by the individual organism), even though the area-wide density remains constant. The consequences of the crowding caused by the dispersion pattern of a population should be a major concern in the study of population dynamics.

For the southern pine beetle (SPB), *Dendroctonus frontalis* Zimm., localized crowding is mediated by a pheromone system that results in aggregation of both beetle sexes at host trees selected by females (Kinzer et al. 1969, Renwick and Vité 1969). This aggregation is a key step in the colonization of host trees since adequate numbers of beetles are required to overcome tree resistance mechanisms and to initiate mating and gallery construction within the tree. Secondarily, aggregation is also important to subsequent brood production since survival of new brood is associated with physiological deterioration of the host, which, in turn, is dependent on adequate colonization (Borden 1974).

The attractant pheromone system of SPB induces aggregation of a population; it may influence dispersal of a population; and it may also affect the dispersion pattern of the population. These three terms--aggregation, dispersal, and dispersion--have distinct meanings in this paper. *Aggregation* of SPB is the process of forming clusters of flying beetles around freshly attacked trees in response to attractants. The resulting clusters may be called aggregations. *Dispersal* refers to the movement away from a populated place, resulting in the scattering of at least some of the original population. We use the term in the sense of Andrewartha and Birch (1954), who said, "We are more interested in dispersal over shorter distances, the sort of scattering that results not in the extension of the distribution beyond ecological barriers but merely in the reshuffling of the individuals within the area in which the animals are distributed." *Dispersion*, on the other hand, refers to the numerical pattern of distribution of a population in its environment. Dispersion is not a process, in a population dynamics sense, but rather a group attribute arising from, among other things, aggregation and dispersal processes of a population.

In this paper, we are concerned primarily with dispersion of flying SPB populations within infestations and how dispersion patterns may be measured for use in assessing the effectiveness of deployment strategies of synthetic behavioral chemicals. We (Coster and Johnson 1979) have shown that SPB dispersion within infestations may be adequately characterized by regression of the mean crowding parameter, MC, on the mean quadrat density, M (Iwao and Kuno 1971). This technique could be used to evaluate the influence of behavioral chemicals treatments for SPB control on dispersion of the flying SPB population.

[1] Research Associate, School of Forestry, Stephen F. Austin State Univ., Nacogdoches, Tex.; and Applications Coordinator, Expanded Southern Pine Beetle Res. & Appl. Prog., USDA Forest Service, Pineville, La.

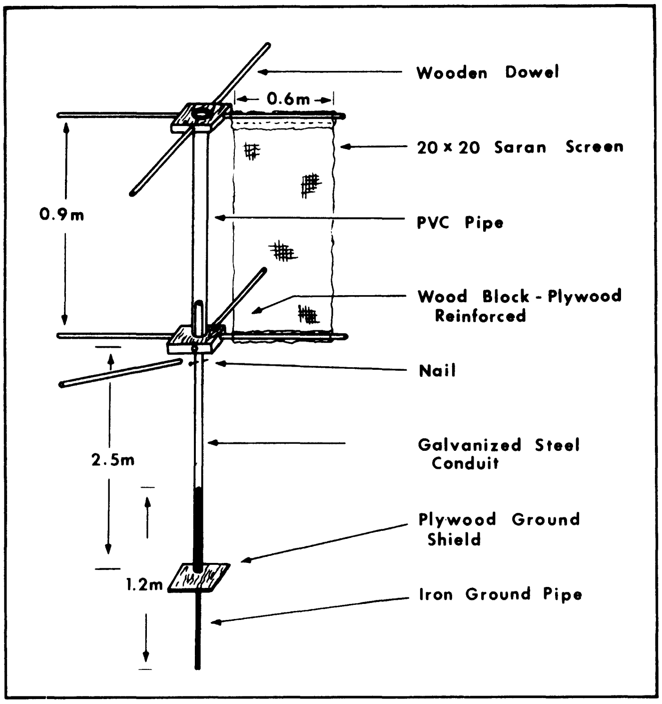


Figure 1.--Schematic of a flight trap for monitoring SPB dispersion.

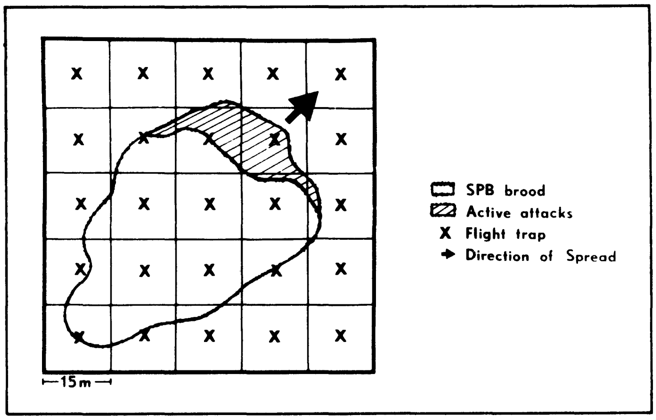


Figure 2.--Flight trap placement on 15-m centers in a 5 × 5 grid around a SPB infestation.

The rationale for using indices of dispersion to evaluate behavioral chemicals treatments is twofold. First, many behavioral chemicals control procedures under consideration for bark beetles are designed either to enhance or interrupt the aggregation phase of mass attack (Borden 1977). It is logical to expect their effect to be exhibited in nonnormal dispersion patterns of the flying beetles. Second, if an effect is not detected, then information concerning the mode of operation of the behavioral chemical has still been gained (e.g., if an inhibitor does not influence the dispersion of the flying SPB, then it must act only on the landing and/or attack behavior of the beetle).

In this paper, we outline a technique for evaluating the influence of behavioral chemicals on SPB dispersion. We hope that this paper may serve as a procedural guide for the inclusion of dispersion as a measure of treatment efficacy during evaluation of SPB control procedures.

MATERIALS AND METHODS

The technique requires daily monitoring of flying population density using a systematic grid of flight traps. Any flight trap which gives a relative measure of flying SPB population density at a point in space may be used. The trap shown schematically in figure 1 has proved to be easily monitored and maintained under field conditions. It was adapted from the design used for western pine beetle (Browne 1978).

The flight trap consists of a central PVC pipe to which four vanes of Stikem Special®-coated saran screening (20 × 20 mesh) are attached by wooden dowels or aluminum conduit inserted into wooden blocks affixed to the ends of the PVC pipe. The PVC pipe is free to move up and down a galvanized steel conduit nested within the PVC and placed over an iron ground pipe. A nail inserted through appropriately spaced holes in the galvanized steel conduit allows the trap to be raised and lowered easily for removal of beetles. The vanes may vary in size, depending on expected SPB densities, but vanes of 0.6 × 0.9 m have proved most useful in our studies. The traps should be centered at approximately 3 m above the ground, which corresponds to the peak height of landing activity on trees (Coster et al. 1977).

The traps are placed in a centric systematic sampling scheme on 15-m centers surrounding the active head of the infestations (that portion of the infestation containing the newly attacked trees), as shown in figure 2. The number of traps required depends on the size of the infestation; however, a 5 × 5 grid (25 traps) should prove adequate for most small- to intermediate-sized infestations.

Traps are inspected daily and SPB are removed. This must be completed by about 10:00 A.M. to prevent overlapping catch between successive flight periods. The SPB may be tallied for each trap in the field, or they may be placed in hexane-filled vials along with a tag noting trap number and date for later counting in the lab. Sexing of the SPB may be desirable if a differential effect on males and females is suspected. Lab personnel can estimate sex ratio for large trap catches using a sequential sampling routine described by Johnson (1977).

The following parameters are calculated from the trap catch data: (1) mean quadrat density (M), (2) Lloyd's (1967) mean crowding (MC), and (3) Lloyd's (1967) Index of Patchiness (IP). The appropriate formulae are

$$M = \frac{\sum_{i=1}^{n} X_i}{n}, \qquad (1)$$

$$MC = \frac{\sum_{i=1}^{n} X_i(X_i-1)}{\sum_{i=1}^{n} X_i}, \qquad (2)$$

and

$$IP = \frac{MC}{M}, \qquad (3)$$

where X_i = individual trap catch for trap *i*, and n = the number of traps.

The M-MC pairs for each day will be used for comparison to a normal dispersion pattern developed from an appropriate data base (discussed below), while the IP value represents a measure of the dispersion of the flying population for that day's catch. The IP value has the following relation to unity:

IP > 1.0	Aggregated population
IP = 1.0	Randomly distributed population
IP < 1.0	Uniformly distributed population.

Lloyd (1967) points out that the use of IP should be restricted to measures of quadrat density taken within the smallest aggregation size (i.e., the distribution in the quadrat is random or uniform). Since the distribution in the immediate vicinity of the flight trap is assuredly random--SPB do not fly in formation--this assumption is met for our flight trap catch.

The above parameters are used to quantify experimentally induced dispersion patterns and, then, to compare these dispersion patterns to normal patterns of the beetle. L. R. Taylor (1971) shows that an insect species has a characteristic dispersion pattern. We determine SPB's normal dispersion from an appropriate data base consisting of a series of daily observations from several infestations with a range in size which includes the target infestation of the behavioral chemicals test. The number of days and infestations in the data base determine the accuracy of the evaluation technique and in practice represent a compromise between desired accuracy and available funds and time. A data base, once assembled, may be used for any number of evaluations provided the treatment areas are comparable to the data base areas. The normal dispersion pattern is determined using the same trapping procedures outlined above.

A simple linear regression of MC on M is used to characterize the normal aggregation of the SPB under a variety of density and environmental conditions. The slope of the regression (β) is termed the density-contagiousness coefficient (Iwao and Kuno 1971), and is a measure of the normal dispersion of the basic population units (individuals or groups of individuals if the species is colonial). β bears the same relationship to unity as does IP, and is equivalent to IP if α, the Y-intercept (termed the index of basic contagion or basic population unit by Iwao and Kuno 1971), equals zero. That is, if the basic unit of population is the individual, β is equivalent to IP and measures the dispersion of individuals; if α is greater than zero, the basic population unit is a group of individuals and β does not equal IP (in fact, IP does not represent a valid measure of dispersion under these conditions due to violation of the assumption that you are measuring density within the smallest unit of aggregation, i.e., that dispersion in the immediate vicinity of the trap or within the sampled quadrat is random or uniform). β now measures the dispersion of the groups of individuals.

Expected variation in daily dispersion pattern is represented by the 95 percent confidence limits (CL) about the regression line. This is the variation we might expect due to normal environmental processes such as weather. Since we would expect the basic unit of SPB population distribution to be the individual (i.e., SPB do not fly in formation or swarms), then we would expect our estimate of α to be approximately zero. If the 95 percent CL about the regression includes zero at the Y-intercept, then α does not deviate significantly from zero. If α does deviate significantly from zero, our data base is probably inadequate and should be enlarged.

Construction of 95 percent prediction limits (PL) about the regression line allows a statistical evaluation of the influence of the behavioral chemicals treatment. Comparison of individual daily M-MC pairs to the 95 percent PL about the regression allows us to detect significant deviation from normal dispersion at the existing mean density. If the M-MC pair falls above the upper 95 percent PL, then aggregation has been significantly increased by the treatment. If the pair falls below the lower 95 percent PL, then aggregation has been significantly reduced by the treatment. Pairs falling within the 95 percent PL represent no significant treatment effect.

Appropriate formulae for construction of the 95 percent CL and PL about an estimated value of Y ($\hat{Y}_i$) at X_i are provided below (Sokal and Rohlf 1969):

$$95 \text{ percent CL} = \hat{Y}_i \pm t_{.05[v]} S_{\hat{Y}} \qquad (4)$$

and

$$95 \text{ percent PL} = \hat{Y}_i \pm t_{.05[v]} \hat{S}_Y \qquad (5)$$

The standard errors, $S_{\hat{Y}}$ and $\hat{S}_Y$, are provided by:

$$S_{\hat{Y}} = \sqrt{S^2_{y \cdot x} \left[\frac{1}{n} + \frac{(X_i - \bar{X})^2}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \right]}, \quad v = n-2, \qquad (6)$$

$$\hat{S}_Y = \sqrt{S^2_{y \cdot x} \left[1 + \frac{1}{n} + \frac{(X_i - \bar{X})^2}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \right]}, \quad v = n-2 \qquad (7)$$

where: $S_{\hat{Y}}$ = standard error for estimated Y for X_i,

$\hat{S}_Y$ = standard error for a predicted Y for X_i,

$S^2_{y \cdot x}$ = Residual Mean Square (unexplained variance),

n = number of observation,

$\bar{X}$ = mean x-value,

X_i = specified value of X for which the estimate or prediction is made,

t = Students t for α = .05,

and v = degrees of freedom for t.

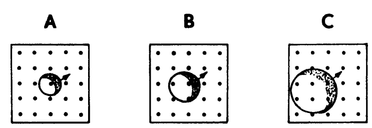
Appendix 1 provides a brief description of the application of this technique to SPB flight trap catch data collected by Reeve (1975) from three infestations in east Texas.

Treatment effects may also be evaluated in the absence of an appropriate data base. This involves an analysis of covariance (ANCOVA) in a regression format (allowing evaluation of factor × covariate interaction). If a significant treatment × mean density interaction is found, the treatment is significantly affecting the M-MC relationship (i.e., the slope of the regression line). This technique, however, requires an extensive control period as well as treatment period and is statistically more complex. Procedures for regression format ANCOVA using dummy variables are available in most computer statistical packages (e.g., Nie et al. 1975).

DISCUSSION AND CONCLUSIONS

This regression analysis of treatment effect on dispersion is appropriate for use with any treatment suspected of having an effect on SPB dispersion within infestations (e.g., cut-and-leave, salvage). It is, however, subject to three limitations: (1) Grid size must be adjusted to the size of the infestation, (2) the grid must be properly located with respect to the active front of the infestation, and (3) the PL's and CL's from the characteristic regression of MC on M must not be extrapolated to M-MC pairs obtained from infestations outside the range of the data base.

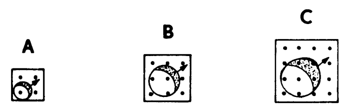
The problem of selecting an appropriate grid size is illustrated in figure 3. The figure represents three hypothetical infestations of differing sizes. In each, the measure of dispersion is based on a 5 × 5 grid. For the sake of illustration, beetles were assumed to be uniformly distributed within the infestation and trap catches were set at five per trap within the infestation. No beetles were caught outside the infestation. The analysis shows that as the infestation size increases relative to the total grid area (i.e., the ratio of traps inside the infestation, I, to traps outside the infestation, O, increases), the estimate of M increases, the estimate of IP decreases, and the value of MC remains constant. These changes occur because MC depends only on those traps having a catch > 0, while M is influenced by all traps (formulae 1-3); therefore, as the number of traps outside the infestation



Parameter	A	B	C
I:O	1:24	3:22	6:19
M	0.20	0.60	1.20
MC	4.00	4.00	4.00
IP	20.00	6.67	3.33

Key: ○ infestation; ❩ active front; · trap; → direction of spread

Figure 3.--Hypothetical representation of the effect of infestation size on the measure of dispersion. Traps within the infestation (I) catch 5 SPB/trap; traps outside the infestation (O) catch 0 SPB/trap.



Parameter	A	B	C
I:O	1:3	3:6	6:10
M	1.25	1.88	1.88
MC	4.00	4.00	4.00
IP	3.20	2.13	2.13

Key: ○ infestation; active front; · trap; → direction of spread

Figure 4.--Hypothetical representation of the adjustment of grid size to stabilize the measure of dispersion. Traps within the infestation (I) catch 5 SPB/trap; traps outside the infestation catch 0 SPB/trap.

increases, M is reduced without a concomitant change in MC. This gives a misleading impression of increased aggregation, when actually the population distribution has not changed.

If, on the other hand, the grid size is adjusted to the size of the infestation so that the trapping area outside the infestation remains proportionate to the area within the infestation (approximately a 1:2 ratio), the measure of dispersion stabilizes. For example, in figure 4, M increases only slightly from A to B, and consequently IP is reduced slightly, while M and IP for B and C are equivalent.

Our recommendation, therefore, is to adjust the grid size such that it is just large enough to include all trees with living SPB (adults, larvae, pupae), while excluding trees from which SPB have already emerged. Furthermore, the grid should be centered on the active front to allow for infestation growth during the study. In the small- to medium-sized infestations used in our studies, the number of trees attacked per day ranged from 0 to 3. Therefore, when studies run for several days, it may be necessary to reposition and/or increase the size of the grid. Changes in position and number of traps present no serious restrictions on subsequent analyses provided the guidelines for adjustment discussed above are followed. With traps on 15-m centers, grid sizes between 3 × 3 and 5 × 5 will be adequate for a wide range of infestations (encompassing 0.10 and 0.56 ha respectively).

As stated earlier, trap design is not a serious problem as long as the design actually does catch beetles. We have used relatively large traps so as to increase the chances of capturing beetles during periods, or in locations, where flight activity was low. It is desirable, however, that trap size and design be the same in the data base studies as in the treatment trials. Although comparisons are possible between differing trap sizes (provided the proportionate change in catch with change in trap is known), this introduces undesirable error and should be avoided. If comparison to a data base with a different trap size is necessary, the treatment study trap catch values should be adjusted for their proportionate catch prior to calculation of the dispersion parameters. That is, if a treatment study trap is known to catch twice the number of SPB as the traps in the data base study (under equivalent SPB population densities and environmental conditions), its catch should be halved prior to calculation of the M-MC pairs.

Some consideration of labor requirements, materials costs, and expertise required to operate a typical grid would seem appropriate. Table 1 provides estimates of construction costs for 30 flight traps of the type shown in figure 1 (0.6 × 0.9-m vanes), including an estimate of man-hours required to construct them. Given this supply of traps (with sufficient extras for replacement of damaged traps during the experiment), table 2 provides estimates of the man-hours required for setup and monitoring of a

Table 1.--Construction cost for 30 flight traps (0.6 × 0.9-m vanes)

Item Description	Amount	Cost[1]
PVC pipe (1¼ in, 200 PSI)	6 20-ft joints	$ 20.70
Galvanized steel conduit (1 in ID)	30 10-ft rods	120.00
Thick-walled iron pipe (3/4 in. OD)	30 4-ft rods	-----[2]
Wooden dowelling (½ in)	240 3-ft pieces	96.00
Plywood (¼ in A-C exterior, ground shield and block reinforcement)	1½ 4 ft × 8 ft sheets	15.38
Wooden blocks (2 in × 6 in)	ca. 30 fbm	11.40
Saran screen (20 × 20 mesh, 72 in width)	100 linear ft	114.00[3]
Miscellaneous supplies (cement, nails, etc.)	-----	20.00
Estimated man-hours construction	80 hours	232.00[4]
Total for 30 traps		$629.48

[1] 1979 prices; local suppliers except as noted.
[2] Price unavailable.
[3] Chicopee Mfg. Co., Cornelia, GA.
[4] Minimum Wage, $3.10/hr.

Table 2.--Daily man-hour requirements for monitoring a trapping grid (reduced to a per trap basis)

Activity	Estimated man-hours per trap
Grid layout and trap placement	1.00
Stikem application and hanging vanes	0.75
Daily SPB collection[1]	0.50[2]
Laboratory counting	0.10[2]
Laboratory sexing	1.00[2]

[1] Including counting and recording if done in field.
[2] Dependent on SPB population density; estimate based on mean trap catch of 30 SPB/trap.

trapping grid, on a per trap basis. Note that considerable time may be saved if counting is carried out in the field (with no sex ratio estimation), but accuracy is probably reduced.

The daily field operations can be handled by competent technicians who can discriminate between SPB and other similar beetles. An ability to concentrate under what are usually boring and tedious work conditions is desirable. Sexing of SPB catch requires a similar level of expertise.

With regard to analysis, familiarity with simple linear regressions is sufficient statistical training, with the calculation of the 95 percent CL and PL being the most difficult step. Although statistical computer packages can be used, these analyses can be readily handled on a standard calculator (preferably programmable). These analyses need be done only once--when establishing the CL's and PL's around the regression line for the data base. Plotting of daily M-MC pairs against a graphical representation of the regression and PL's (as in sequential sampling) simplifies the procedure during evaluation trials tremendously (see Appendix 1 and figure 5).

In conclusion, we feel that this measure of dispersion pattern can be easily applied in the framework of a field test of a SPB control tactic and that it would be instrumental in elucidating the mode of operation of the proposed tactic. A major advantage of the procedure is that it may be run in the absence of simultaneous control trapping grids; therefore, development of an appropriate data base should precede the evaluation trials but could be run concurrently if necessary.

Moreover, this procedure has potential for application to the dispersion of SPB infestations on an area-wide basis, and may prove useful in determining the influence of control procedures on infestation distribution (i.e., proliferation of infestations) within a larger forested area. In this case, the quadrats would be a series of map grids within which infestations would be tabulated and the characteristic M-MC regression for infestation distribution determined. Studies concerning this application are currently underway in Texas.

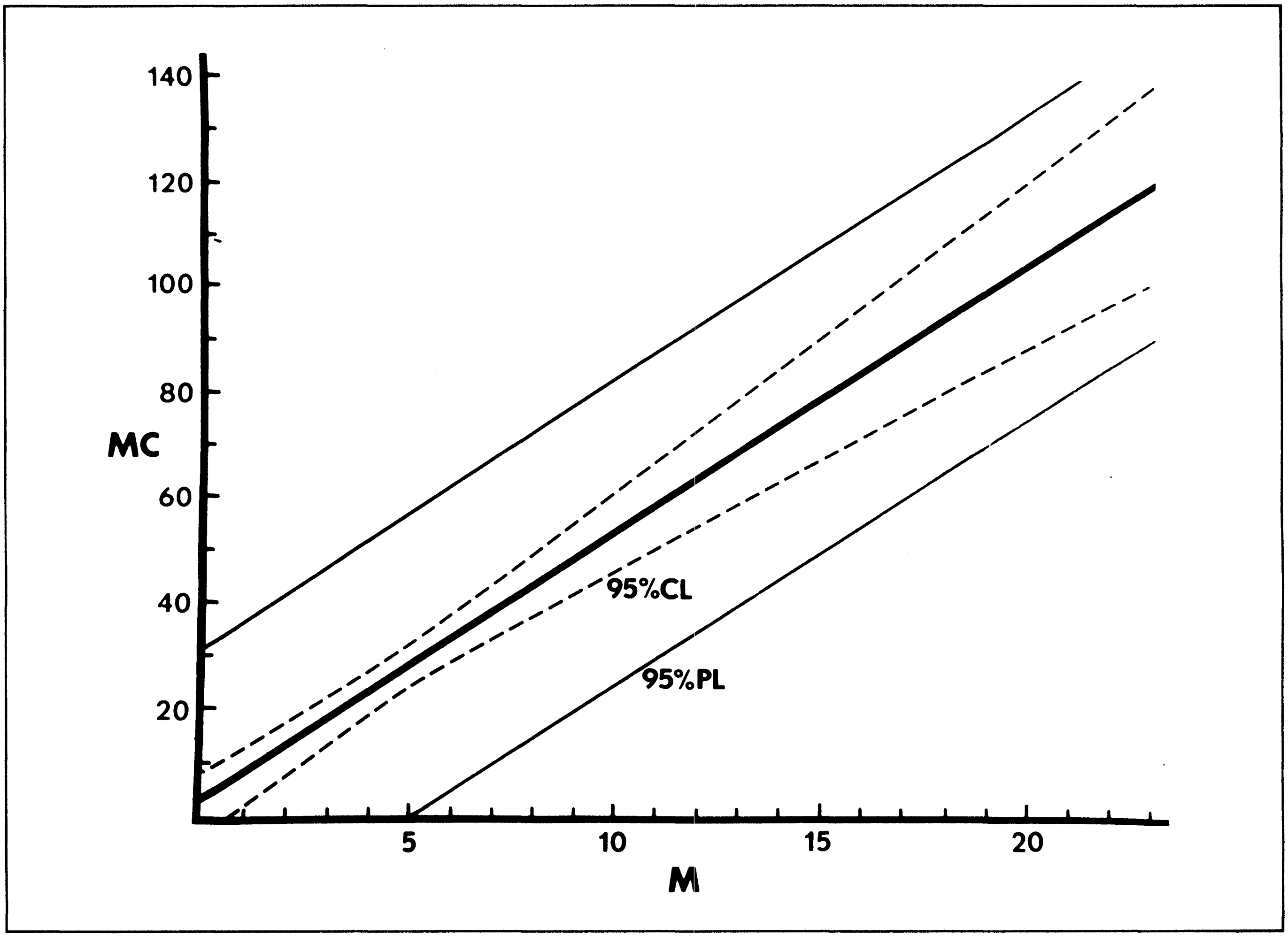


Figure 5.--The M-MC regression for SPB trap catch with 95 percent CL and PL shown.

LITERATURE CITED

Andrewartha, A. J., and L. C. Birch. 1954. The distribution and abundance of animals. 782 p. Univ. Chicago Press, Chicago, Ill.

Borden J. 1974. Aggregation pheromones in the Scolytidae. *In* Pheromones. p. 135-160. M. C. Birch, ed. North-Holland, Amsterdam.

Borden, J. 1977. Behavioral responses of Coleoptera to pheromones, allomones, and kairomones. *In* Chemical control of insect behavior. p. 169-198. H. H. Shorey and J. J. McKelvey, Jr., eds. John Wiley & Sons, New York.

Browne, L. E. 1978. A trapping system for the western pine beetle using attractive pheromones. J. Chem. Ecol. 4:261-275.

Coster, J. E., and P. C. Johnson. 1979. Characterizing flight aggregation of the southern pine beetle. Environ. Entomol. 8:381-387.

Coster, J. E., T. L. Payne, E. R. Hart, and L. J. Edson. 1977. Aggregation of the southern pine beetle in response to attractive host trees. Environ. Entomol. 6:725-731.

Iwao, S., and E. Kuno. 1971. An approach to the analysis of aggregation pattern in biological populations. *In* Statistical ecology, Vol. 1: Spatial patterns and statistical distributions. p. 461-513. G. P. Patil, E. C. Pielou, and W. E. Waters, eds. Penn. State Univ. Press, University Park, Penn.

Johnson, P. C. 1977. Sex-ratio estimation, sequential sampling, and the programmable pocket calculator. Bull. Entomol. Soc. Am. 23:251-254.

Kinzer, G. W., A. F. Fentiman, R. F. Page, R. L. Foltz, J. P. Vité, and G. B. Pitman. 1969. Bark beetle attractants: Identification, synthesis, and field bioassay of a new compound isolated from *Dendroctonus*. Nature 221:477-478.

Lloyd, M. 1967. Mean crowding. J. Anim. Ecol. 36:1-30.

Nie, N. H., C. H. Hull, J. G. Jenkins, K. Steinbrenner, and D. H. Bent. 1975. SPSS: Statistical package for the social sciences. (2nd ed.) McGraw-Hill, New York.

Reeve, R. J. 1975. Temporal and spatial distribution of flying *Dendroctonus frontalis* Zimmerman (Coleoptera: Scolytidae) and the predator *Thanasimus dubius* F. (Coleoptera:Cleridae) in and near small infestations. M. S. Thesis. Stephen F. Austin State University, Nacogdoches, Tex.

Renwick, J.A.A., and J. P. Vité. 1969. Bark beetle attractants: Mechanism of colonization by *Dendroctonus frontalis*. Nature 224:1222-1223.

Sokal, R. R., and F. J. Rohlf. 1969. Biometry: The principles and practice of statistics in biological research. 775 p. W. H. Freeman and Co., San Francisco.

Taylor, L. R. 1971. Aggregation as a species characteristic. *In* Statistical ecology, Vol. 1: Spatial patterns and statistical distributions. p. 357-377. G. P. Patil, E. C. Pielou, W. E. Waters, eds. Penn. State Univ. Press, University Park, Penn.

Table 3.--Mean-mean crowding regression parameters for SPB trap catch

$$\hat{MC} = \alpha + \beta M$$

α	β	r^2	$S_{y \cdot x}$	S_β	n	$\bar{X}$	$\bar{Y}$
2.60	5.11	0.72	13.40	0.43	57	3.65	21.27

APPENDIX 1

The validity of the Iwao and Kuno (1971) approach to measurement of dispersion as a species characteristic was examined by Coster and Johnson (1979). The data base consisted of flight trap monitoring of three intermediate-sized infestations in southeast Texas, conducted by R. J. Reeve (1975). In all, 57 trapping days (20, 20, 17) from 30 trap grids (5 × 6, centered on the active front, with long axis in the direction of spread) were included in the data base. Daily M-MC pairs were calculated (formulae 1 and 2) and a simple linear regression of MC on M performed. Results are presented in table 3. The r^2 value (0.72) indicates a reasonable fit for the regression model, $\hat{MC} = 2.60 + 5.11\ M$, shown graphically in figure 5 with the 95 percent CL and 95 percent PL included. Since the 95 percent CL at M = 0 includes MC = 0, α does not deviate significantly from zero, and the individual is the basic unit of population dispersion. Therefore, β = IP, and daily IP values may be used for describing dispersion under the existing environmental regime.

In addition to the development of the simple linear regression of MC on M, an ANCOVA in a regression format (using dummy variables) was run to test for infestation × mean interaction--i.e., did β in the M-MC regression differ significantly between the three infestations. The analysis indicated no significant infestation × mean interaction or infestation main effect (i.e., displacement of α). Therefore, the M-MC regression as presented in table 3 and figure 5 serves to characterize normal SPB dispersion over the range of mean values (0 to 10) represented in the data base. Comparison of daily M-MC pairs from behavioral chemical treatments could be made, provided the trap design used in the data base is used in the treatment tests.

Assume, for example, that we are testing the efficacy of a behavioral chemicals treatment in a small-sized infestation using traps of the Reeve (1975) design in a 3 × 3 grid properly adjusted to the infestation. The stepwise procedure for evaluating the effect of the treatment on dispersal for a specific day's catch would be

SPB	Catch/Trap	
0	0	5
5	16	3
0	9	2

1. Compute $MC = \dfrac{\sum_{i=1}^{n} X_i\ (X_i - 1)}{\sum_{i=1}^{n} X_i}$:

$$MC = \frac{(0)(-1) + (0)(-1) + \ldots + (9)(8) + (2)(1)}{0 + 0 + \ldots + 9 + 2}$$

$$MC = \frac{360}{40} = 9.00$$

2. Compute $M = \dfrac{\sum_{i=1}^{n} X_i}{n}$:

$$M = \frac{0 + 0 \ldots + 9 + 2}{9} = \frac{40}{9} = 4.44$$

3. Compare the M-MC pair (4.44, 9.00) to the 95 percent PL in figure 5. Since the M-MC pair falls within the 95 percent PL in figure 5, we conclude that our treatment has had no significant effect on dispersion (P > 0.05).

4. Use IP to describe dispersion on this specific day:

$$IP = \frac{MC}{M} = \frac{9}{4.44} = 2.03,$$

which represents a mildly aggregated population.

EVALUATING SUPPRESSION TACTICS FOR *DENDROCTONUS FRONTALIS* IN INFESTATIONS[1]

Robert N. Coulson, Richard M. Feldman, W. Scott Fargo,

P.J.H. Sharpe, Guy L. Curry, and Paul E. Pulley[2]

Abstract.--The task of evaluating treatment tactics directed to suppression of *Dendroctonus frontalis* in infestations includes three separate aspects of the problem: (1) development of a protocol for evaluating tactics, (2) use of the TAMBEETLE simulation model to test efficacy of treatments, and (3) definition of procedures necessary for conducting a field evaluation. Focus in the discussion is directed to the infestation level. Our six-step protocol for structuring evaluations at the infestation level includes use of population dynamics, impact, and utilization models, as well as actual field testing. The TAMBEETLE population dynamics model, which is described, is used to illustrate the utility of the modeling approach for evaluating treatment tactics. Three potential treatment tactics (a stand density manipulation, an increase in within-tree mortality, and an increase in between-tree mortality) are simulated and compared to a set of control simulations. Our logistical protocol, useful for structuring the activities involved in conducting a field experiment for testing treatment efficacy, considers sampling and estimation technology, procedures for collection of necessary data, and methods of summary and analysis of field-collected data.

INTRODUCTION

Evaluation of treatment tactics applied to suppress populations of *Dendroctonus frontalis* has proven to be a more complicated task than originally anticipated. We know now that development of reliable means of evaluating tactics is in itself a formidable research undertaking.

Scrutiny of the problem reveals that predicting treatment efficacy requires sophisticated understanding of insect-host population dynamics, a mechanism for evaluating simultaneous interaction of multiple variables, estimation procedures with defined precision and accuracy, and a procedure for measuring cost effectiveness. This theme is recurrent in practically every text dealing with pest management that has appeared during the last decade (e.g., National Academy of Sciences 1969, 1972, and 1975; Rabb and Guthrie 1972; Stark and Gittins 1973; Metcalf and Luckman 1975; and Apple and Smith 1976). The ESPBRAP and EPA-NSF-IPM research programs recognized these needs and supported research to find solutions for each problem. Those individuals involved in the resulting research activities developed a new appreciation for the complexity of the problem. Potential users, aware of the research findings, expressed pessimism about whether the advanced understanding and new technology could be applied operationally.

One of our charges as participants in the ESPBRAP is to transfer technology forward to the practitioner in State, Federal, and private sectors. Bearing this charge in mind, we initiated the present study with the following objectives: (1) to develop a protocol for evaluating efficacy of treatment applied to *D. frontalis* at the infestation level of organization, (2) to demonstrate the

---

[1] Texas Agricultural Experiment Station Paper No. TA14873.

[2] The authors are, respectively, Associate Professor, Dept. of Entomology; Assistant Professor, Dept. of Industrial Engineering, Biosystems Research Division; Graduate Research Assistant, Dept. of Entomology; Associate Professor, Dept. of Industrial Engineering, Biosystems Research Division; Associate Professor, Dept. of Industrial Engineering and Head, Biosystems Research Division; and Associate Research Engineer, Data Processing Center, Texas A&M University, College Station, Tex.

application of this protocol using the TAMBEETLE model of *D. frontalis* population dynamics, and (3) to outline procedures necessary for conducting a field experiment to validate the results of simulated treatments. This discussion will be developed in three phases, each dealing with one of the specific objectives.

A PROTOCOL FOR EVALUATING TREATMENT EFFICACY AT THE INFESTATION LEVEL OF ORGANIZATION

Rationale for the Infestation as a Target for Treatment Evaluation

Evaluation of the efficacy of a treatment applied to *D. frontalis* can be directed to several different levels of organizational complexity. These levels include (1) the individual beetle life stages, (2) populations of beetles in trees or sections of trees, (3) populations of beetles in infestations, and (4) populations of beetles in forests. Inferences regarding utility of treatment results obtained at one level of organization cannot necessarily be projected to the next higher level(s).

Final conclusions on the utility of any treatment tactic applied to *D. frontalis* are generally based on how much the treatment reduced tree mortality compared to what would have occurred in the absence of the treatment. Experimentally, it is difficult to separate treatment effects from the many other sources of variation associated with *D. frontalis* in infestations or forests. The problem of beetle-induced tree mortality is a function of the distribution and abundance of both *trees* and *beetles* through space and time. Therefore, in evaluating efficacy of a treatment, emphasis should be placed on the level of organizational structure where the insect and host interact dynamically. This dynamic interaction occurs first at the infestation level and is promulgated to the next higher level, the forest.

Recent research on population dynamics of *D. frontalis* at the infestation level has revealed several different survival strategies that do not operate at lower levels of organization. These strategies include (1) density-dependent egg population regulation (Coulson et al. 1976a), (2) reemergence of parent adults (Coulson et al. 1978, and Cooper and Stephen 1978), (3) blending of emerged brood adults and reemerged parent adults to form the attacking adult population (Coulson et al. 1979), and (4) incremental allocation of both emerged and reemerged adults (Fargo et al. 1978). A detailed discussion of population structure of *D. frontalis* operating at the various levels of organizational complexity (tree, infestation, and forest) is provided by Coulson (1979).

Survival mechanisms have evolved through time and enhance the perpetuation of the insect in the presence of many biotic and abiotic mortality agents. Treatment tactics can be viewed simply as another mortality agent. To be effective, a tactic must disrupt the sophisticated survival mechanisms of the beetle that have evolved to prevent this event. This disruption can be measured only at the infestation or higher level of organization.

Evaluation at the dynamic level of insect-host interaction, i.e., the infestation, should provide the data needed to identify how, when, and where a treatment is effective (or ineffective). Focus on the individual infestation does not preclude simultaneous evaluation of multiple infestations in an area.

A Stepwise Protocol for Evaluating Treatment Tactics

As indicated previously, evaluation of treatment tactics is a complicated undertaking and requires use of certain advanced technologies. These include mathematical models dealing with insect-host population dynamics, impact, and perhaps forest utilization; and quantitative estimation procedures for within-tree and within-infestation populations.

A population dynamics model is useful for testing hypotheses or developing new hypotheses regarding the utility (or disutility) of actual or potential treatments. In the following discussion we will use the TAMBEETLE population dynamics model, developed at Texas A&M University, to illustrate how treatments can be evaluated.

Impact and utilization models are useful in evaluating cost effectiveness in light of multiple forest use patterns. As our main focus in this paper is to present a rather pragmatic approach to evaluating the entomological components of treatment tactics, we will not include a discussion of impact. Suffice it to say that no evaluation is complete without an analysis of cost effectiveness. Impact models are being developed by W. A. Leuschner at VPI&SU as part of the ESPBRAP.

Quantitative estimation procedures with defined accuracy and precision for within-tree and within-infestation populations of *D. frontalis* have been extensively researched (Pulley et al. 1976 and 1977a, b, & c; Foltz et al. 1977; Coulson et al. 1976b; Hain et al. 1978; and Stephen and Taha 1976). Several different sampling options are available. Generally as the requirement for precision increases, so does the cost of sampling. However, available sampling procedures permit quantitative estimation of *D. frontalis* populations and, therefore, effects of treatments applied to populations.

With the mathematical models and sampling and estimation tools, we are now in a position to begin to evaluate potential efficacy of a treatment tactic. There are several separate steps involved in conducting an evaluation of a proposed treatment tactic.

Step 1: Consider and define the probable effects of the proposed treatment in light of contemporary knowledge of population dynamics of *D. frontalis* and the host species. This definition of probable effects can be subjective. The goal is to define in detail specifically what the tactic is supposed to accomplish and how it will be administered. The final consideration in this first phase is cost, i.e., can the proposed treatment be economically applied. Again, this judgment can be subjective.

Step 2: If the proposed tactic appears to be useful, based on judgments made at the first step, simulate *D. frontalis* infestations in both the presence and absence of the treatment, using the TAMBEETLE population dynamics model. Variables such as initial infestation size, stand density, and weather can be manipulated to test the treatment under a variety of different conditions. Analysis of the results of the simulations should indicate the conditions where the treatment is effective or ineffective.

Step 3: If the tactic still appears to be useful after Step 2, initiate a cost-benefit analysis using the economic impact and utilization models. Again, a variety of conditions can be tested. The results should be analyzed in the same depth and breadth as in Step 2.

Step 4: If the tactic is still judged to be promising, any unsubstantiated hypothesis regarding the mode of action of the tactic should be verified experimentally. For example, if the treatment is proposed to reduce within-tree survival of brood life stages, this assumption should be tested.

Step 5: If the outcome of the experiments conducted in Step 4 substantiates the proposed mode of action, measure efficacy at the infestation level of organization using quantitative estimation procedures. This step is by far the most complicated and expensive.

Step 6: Reevaluate cost-benefit in light of experimental results obtained in Step 5.

This protocol should be suitable for evaluating any tactic directed to *D. frontalis*. At any step it is possible to stop and return to a previous step for reevaluation. The protocol should provide thorough evaluation of promising procedures using existing knowledge and technology as a standard for judging potential utility. The most expensive step in the evaluation, field testing, will be reserved for only those tactics with a high likelihood of success.

Before any treatment can be implemented, safety and environmental impact must also be evaluated. Discussion of these topics is beyond the scope of this paper. There are Federal- and State-mandated standards for both evaluations.

APPLICATION OF THE TAMBEETLE MODEL OF *D. FRONTALIS* POPULATION DYNAMICS TO EVALUATE TREATMENT EFFICACY

Rationale for the Modeling Approach

A mathematical model of population dynamics can be viewed as a catalog of the best available quantitative statements about a population system. There are two major types of mathematical models for biological systems--statistical regression models and biophysical mechanistic models. Often a combination of the two approaches is used in developing a model, although most models can be classified as either predominantly statistical or biophysical. Before evaluating treatment tactics with a particular model, it is extremely beneficial for the user to be aware of which modeling approach was taken during the model's development.

The statistical approach provides one of the best ways of summarizing data collected under changing conditions subject to random variation. Analysis of data via regression highlights the important variables contributing to the system dynamics. However, such a model cannot be used for conditions other than those in which the original data were collected. Therefore, one must be very careful that the treatment tactic under consideration does not depend on those sections of the model that rely on the statistical approach.

The biophysical approach, on the other hand, requires a search for mechanisms which could possibly account for what is observed. This modeling approach mathematically describes individual scientific hypotheses and then integrates them into an overall system model. Thus, such a model allows for the prediction of a response outside the range for which the original data were collected. It is therefore possible to estimate effectiveness of a suggested treatment via the model where only limited data are available.

A mechanistic model need not be fully validated before it can provide reasonable estimates of likely treatment outcomes. In a partially validated state, a mechanistic model can show trends and suggest usefulness of certain approaches. As the degree of component validation improves, so does confidence in the predicted outcome.

The TAMBEETLE model is an example of a biophysical mechanistic model. The purpose of the model is to predict population dynamics of *D. frontalis* in an established infestation. This model is being developed by the Biosystems Research Division of the Department of Industrial Engineering at Texas A&M University, from a blend of new experimentation on population dynamics of *D. frontalis*, published literature, and existing data files. The TAMBEETLE model is based on an assembled set of scientific hypotheses formulated from the three data sources. Statistical modeling techniques were used to validate the underlying hypotheses included in the larger model. This process of statistical testing of biological hypotheses is continuing within our program. As confidence in these hypotheses is developed, they are formulated mathematically into the infestation dynamics model.

Model development has not been completed, and our objective here is to illustrate the utility of the modeling approach rather than demonstrate an accurate predictor.

The modeling component of a treatment evaluation is useful for several reasons. First, it is possible to estimate the effectiveness of a proposed tactic without the large financial investment required for field evaluation. After consideration of a number of alternative tactics, only the most promising need be field tested. The simulated evaluations can be conducted under many different conditions, such as season of the year, varying stand density, infestation size, etc. This latitude of test conditions would be prohibitively expensive in a field evaluation. Furthermore, several tactics (a strategy) can be tested simultaneously. In a field test it would not be possible to separate the effects of the individual treatments. This first use is essentially a hypothesis-testing application. Second, it is possible to synthesize potential tactics and measure their efficacy. This use is a hypothesis-formulation application. Third, when counterintuitive results are obtained from simulated evaluations (either in the first or second application), which is often the case, it is possible to trace back and identify the cause(s). This type of analysis is not possible in field experiments.

There are essentially four general categories of treatments available for *D. frontalis:* (1) a treatment that directly decreases within-tree survival (e.g., an insecticide application); (2) a treatment that directly decreases between-tree survival (e.g., disruption of the colonization process through application of behavior-modifying chemicals); (3) a silvicultural treatment, which may affect both within- and between-tree survival (e.g., maintenance of a prescribed stand density that favors vigorous tree growth and wide spacing); and (4) a combination of the above treatments. The TAMBEETLE model can be used to test the effects of any or all of these potential tactics relative to the results that would be expected in the absence of the treatment(s).

TAMBEETLE Model Description

The purpose of the TAMBEETLE population dynamics model is to predict the future growth of an already established infestation. The basis of the model is a series of process submodels interconnected through mathematical techniques to account for reproduction and mortality of the beetles within the infestation. The model is organized around trees which are active, inactive, or potentially active.

Active trees are those that have been recently attacked and currently have developing brood resident. Inactive trees are those that have been previously attacked and both the reemergence and emergence processes have been completed. Potentially active trees are close to active trees and are situated in positions where a pheromone plume from attacking beetles could cause aggregation and thus attack. The model is set up to include both tree cohorts and beetle cohorts. *Tree cohorts* refers to all those trees that were initially attacked on the same day.

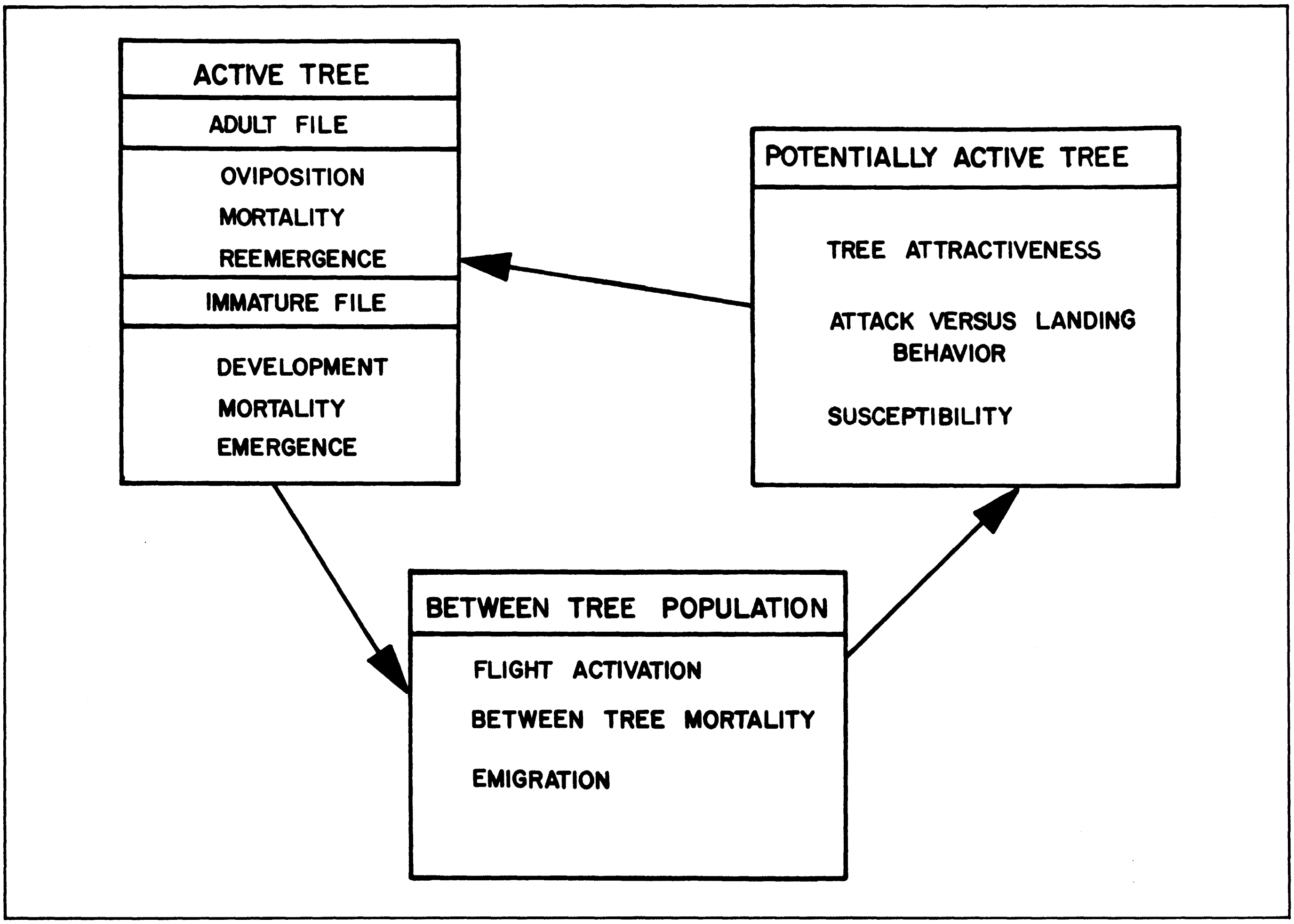


Figure 1.--Population growth sequence followed in the TAMBEETLE infestation dynamics model.

After successful attack, gallery construction is initiated and followed a few days later by oviposition. For computational ease, all eggs oviposited within all trees on a given day form an immature beetle cohort. Thus the model follows both the progress of the developing beetle cohorts and the infested tree cohorts. There will be more cohorts in winter than in spring, summer, or fall. This condition occurs because beetle development and colonization are prolonged at low temperatures.

Within-tree beetle processes of development, mortality, adult reemergence, and brood emergence are calculated using the techniques published by Sharpe and DeMichele (1977), Sharpe et al. (1977), and Curry et al. (1978a, 1978b). The applicability of these techniques to the *D. frontalis* infestations has been established by the laboratory and modeling studies of Gagne, Wagner, Sharpe, and Coulson (unpublished).

The development, reproductive, and mortality components of the model are temperature driven. Later versions of the model will include an additional moisture component. The model is set up on a daily increment basis. All temperature-dependent processes, including flight activation probability (White and Franklin 1976), are calculated at the start of each day. As development is completed, beetles emerge following an extended probability distribution whose shape is determined by the previous temperature history experienced by the brood during development (Sharpe et al. 1976, and Curry et al. 1978b).

Following emergence, beetles enter the between-tree population, which provides the nucleus for beetle attack in active trees and on the potentially active trees nearby. To enable the reader to visualize the overall organization of the model, figure 1 shows the cyclic nature of the progressive growth of population in an expanding infestation.

Potentially active trees are identified by their proximity to active trees and the extent to which a pheromone plume would render them an attractive target for landing. The radius of attractiveness of potentially active trees from active trees varies with the climatic conditions. An inversion type environment provides the largest radius, while a lapse condition provides the smallest (Fares et al., unpublished). Based upon the radius of attractiveness, beetles are allocated from the available source in the between-tree files, to potentially active trees. This allocation refers to landing only. The probability that a beetle successfully attacks an active tree after landing is a function of the degree of gallery construction already completed within the tree. The gallery construction factor acts to signal landing beetles that the tree is occupied or full. This factor is equivalent in function to an inhibitor for further attack.

Landing beetles that do not attack a particular tree are available to attack other potentially active trees. The mechanism by which potentially active trees become active is determined by a susceptibility factor. The susceptibility factor is a tree vigor parameter which refers to the number of beetles that must initially attack the tree and successfully establish galleries before the tree becomes an aggregator.

At the end of each day, all reemerging adults and emerging brood are combined for possible allocation at the start of the next day. Synchrony is important in the model. If a large number of between-tree beetles accumulate within the model but no active trees develop, the beetle population will disperse, causing retardation of the infestation. Factors limiting the development of new active trees include low susceptibility of new trees, wide tree spacing, and weather conditions that do not favor pheromone communication and/or flight activation.

To use the model, it is necessary to begin with an initial population. To start the model, an interactive question and answer routine is available for the user to input current information. This initiation routine is set up to follow the sampling procedures outlined by Coulson et al. (1976b) and Foltz et al. (1977). Thus the model is immediately compatible with field data collected via the ESPBRAP.

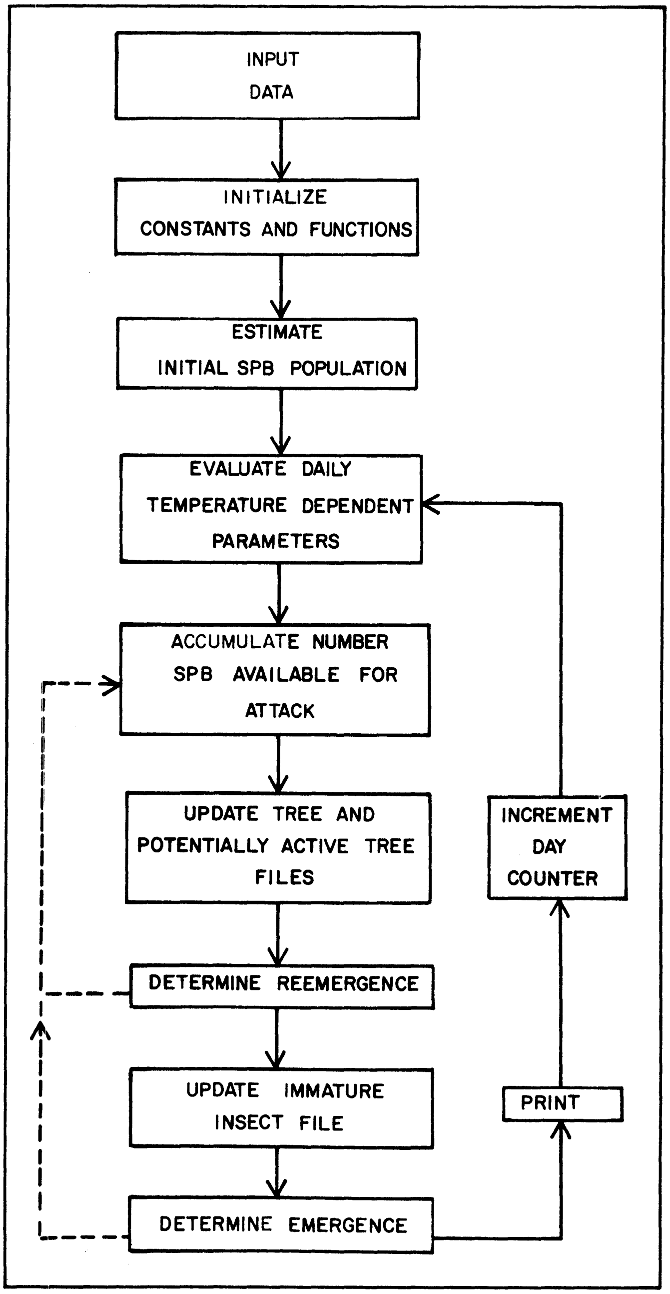


Figure 2.--Information flow chart for the TAMBEETLE infestation dynamics model.

Figure 2 outlines the flow logic for the model. The first three blocks refer to the initiation routine to get the model started. It then cycles through the next six boxes, updating weather-dependent parameters; accumulating beetles for possible allocation; attacking trees; determining oviposition, mortality, and reemergence; establishing immature cohorts; determining development, mortality, and emergence of brood. Having completed this cycle, it repeats the same cycle for the next day.

Design of the TAMBEETLE Modeling Experiment

The goal of the experiment was to use the TAMBEETLE model to test the efficacy of three potential treatments applied to existing infestations. These treatments consisted of (1) a silvicultural thinning, (2) a decrease in within-tree brood survival, and (3) a decrease in between-tree survival of reemerging and emerging adults. The general approach taken was to simulate a series of "control" infestations and then compare the results of perturbations created by the treatments applied under the same conditions. Infestation variables that were manipulated included initial infestation size (5, 10, and 20 trees), basal area classes (50, 100, and 150 ft^2/acre), and season of the year (late spring, midsummer, early fall). It should be remembered that the purpose of this experiment is to illustrate the use of the TAMBEETLE model for evaluating treatment tactics and that the model is still in the development stages.

Initial Infestation Conditions

For the purpose of this experiment we made certain assumptions regarding the initial infestation structure, within-tree population structure, and temperature regimes provided for infestation development. These assumptions are within the range normally observed in nature.

The simulations were conducted with homogenous-sized trees each infested to 12.5 m, d.b.h. 35.3 cm, and bark thickness at 2.0 m of 1.14 cm. Tree susceptibility was directly related to the tree's previous 5-year radial growth, which was varied inversely with the basal area of the stand, i.e., the higher the basal area of the stand, the higher the susceptibility of the host and the lower the radial growth. The three basal areas used in this study and the 5-year radial growth associated with each were as follows: 50 ft^2/acre--2.5 cm, 100 ft^2/acre--1.5 cm, and 150 ft^2/acre--1.0 cm.

At any one time, infestations of *D. frontalis* are generally comprised of a number of trees each represented by a predominant life stage. Accordingly we initialized each simulated infestation to represent an equal number of trees containing attacking adults (PAL), eggs (GAL), third- or fourth-instar larvae (LAL), pupae-callow adults (PUP), and brood adults (BAL). The actual number of trees in each group varied with the size of the initial simulated infestation in the following manner: one tree in each class for the 5-tree infestations, two trees each in the 10-tree infestations, and four trees each in the 20-tree infestations.

Table 1.--Life stage density used to initialize simulated infestations of *D. frontalis* (based on 113 trees sampled during 1972-74)

	Number in each lifestage/100 cm^2				
Group	Parent Adults (PAL)	Gallery Length[1] (GAL)	Larvae (LAL)	Pupae (PUP)	Brood Adults (BAL)
1	9	24	0	0	0
2	6	62	12	0	0
3	2	62	38	4	0
4	2	60	14	19	2
5	1	58	2	2	12

[1] Eggs = 1.59 × GL (Foltz et al. 1976)

We obtained the initial life-stage density in infested trees for each group from average results observed from 113 naturally infested trees sampled during 1972 to 1974 in east Texas. Table 1 lists the life-stage densities used.

Rate of infestation development has been observed to vary with season. Therefore, we varied temperature regimes for infestation simulations by utilizing observed field temperatures for those periods considered. The three starting dates were Julian dates 122, 180, and 240, corresponding to May 2, June 29, and August 28, 1976, respectively.

Measures of Treatment Effectiveness

Experiments involving the use of a simulation model generate a tremendous quantity of data. Simulation experiments require the same care in the selection of variables to measure and in the interpretation of data collected as field studies do. In selecting measures of treatment effectiveness, we have focused on several indices that appear useful in characterizing infestation development. These indices have not been selected arbitrarily but are based on research on population dynamics of *D. frontalis* conducted at the infestation level of organization.

The measures of effectiveness used in interpreting the results of the simulations include the following:

TREES--the total number of trees killed in the simulation (includes initial trees)

HOT TREES--trees that were still attractive to attacking adults at the end of the trial

REEM--reemerging parent adults

EMER--emerging brood adults

ALLOC--REEM + EMER

ATK--attacking adults

WTS--average within-tree survival of brood over the simulation

BTSE--average between-tree survival of emerging brood adults over the simulation

BTSR--average between-tree survival of reemerging adults over the simulation

S/D--average supply (ALLOC) of beetles per day available for colonization over the simulation

D/D--average demand of beetles per day available for colonization over the simulation

SPOT RATIO--supply divided by demand

NEW TREES/DAY--average trees attacked per day over the simulation

Other abbreviations used to describe the results of the simulations include

SPB--southern pine beetle, *Dendroctonus frontalis*

SPOT SIZE--the initial infestation size

BA--basal area (ft^2/acre)

JD--beginning Julian date on temperature file

The indices of effectiveness are presented in two ways, either as a summary for the total period of simulation or as daily observations. The summary statistics are most useful in judging the ultimate effectiveness, whereas the daily observations often provide the explanation for why a result occurred (or did not occur).

Results of the Simulation Experiment

Control Simulations

Before the treatments were undertaken, we ran a group of 17 "control" simulations. These simulations were conducted in order to assess the sensitivity of the model to initial infestation size, stand density, and temperature conditions. The control simulations were structured in a 3^3 factorial design combining the three levels of initial infestation size (5, 10, and 20 trees), the three stand densities (50, 100, and 150 ft^2/acre), and the three temperature regimes (JD 122, 180, and 240) (table 2). Columns 1-3 of table 3 contain the various combinations of these three parameters. One observation was made per cell because there is no stochasticity in the model and multiple trials would be identical. Each simulation was run for 56 days.

Table 2.--Outline of conditions for the control and treatment simulations conducted

Basal Area[1]	Temp. Cond.[2]	Initial Spot Size[3]		
		5	10	20
50	122	C	C	C T W B[4]
	180	C	C	C
	240	C	C	C
100	122	C	C	C T W B
	180	C	C	C
	240	C	C	C
150	122	C	C	C T W B
	180	C	C	C
	240	C	C	C

[1] Basal Area = ft^2/acre.
[2] Temperature conditions indicate Julian date the infestation was initiated.
[3] Spot size is the number of trees initially occurring in the infestation.
[4] C = Control, T = Thinning, W = Within-tree TRT, B = Between-tree TRT.

The summary results of the control simulations are presented in columns 4-13 in table 3 for the various measures of treatment effectiveness: TREES, HOT TREES, etc. The control simulations showed that within any initial infestation size and stand density, the model was rather insensitive to changes in the starting point on the temperature file. At the present time, this occurrence was expected as the poikilotherm development, tree drying, and pheromone communication submodels have not been fully implemented. The pattern evident in the number of trees killed (TREES) was that the infestations grew larger when initiated in the spring and fall and were depressed in size when initiated in midsummer. Therefore, while the model seemed to correctly identify the pattern of expected final infestation size, the amplitude of the differences may be somewhat conservative. Initial infestation size and stand density had the most obvious effects on the final number of trees killed (table 3). These results were expected.

The daily pattern of the beetle-related variables will be discussed below and compared with the results observed in the treatments.

Table 3.--Final results of control simulations of D. frontalis infestation growth over a 56-day period. Simulations were conducted on three initial infestation sizes (5, 10, and 20 trees), three basal area classes (50, 100, and 150 ft^2/acre), and three temperature regimes (beginning Julian date 122, 180, and 240). See text for explanation of measures of infestation growth.

Spot Size	BA	JD	Trees	Hot trees	Reem SPB	Emer SPB	WTS	BTSE	BTSR	S/D	D/D	Ratio	New trees per day
5	50	122	5.00	.00	.0	185.5	.1049	.0309	.0386	1137.0	68.4	16.6350	.0000
5	50	180	5.00	.00	1.4	.0	.0859	.0665	.0831	707.5	95.7	7.3914	.0000
5	50	240	5.00	.00	.0	59.5	.0958	.0410	.0512	770.3	86.3	8.9215	.0000
5	100	122	22.61	6.06	797.7	1451.5	.1027	.3315	.4144	1829.3	670.1	2.7297	.3144
5	100	180	21.85	8.51	775.8	729.7	.0859	.3378	.4223	1371.6	577.2	2.3764	.3009
5	100	240	20.02	5.58	517.5	1207.5	.0959	.3211	.4014	1434.3	533.1	2.6907	.2682
5	150	122	31.16	14.64	844.6	1575.0	.1027	.3437	.4296	1831.3	696.5	2.6294	.4671
5	150	180	27.75	13.16	805.9	813.8	.0859	.3489	.4362	1423.4	623.0	2.2849	.4062
5	150	240	27.24	10.28	631.5	1398.4	.0959	.3328	.4160	1497.6	594.9	2.5175	.3972
10	50	122	27.01	2.00	2313.4	1657.0	.1027	.3783	.4729	3943.0	1670.1	2.3610	.3038
10	50	180	21.01	3.00	1435.0	605.7	.0859	.3604	.4504	2667.7	1103.3	2.4179	.1966
10	50	240	25.01	1.00	1717.4	1618.1	.0959	.3684	.4605	3327.5	1427.0	2.3319	.2681
10	100	122	45.59	9.37	2346.6	3220.3	.1027	.3731	.4664	4031.4	1647.5	2.4470	.6356
10	100	180	44.04	5.97	2103.0	1691.6	.0859	.3769	.4712	3044.9	1339.2	2.2737	.6078
10	100	240	39.85	5.99	2015.7	2792.2	.0959	.3733	.4667	3488.8	1507.7	2.3140	.5330
10	150	122	56.77	7.75	2383.9	3438.7	.1027	.3746	.4682	3995.9	1630.6	2.4506	.8351
10	150	180	51.09	5.94	1879.2	1745.3	.0859	.3744	.4680	2981.7	1318.8	2.2609	.7338
10	150	240	50.50	10.88	1654.2	3026.8	.0959	.3727	.4659	3341.8	1425.5	2.3443	.7232
20	50	122	60.38	3.16	7680.6	4132.5	.1027	.3934	.4917	9367.2	4125.2	2.2707	.7211
20	50	180	48.97	4.00	4725.9	1641.7	.0859	.3851	.4814	5933.2	2608.7	2.2744	.5174
20	50	240	51.16	2.92	3912.9	3262.6	.0959	.3876	.4844	6748.4	3021.7	2.2333	.5565
20	100	122	91.79	9.11	6507.8	6690.2	.1027	.3902	.4878	8662.8	3734.3	2.3198	1.2820
20	100	180	84.13	10.00	4999.5	2556.0	.0859	.3902	.4878	6520.3	2928.5	2.2265	1.1453
20	100	240	87.34	4.91	5787.1	6277.0	.0959	.3925	.4906	8010.4	3620.9	2.2122	1.2025
20	150	122	121.76	14.73	7268.7	7404.6	.1027	.3935	.4918	9662.1	4313.8	2.2398	1.8172
20	150	180	106.53	13.67	5259.6	3607.1	.0859	.3917	.4897	6613.4	2983.1	2.2170	1.5453
20	150	240	102.96	6.25	4905.2	6057.9	.0959	.3919	.4899	7664.0	3545.6	2.1616	1.4815

Table 4.--Final results of thinning (A), within-tree (B), and between-tree treatment simulations on D. frontalis infestation growth over a 56-day period. Simulations were conducted on 20-tree infestations initiated on Julian date 122 in stands with basal area = 50, 100, or 150 ft^2/acre. See text for explanation of measures of infestation growth.

A. Final results of the thinning treatment (at 56 days).

BA	Trees	Hot trees	Reem SPB	Emer SPB	WTS	BTSE	BTSR	S/D	D/D	Spot ratio	New trees per day
50	60.38	3.16	7680.6	4132.5	.1027	.3934	.4917	9367.2	4125.2	2.2707	.7211
100	91.79	9.11	6507.8	6690.2	.1027	.3902	.4878	8662.8	3734.3	2.3198	1.2820
150	121.76	14.73	7268.7	7404.6	.1027	.3935	.4918	9662.1	4313.8	2.2398	1.8172

B. Final results of the within-tree treatment (at 56 days).

BA	Trees	Hot trees	Reem SPB	Emer SPB	WTS	BTSE	BTSR	S/D	D/D	Spot ratio	New trees per day
50	55.65	6.01	5193.2	1476.1	.0514	.3899	.4873	6612.7	2964.9	2.2303	.6366
100	79.09	16.96	4939.8	2626.2	.0514	.3889	.4861	6379.0	2817.2	2.2643	1.0551
150	99.35	6.74	4909.6	3060.2	.0514	.3918	.4897	6858.4	3103.1	2.2102	1.4169

C. Final results of the between-tree treatment (at 56 days).

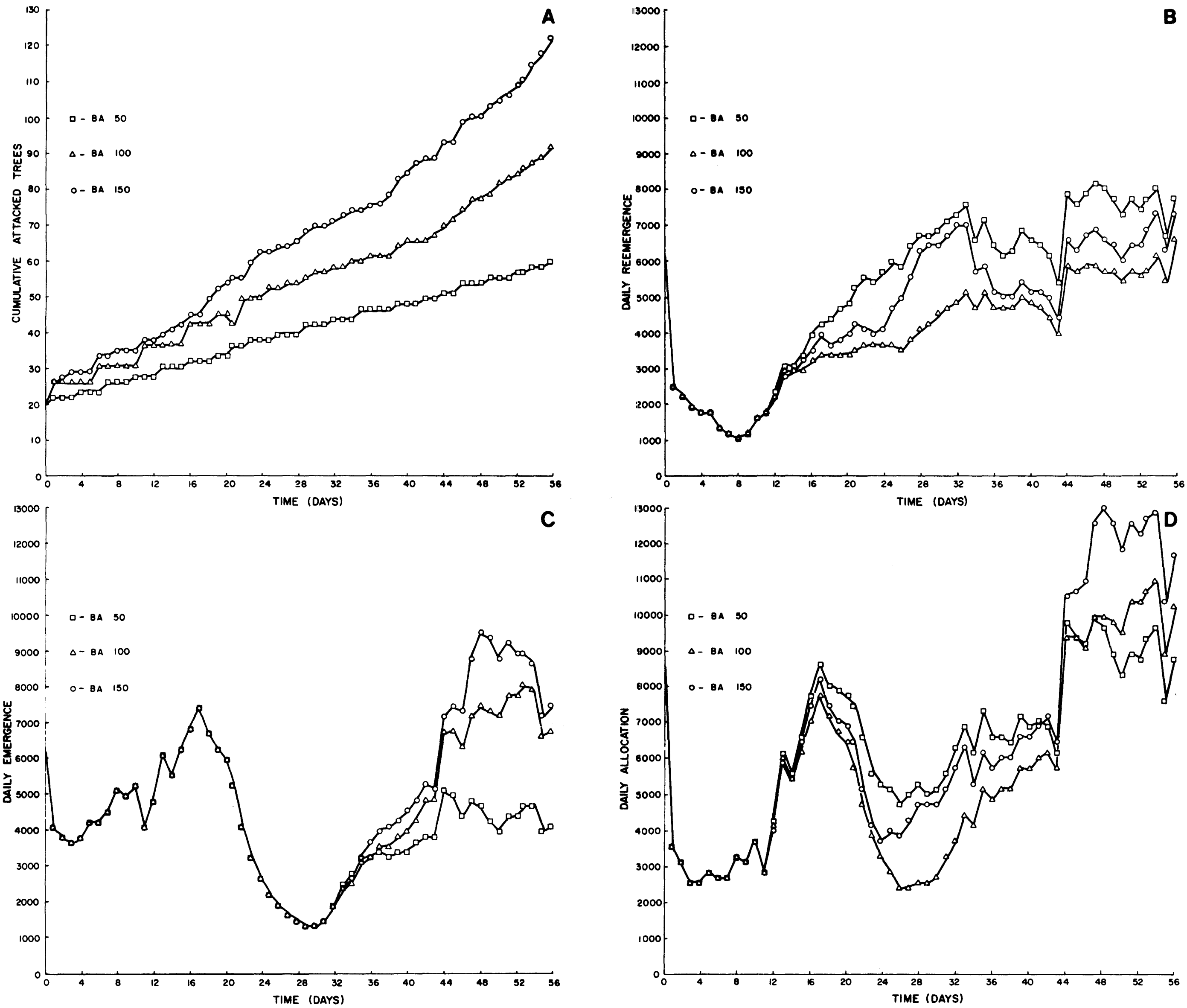
BA	Trees	Hot trees	Reem SPB	Emer SPB	WTS	BTSE	BTSR	S/D	D/D	Spot ratio	New trees per day
50	47.69	4.95	1831.3	2782.8	.1027	.1868	.2335	6248.6	1305.4	4.7867	.4945
100	49.23	5.37	1341.9	2766.7	.1027	.1806	.2257	5776.7	1162.8	4.9678	.5220
150	58.09	13.69	1201.8	3190.5	.1027	.1816	.2270	5807.9	1173.5	4.9490	.6801

The Thinning Experiment

We tested the effect of a potential thinning treatment on infestation development by changing stand density while holding all other variables constant. The starting points for the simulations were JD 122, and the initial infestation size was 10 trees (table 2). Each simulation was run for 56 days.

Results of the simulations are contained in table 3 and summarized in table 4A. Figure 3 (A-E) illustrates daily results for five selected variables. This figure demonstrates the patterns in the variables that are due to changes in stand density (BA).

The general trend was for beetle-induced tree mortality to increase with increasing stand density (fig. 3A). This pattern was established immediately and continued for the 56 days of simulation.



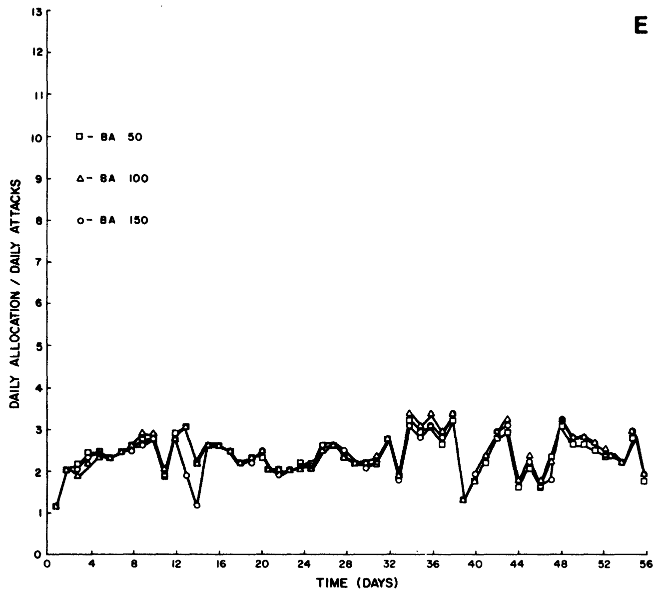


Figure 3.--Simulated results of a hypothetical thinning treatment applied to suppress within-infestation populations of *D. frontalis*. The treatment conditions consisted of a 20-tree infestation initiated on Julian date 122 in three stands of varying density (basal area 50, 100, and 150 ft^2/acre). Measures of treatment effectiveness include (A) cumulative attacked trees, (B) daily reemergence, (C) daily emergence, (D) daily allocation (= reemergence + emergence), and (E) daily allocation/daily attacks.

Table 5.--Comparison of final results of the control, within-tree treatment, and between-tree treatment simulation. Simulations were conducted on 20-tree infestations initiated on Julian date 122, in the basal area classes of 50 (A), 100 (B), and 150 (C) ft²/acre. See text for explanation of measures of infestation growth.

	Trees		Reem	Emer						Spot	New trees
	Number	Hot	SPB	SPB	WTS	BTSE	BTSR	S/D	D/D	ratio	per day
A. Basal area = 50 ft²/acre.											
Control	60.38	3.16	7680.6	4132.5	.1027	.3934	.4917	9367.2	4125.2	2.2707	.7211
Within-tree	55.65	6.01	5193.2	1476.1	.0514	.3899	.4874	6612.7	2964.9	2.2303	.6366
Between-tree	47.69	4.95	1831.3	2782.8	.1027	.1868	.2335	6248.6	1305.4	4.7867	.4945
B. Basal area = 100 ft²/acre.											
Control	91.79	9.11	6507.8	6690.2	.1027	.3902	.4878	8662.8	3734.3	2.3198	1.2820
Within-tree	79.09	16.96	4949.8	2626.2	.0514	.3889	.4861	6379.0	2817.2	2.2643	1.0551
Between-tree	49.23	5.37	1341.9	2766.7	.1027	.1806	.2257	5776.7	1162.8	4.9678	.5220
C. Basal area = 150 ft²/acre.											
Control	121.76	14.73	7268.7	7404.6	.1027	.3935	.4918	9662.1	4313.8	2.2398	1.8172
Within-tree	99.35	6.74	4909.6	3060.2	.0514	.3918	.4897	6858.4	3103.1	2.2102	1.4169
Between-tree	58.09	13.69	1201.8	3190.5	.1027	.1816	.2270	5807.9	1173.5	4.9490	.6801

Daily REM was the same for all three stand densities until about day 11. The pattern thereafter was for REM to be highest in the BA 50, lowest in the BA 100, and intermediate for the BA 150 infestation (fig. 3B).

Daily EM in the three infestations remained the same until day 32. From this point EM increased progressively in the BA 50 to 100 to 150 infestations (fig. 3C).

Daily ALLOC (= sum of daily REM + EM) remained approximately the same through about day 15 (fig. 3D). From this point until about day 40 there were more beetles available in the BA 50 infestation than either of the other two. By day 49, however, the trend was for beetle availability to increase with increasing stand density. We expect this final trend to become more pronounced in longer simulations.

ALLOC/ATK is a ratio that represents the number of adults available in the infestation divided by the number of observed attacks. This ratio is a measure of potential infestation growth. A low ratio indicates low between-tree mortality. If the ratio were exactly 1.0, all adults leaving trees would be attacking new trees. Obviously, if the ratio is high, more adults are dying or emigrating from the infestation. For the three stand densities examined, the curves track very closely (fig. 3E). Intuitively one would expect greater between-tree mortality in the less dense stands, but this trend was not evident for the tree stand densities investigated.

Within- and Between-Tree Treatments

Two additional sets of simulations were conducted to test efficacy of treatments aimed at increasing within-tree and between-tree mortality. Most suppression projects in the past have attempted to exploit one or the other of these tactics.

The approach taken for the within-tree treatment was to reduce brood survival from about 10 percent, used for the control and thinning simulations, to about 5 percent. Simulations were conducted on stands with BA 50, 100, and 150 ft²/acre. The initial infestation size was 20 trees and the starting date on the temperature file was 122 (table 2). Each simulation was allowed to run 56 days. Table 4B presents summary results.

The approach taken for the between-tree treatment was to reduce between-tree survival of reemerging and emerging adults relative to the control simulations. Reemerging adult survival was reduced from 40 percent to 20 percent, and emerging adult survival reduced from 50 percent to 25 percent. Again, simulations were conducted on stands with BA 50, 100, and 150 ft²/acre. The initial infestation size was 20 trees and the starting date on the temperature file was 122 (table 2). The simulations were run for 56 days. Table 4C provides summary results.

In order to simplify comparisons between treatments, we grouped the final results of the simulations by stand density (table 5). In table 5, the first line in each group corresponds to a control infestation, the second line to a within-tree treatment, and the third line to a between-tree treatment. Table 5A represents the BA 50 stand, 5B the BA 100 stand, and 5C the BA 150 stand. Perusal of table 5 reveals that the within-tree treatment was consistently less effective than the between-tree treatment. However, both treatments effectively reduced tree mortality relative to the control. The within-tree treatment decreased final infestation size by an average of about 14 percent, while the between-tree treatment reduced the final size by about 40 percent.

Daily results for selected variables are illustrated in figure 4 (A-E) for the two treatments and the control simulations. Unique patterns in the variable result from the two treatments.

Total attacked trees are decreased slightly by the within-tree treatment throughout the course of simulation. The between-tree treatment was much more effective (fig. 4A). It would be instructive to increase the length of simulation time for the between-tree treatment, as it appears that there is a reasonable likelihood that the infestation would become inactive.

Daily REM (fig. 4B) was similar in the two treatments and control through about day 12. After some oscillation, a pattern appeared where less daily reemergence occurred in the within-tree treatment than either the between-tree treatment or control. Again, given sufficient time it is doubtful that the infestation could continue to enlarge without reemerging adults.

In the simulations of EMER (fig. 4C) the control and within-tree treatment tracked together through about day 31. EMER in the between-tree treatment was slightly lower. After day 31, EMER tailed off dramatically in both treatments relative to the control.

The trend for ALLOC (fig. 4D) followed that observed for REM and EMER. Toward the end of the simulations a dramatic reduction in the number of adults took place in both treatments. The between-tree treatment was much more effective in reducing *D. frontalis* populations in the infestations.

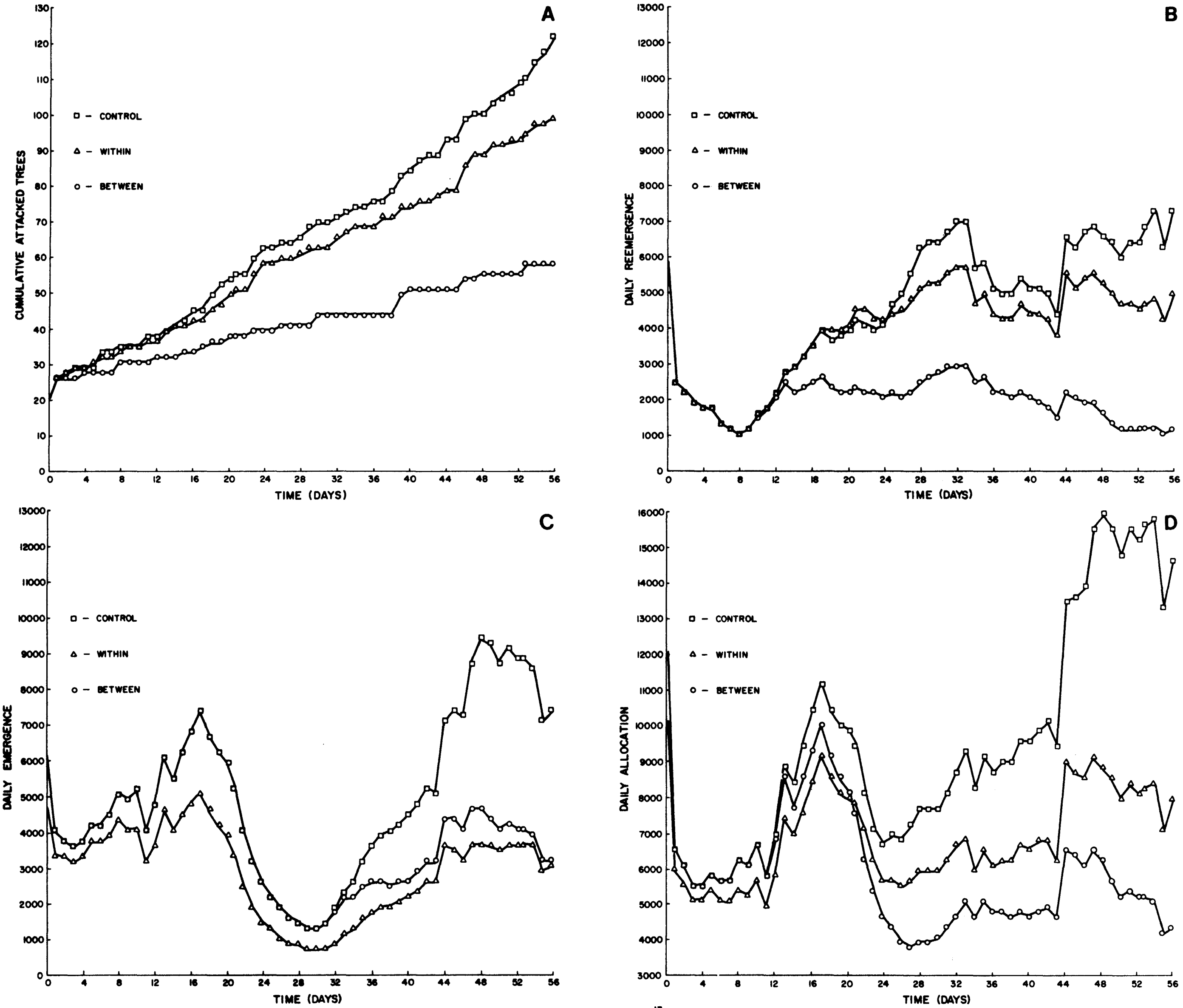
The ratio ALLOC/ATK (fig. 4E) illustrated the similarity that existed between the control and within-tree treatment and the obvious difference for the between-tree treatment. The high ratio was attributable to the increased between-tree mortality. More colonizing adults died before attack. This mortality produced an increase in the numerator and a decrease in the denominator of the ratio, which results in an increased magnitude in the measure.

Conclusions from the Simulation Experiment

We can draw several noteworthy conclusions from the simulation experiments. First, an infestation-level simulation model is a powerful tool available for evaluating treatment tactics economically. Although the TAMBEETLE model is still in the developmental stages, the results presented follow generally expected results. Second, use of the simulation model approach should enhance our ability to make judicious decisions regarding the potential utility of various treatment tactics. Third, we have not attempted any more than a graphic analysis of tabulated data in this paper. The reason for this approach is that understanding of population dynamics at the infestation level, which is the heart of the problem of evaluating simulated results, is just beginning to solidify as a result of ESPBRAP-funded research. Therefore, the utility and limitations of the simulation modeling approach have not been scrutinized to any depth. Fourth, we have not made a judgment on whether or not the simulated treatments worked. The model illustrated differences between treatments and controls, but the simulations were terminated after 56 days. We did not consider the corollary question in evaluating effectiveness, namely how long does it take for the treatment to produce a desired result. The simulation model can be used to answer this question as well.

FIELD AND LABORATORY PROCEDURES FOR EVALUATING TREATMENTS

Once a decision has been made that a proposed treatment appears useful, based on the simulation study and impact assessment, the next step is field evaluation. The goal of the field evaluation is to quantitatively measure efficacy of the treatment at the infestation (dynamic) level of organization. Field evaluations are logistically complicated and expensive to conduct. Therefore, careful planning and execution are required.



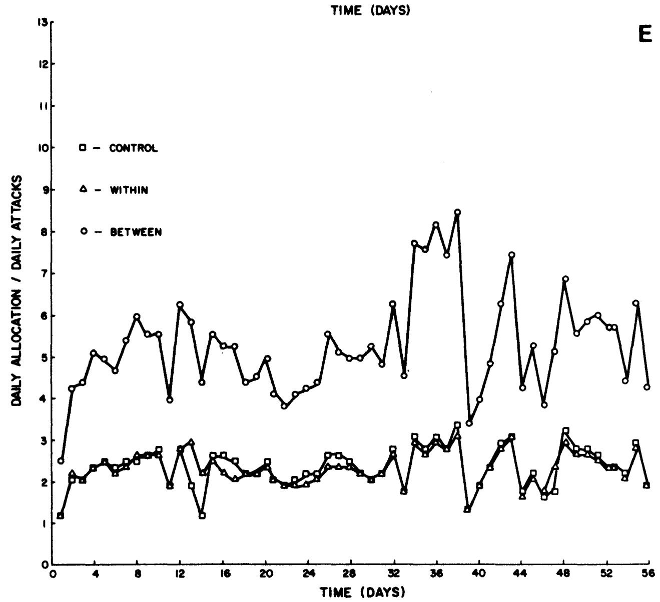


Figure 4.--Simulated results of two hypothetical treatments applied to suppress within-tree and between-tree populations of *D. frontalis*. The treatment condition consisted of a 20-tree infestation initiated on Julian date 122 in a stand with basal area = 150 ft^2/acre. Measures of treatment effectiveness include (A) cumulative attacked trees, (B) daily reemergence, (C) daily emergence, (D) daily allocation (= reemergence + emergence), and (E) daily allocation/daily attacks.

Research on *D. frontalis* at the infestation level has provided a general procedural protocol suitable for obtaining quantitative measurements of population dynamics. These procedures are directly applicable for evaluating treatment tactics. Our objective in this section is to outline general procedural requirements for conducting a field evaluation.

Fundamental Information Needed for an Evaluation

Measurement of changes in the distribution and abundance of *D. frontalis* at the infestation level requires (1) knowledge of the basic within-tree population unit, (2) quantitative sampling technology, and (3) a procedural protocol for organization and collection of data.

The processes comprising the basic population system for *D. frontalis* [attack (ATK), egg gallery construction (GAL), reemergence (REM), survivorship (SUR), and emergence (EMER)] have been described quantitatively in detail by Coulson et al. (1977, 1978, and 1979) and Fargo et al. (1978). The TAMBEETLE model is structured around these basic processes.

Quantitative estimation procedures, suitable for a variety of different sampling objectives, have been developed for within-tree (Pulley et al. 1977, Coulson et al. 1976b) and within-infestation (Pulley et al. 1977b, Foltz et al. 1977) populations of *D. frontalis*. One of the most useful and versatile of the estimation procedures, the TG-PDF technique, utilizes the tree geometry model developed by Foltz et al. (1976) to estimate tree surface area, and the probability (proportional) density functions described by Mayyasi et al. (1976) to estimate beetle density. The TG-PDF procedure is applicable for estimating within-tree populations of attacking adults, eggs, reemerged adults, larvae, pupae, and emerged adults. Estimates of these life stages on consecutively attacked trees in infestations are suitable for characterizing the basic processes of the population system.

Developing a procedural protocol for organizing and collecting data has received much less attention than defining the basic population unit and developing estimation procedures. In a complicated field research study or evaluation project involving measurement of population dynamics of *D. frontalis*, success or failure in achieving Program goals is primarily a function of (1) coordinating logistics of data collection and processing, (2) coordinating personnel involved in the project, and (3) insuring quality control.

With an understanding of the basic elements of the population system, quantitative sampling procedures, and a logistical protocol, we are in a position to measure population dynamics. The actual procedure that will be followed includes these steps:

(1) Obtain point estimates of attacking adults, gallery length, reemerged adults, larvae, pupae, and emerged adults on all trees throughout the development of the infestation.

(2) Organize and distribute these estimates to reflect the processes of ATK, GL, REM, SUR, and EMER for each tree in the infestation.

(3) Sum each process occurring on all trees through time.

This final step provides a continuous record of the total beetles involved in each process throughout the course of infestation development. This record is equivalent in structure to the output reported for the TAMBEETLE simulations.

Population Sampling

Methods and procedures for field collecting and laboratory processing of data on populations of *D. frontalis* have been described by Coulson et al. (1975) and McClelland et al. (1978). Generally there are three types of data needed: measurements of host tree physical characteristics, measurement of within-tree beetle life stages, and measurements of reemergence and emergence. Specific details for collecting this information are contained in the references and will not be discussed here. Rather, we will focus on a scheduling routine that permits collection of data on the life stages. This schedule is designed to be used with the TG-PDF sampling procedure (Coulson et al. 1976b, and Foltz et al. 1976a).

Scheduling and Timing of Sampling

The general sampling sequence for each tree includes timing and coordination of several activities. The first step is to identify attacked trees in the infestation. This identification can be made by inspecting for pitch tubes at midbole and boring frass on leaves of understory vegetation. The date of initial colonization should be recorded.

About 4 to 7 days after initial attack, four standard emergence traps (McClelland et al. 1978) are installed at 3.5 and 6.5 m. These traps are subsequently monitored at routine intervals for the accumulation parent adults. Monitoring at 2- or 3-day intervals is frequent enough for checking the traps when alcohol is used as a preservative.

When the developing brood within the trees migrate into the outer bark (fourth-instar larvae, Goldman and Franklin 1977), bark disk samples are extracted at 3.5 and 6.5 m (four 100-cm disks/level). The date of sampling should be recorded. Development and migration of larvae can be monitored by removing chips of bark at the time the traps are checked for reemergence, i.e., on a 2- or 3-day interval. Subsequent radiographs and/or dissections of the bark samples provide measurements of centimeters of gallery constructed, residual parent adult density, or larval density.

Traps are monitored on the same 2- or 3-day interval throughout the course of adult emergence. Generally there will be a brief period, at the end of reemergence and just prior to the beginning of emergence, when no beetles are accumulated in the traps. The dates for the beginning and ending of emergence should be recorded.

Using this scheduling routine it is possible to obtain population estimates of attack, gallery length, reemergence, larvae, and emergence. These estimates are suitable for use with the TG-PDF procedure. The various beetles' life stages are accumulated as follows: (1) attacking adult density = Σ reemergence plus the residual beetles in the bark disk samples, (2) gallery length = centimeters of gallery in the bark disk samples (eggs = 1.59 × gallery length--Foltz et al. 1976b), (3) reemergence = Σ reemergence into traps, (4) larval density = larvae in the disk samples, and (5) emergence = Σ emerging beetles in the traps.

Measurement of tree physical characteristics can be taken at any point in the sequence after colonization is completed. Generally these measurements are made most easily at the time of trap monitoring or disk sampling.

This sequencing procedure was developed to reduce judgment decisions concerning when to collect samples and to provide the basic information needed to measure populations with the least amount of sampling effort.

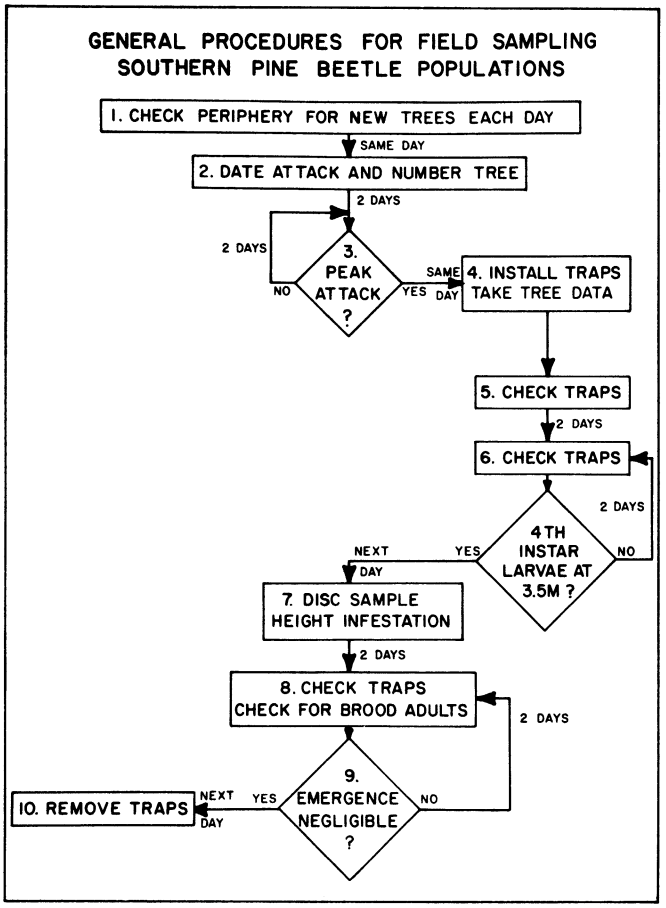


Figure 5.--Activity flow chart of the sequence of steps involved in field sampling within-tree populations of *D. frontalis*.

Figure 5 illustrates diagrammatically the general steps involved in the sampling sequence.

Laboratory Processing of Field Data

The goal of the laboratory phase of the field experimental program is to process bark disk samples, tree data, and records of reemergence-emergence counts. Each category of data is processed differently. The desired end product is a series of verified computer files of the original observations.

As with the field activities, procedures for laboratory processing of data have been described by Coulson et al. (1975). Figure 6 outlines the general sequence for processing field samples through the laboratory to the computer-readable stage. This sequence traces the flow of information and activity for the three types of data collected.

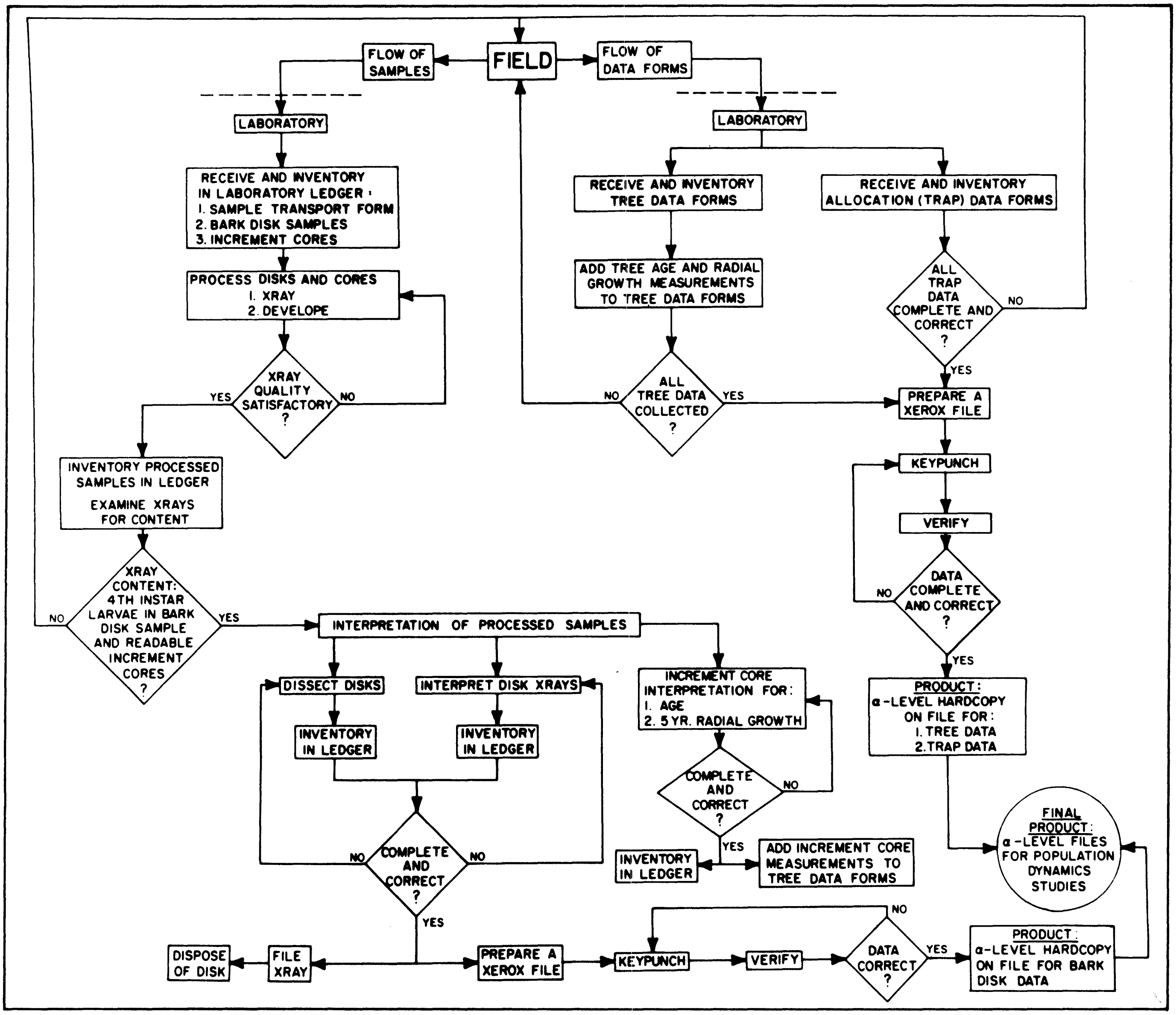


Figure 6.--Activity flow chart of the sequence of steps involved in processing field-collected *D. frontalis* population samples and host tree data through the laboratory.

General Analytical Sequence for Field Data

Once the data are machine-readable, the sequence of data summary is as follows: calculate within-tree populations using the TG-PDF procedure; distribute population estimates over the process timespan using the appropriate model for ATK, GAL (Fargo et al. 1978), SUR (Coulson et al. 1977), REM (Coulson et al. 1978), and EM (Coulson et al. 1979); and finally summarize over all trees in the infestation through time.

The daily estimates for the various beetle processes should provide data suitable for evaluating the effects of the treatment. The form of the data is equivalent to the TAMBEETLE model output.

We indicated at the onset of this paper that one of the charges faced by researchers was to make the technology available for evaluating tactics usable by the practitioner. This charge will clearly be met with the TAMBEETLE model. However, field evaluation of a treatment will likely always remain a research task. The computer software needed to summarize and analyze the results of field evaluations is in large part available. This software would be available to research groups in State, Federal, and private sectors.

LITERATURE CITED

Apple, J. D., and R. F. Smith, eds. 1976. Integrated pest management. 200 p. Plenum Press, New York.

Cooper, M. E., and F. M. Stephen. 1978. Parent adult reemergence in southern pine beetle populations. Environ. Entomol. 7:547-577.

Coulson, R. N. 1979. Population dynamics of bark beetles. Ann. Rev. Entomol. 24:417-447.

Coulson, R. N., F. P. Hain, J. L. Foltz, and A. M. Mayyasi. 1975. Techniques for sampling the dynamics of southern pine beetle populations. 18 p. Tex. Agric. Exp. Stn. Misc. Publ. 1185. College Station, Tex.

Coulson, R. N., A. M. Mayyasi, J. L. Foltz, F. P. Hain, and W. E. Martin. 1976a. Resource utilization by the southern pine beetle, *Dendroctonus frontalis* Zimm. Can. Entomol. 108: 353-362.

Coulson, R. N., P. E. Pulley, J. L. Foltz, and W. C. Martin. 1976b. Procedural guide for quantitatively sampling within-tree populations of *Dendroctonus frontalis*. 29 p. Tex. Agric. Exp. Stn. Misc. Publ. 1267. College Station, Tex.

Coulson, R. N., W. S. Fargo, P. E. Pulley, J. L. Foltz, D. N. Pope, J. V. Richerson, and T. L. Payne. 1978. Evaluation of the reemergence process of parent adult *Dendroctonus frontalis*. Can. Entomol. 110:475-486.

Coulson, R. N., W. S. Fargo, P. E. Pulley, D. N. Pope, J. L. Foltz, and A. M. Bunting. 1979. Spatial and temporal patterns of emergence for within-tree populations of *Dendroctonus frontalis*. Can. Entomol. [In press.]

Curry, G. L., R. M. Feldman, and P.J.H. Sharpe. 1978a. Foundations of stochastic development. J. Theor. Biol. 74:397-410.

Curry, G. L., R. M. Feldman, and K. C. Smith. 1978b. A stochastic model of a temperature-dependent population. Theor. Popul. Biol. 13: 197-213.

Fargo, W. S., R. N. Coulson, P. E. Pulley, and D. N. Pope. 1978. Numerical description of spatial and temporal components of within-tree colonization by *Dendroctonus frontalis*. Can. Entomol. 110:1213-1232.

Foltz, J. L., A. M: Mayyasi, P. E. Pulley, R. N. Coulson, and W. C. Martin. 1976a. Host-tree geometry models for use in southern pine beetle population studies. Environ. Entomol. 5:714-719.

Foltz, J. L., A. M. Mayyasi, F. P. Hain, R. N. Coulson, and W. C. Martin. 1976b. Egg-gallery length relationship and within-tree analyses for the southern pine beetle, *Dendroctonus frontalis* Zimm. (Coleoptera:Scolytidae). Can. Entomol. 108:341:352.

Foltz, J. L., P. E. Pulley, R. N. Coulson, and W. C. Martin. 1977. Procedural guide for estimating within-spot populations of *Dendroctonus frontalis*. 27 p. Tex. Agric. Exp. Stn. Misc. Publ. 1316. College Station, Tex.

Hain, F. P., W. T. McClelland, D. N. Pope, P. E. Pulley, J. L. Foltz, and R. N. Coulson. 1978. Standardized within-tree sampling for populations of *Dendroctonus frontalis*. Environ. Entomol. 7:157-164.

Mayyasi, A. M., P. E. Pulley, R. N. Coulson, D. W. DeMichele, and J. L. Foltz. 1976. Mathematical description of within-tree distributions of the various developmental stages of *Dendroctonus frontalis* Zimm. Res. Pop. Ecol. 18:135-145.

McClelland, W. T., F. P. Hain, C. J. DeMars, W. S. Fargo, R. N. Coulson, and T. E. Nebeker. 1978. Sampling bark beetle emergence: A review of methodologies, a proposal for standardization, and a new trap design. Bull. Entomol. Soc. Am. 24:137-140.

Metcalf, R. L., and W. H. Luckman. 1975. Introduction to pest management. 587 p. John Wiley and Sons, New York.

National Academy of Sciences. 1969. Insect pest management and control. Vol. 3. Principles of plant and animal pest control. 508 p. Natl. Acad. Sci., Washington, D. C.

National Academy of Sciences. 1972. Pest control strategies for the future. 376 p. Natl. Acad. Sci., Washington, D. C.

National Academy of Sciences. 1975. Pest control: An assessment of present and alternative technologies. Vol. 4. Forest pest control. 170 p. Natl. Acad. Sci., Washington, D. C.

Pulley, P. E., R. N. Coulson, J. L. Foltz, W. C. Martin, and C. L. Kelley. 1977. Sampling intensity, informational content of samples, and precision in estimating within-tree populations of *Dendroctonus frontalis*. Environ. Entomol. 6:607-615.

Pulley, P. E., J. L. Foltz, R. N. Coulson, W. C. Martin. 1977. Evaluation of procedures for estimating within-spot populations of attacking adult *Dendroctonus frontalis*. Can. Entomol. 109:1325-1334.

Pulley, P. E., J. L. Foltz, R. N. Coulson, A. M. Mayyasi, and W. C. Martin. 1977. Sampling procedures for within-tree attacking adult populations of the southern pine beetle, *Dendroctonus frontalis* Zimmerman. Can. Entomol. 109:39-48.

Rabb, R. L., and F. E. Guthrie, eds. 1972. Concepts of pest management. 242 p. North Carolina State Univ., Raleigh, N. C.

Sharpe, P.J.H., and D. W. DeMichele. 1977. Reaction kinetics of poikilotherm development. J. Theor. Biol. 64: 649-670.

Sharpe, P.J.H., G. L. Curry, D. W. DeMichele, and C. L. Cole. 1977. Distribution model of organism development times. J. Theor. Biol. 66:21-38.

Stark, R. W., and A. R. Gittins, eds. 1973. Pest management for the 21st century. 102 p. Idaho Research Foundation, Univ. of Idaho, Moscow, Id.

Stephen, F. M., and H. A. Taha. 1976. Optimization of sampling effort for within-tree populations of southern pine beetle and its natural enemies. Environ. Entomol. 5:1001-1007.

White, R. A., and R. T. Franklin. 1976. Activity of the southern pine beetle in response to temperature. J. Ga. Entomol. Soc. 11:370-372.

ACKNOWLEDGMENTS

We acknowledge and thank Y. Fares, C. E. Magnuson, L. J. Edson, J. A. Gagne, T. L. Wagner, and D. N. Pope for their contributions in experimentation, interpretation, and modeling which aided in the development of the TAMBEETLE model.

We are grateful to A. M. Bunting and P. A. Beckley for technical assistance.

Special thanks are extended to Ms. Linda Frieda for clerical assistance.

The research reported herein was supported by the USDA-sponsored Expanded Southern Pine Beetle Research and Applications Program: grant no. 89-106 (19-317), 904-15-2, and 904-15-8. The findings, opinions, and recommendations expressed herein are those of the authors and not necessarily those of the sponsoring agency.

TREE MORTALITY, INFESTED BARK AREA, AND BEETLE POPULATION MEASUREMENTS AS COMPONENTS OF TREATMENT EVALUATION PROCEDURES ON DISCRETE FOREST MANAGEMENT UNITS

F. M. Stephen and H. A. Taha[1]

Abstract.--Our method of area-wide estimation of beetle population numbers makes use of data on SPB population distribution, abundance, and variation collected over the last 3 years in Arkansas. This information is then used in conjunction with survey data taken on numbers of trees infested, tree size, SPB population structure, and infested bark area limits, to provide an index of total SPB population in a given area.

Insect control strategies are by definition directed at reducing, either directly or indirectly, the population density of a target species and thus reducing damage to an acceptable level. Although evaluation of control efforts is usually considered a desirable follow-up of a suppression program, too often these evaluations are either lacking or poorly designed, so that superficial changes in levels of damage become, by inference, changes in insect population levels and thus a measure of control efficacy. While this may not be a scientifically sound procedure, constraints of cost, time, and the lack of trained personnel may force evaluations that do minimize actual measurement of treatment effects on the target population. As our information has increased in regard to developing many southern pine beetle (SPB) sampling strategies, we should now be able to provide population estimation procedures of acceptable precision for detecting treatment effects yet and cheap enough to be used economically in the field without a large force of highly trained personnel.

A number of investigators have detailed technical aspects of sampling SPB populations. The methods described by Coulson et al. (1975, 1976), Pulley et al. (1977a), and Nebeker et al. (1978) can provide highly accurate estimates of SPB numbers within specific trees if the investigators are willing to invest the time, money, and manpower in sampling with the required degree of precision. These methods for estimating SPB numbers within specific trees have been extrapolated to the infestation (i.e., spot) level (Foltz et al. 1977, Pulley et al. 1977b). As is true for the within-tree methods, a high degree of precision with regard to the population estimates can be obtained if required.

Combining survey and sampling procedures, we have developed methods (Stephen and Taha 1976, 1979) for making estimates of SPB numbers over discrete forest stands that may contain numerous spots. These sampling methods provide an index of the population density per unit of infested bark and are not specifically concerned with estimation of SPB numbers within specific trees. Rather, they address the problem of measuring population density as it occurs on an area basis. The within-tree and within-spot methods cited above could also be adapted to area-wide estimation by incorporating suitable survey methods.

The requirements for successfully using any of the methods outlined to this point are considerable, mainly because each technique requires direct measurement of the various SPB life stages as they exist within infested trees. The costs for this are high. Specialized equipment is needed for tree climbing, bark removal, and sample X-raying. Highly trained personnel are essential, not only to perform many of the field aspects of the sampling effort but also to identify correctly the various SPB life-stage forms from the samples collected. In addition to the high costs in trained personnel, equipment, and sampling effort, a further problem associated with these techniques is the long turn-around time between the physical process of sample collection and completion of the laboratory counting and estimation procedures.

Many of the agencies responsible for control programs appreciate the need for determining the effects of control treatments on SPB populations, but given the costs and complexities associated

[1] Dept. of Entomology and Dept. of Industrial Engineering, University of Arkansas, Fayetteville, Ark.

with the sampling methods cited above, are unable or unwilling to make the necessary commitment for this type of evaluation. Do alternatives exist? If so, what are they and what problems are likely to be incurred in using them?

The simplest and thus most likely evaluation method is via numbers of faded trees as counted from photographs, sketch maps, and/or ground checks. The implication here is that numbers or changes in numbers of fades adequately represent SPB population density or changes in density. Although the color of faded trees may be correlated with the stage of SPB contained therein, depending on season and weather conditions, many green infested trees may not be detected and many faded trees may be already abandoned. Unless investigators perform detailed ground checking, these errors can be magnified into a gross misrepresentation of actual beetle populations.

As an illustration of this consider a SPB spot in central Arkansas that we surveyed on July 17, 1978. The beetle population was rapidly expanding, and at that time 339 infested trees were detected and visually categorized. Of the total, 126 were faded to a distinct reddish color, 34 were yellow, and 179 (52 percent) were still green. These green trees contained primarily attacking beetles, eggs, and larvae; but some (18) did have pupae and 5 had some callow adults.

Knowledge of which trees are infested will thus improve the correlation of tree mortality with actual beetle population numbers but may still be far from acceptable. Ground checks of infested spots can determine which trees are currently infested, and with some extra effort investigators can estimate the age structure of the population in the spot by checking the brood stage of each infested tree. This will further assist in correlating tree mortality and beetle numbers.

As large trees have a greater bark surface than smaller trees, the former are also likely to have a greater infested bark area. Measurement of tree size can thus further improve the correlation of infested tree numbers with beetle population numbers. Development of predictive equations to estimate infested bark surface area is underway (Stephen and Hines, in preparation).

This paper presents a method for area-wide estimation of beetle population numbers that is practical for evaluation of control strategies. The technique makes use of the information on SPB population distribution, abundance, and variation we have collected over the past 3 years from a wide range of infestations in Arkansas. This population information is then used in conjunction with survey data taken on numbers of trees infested, tree size, SPB population age structure, and infested bark area limits, to provide an index of total SPB population in the area of concern.

METHODS

Aerial Survey

Investigators must ascertain all spots that are infested in the area to be evaluated. To accomplish this an aerial survey should be a prerequisite to the ground survey work. The photographic techniques detailed by DeMars et al. (this symposium) would provide the most reliable technique for accurately locating infested spots. As indicated by the example we outlined in the introduction (see also Mayyasi et al. 1975), numbers of faded trees are not a satisfactory estimator of currently infested trees and thus the areial survey is primarily for the purpose of determining the location and relative magnitude of the spots within the area. If processing and photo interpretation time is prohibitive, aerial sketch mapping can accomplish these goals (Stephen and Taha 1979).

Ground Survey

Ground surveys are the most essential component of this evaluation procedure. Members of the survey crew must be sufficiently trained with regard to SPB biology to identify correctly all infested trees within each spot and to assess the predominant SPB life stage present at breast height. Additional information that must be obtained is d.b.h. of each infested tree and an estimate of average height at top of SPB infestation in a particular spot. This must be determined by checking beneath the bark at the top of trees that have either been climbed or felled.

Age Structure Estimation

Many investigators have noted, at a given time, variation in SPB life stage along the infested bole. The temporal distribution of the beetle life stages within trees is an extremely complex issue, being a function of season, overall level of infestation, stand conditions, and other abstract variables. However, in order to simplify the survey and estimation process, we will assume a constant life stage along the length of the bole. Our unpublished data suggest that on the average, development in the mid and lower section of the tree progresses at about the same rate while being slightly delayed in the upper section. Assuming a constant developmental stage should not cause a large error if a relatively large heterogeneous population is measured.

Beetle Density Estimation

Since mass attack by a relatively large number of beetles is necessary for successful colonization of a tree by the southern pine beetle, some minimum density must be associated with a successfully attacked tree. Once the attack is complete and the upper and lower limits of the infested bole are established, the infested bark area of that tree forms a constrained universe within which the density of each beetle life stage can only vary between certain upper and lower limits.

During our SPB population dynamics studies (1975-77), we sampled 181 trees from 17 plots at six geographic locations in Arkansas. Approximately 5000 individual samples were collected during all seasons of the year, representing a wide spectrum of infestation levels. The information in this data base provides a means for determining the range in mean densities of each SPB life stage that should be encountered if intensive population sampling were to be conducted.

Frequency distributions of SPB attacks (two adults should be associated with each attack [Linit and Stephen 1978]), egg gallery length, eggs, first-stage larvae, late-stage immatures (larvae, pupae, and brood adults), and emerging adults were constructed from the sample counts in our data base (figures 1-6). It is apparent from these frequency distributions that the density counts for SPB attacks, gallery length, and eggs, plus the first-stage larvae are distributed in an approximately normal manner. The late-stage immatures and the emerging adult stage are somewhat skewed, however. Perhaps a greater percent mortality under high-density conditions produces this skewed distribution. In any case, as a result of the nonnormal distribution of these late life-stage density counts, calculation of confidence limits around the population mean is confounded.

To circumvent this problem, Monte Carlo techniques were used to randomly draw 100 sample counts from the data base and compute a mean for that set.

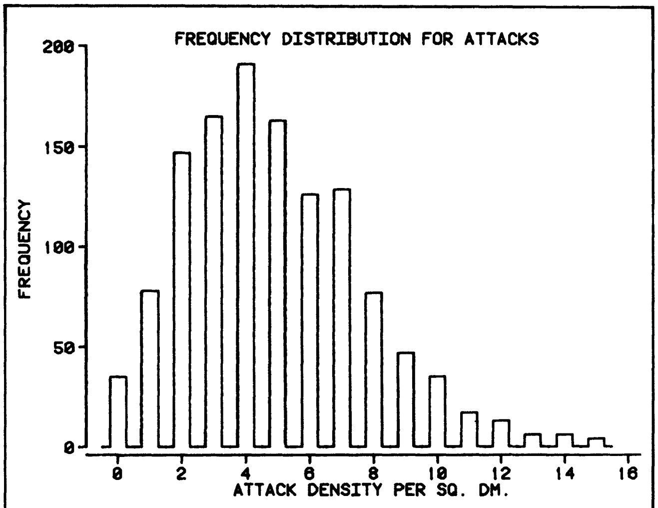


Figure 1.

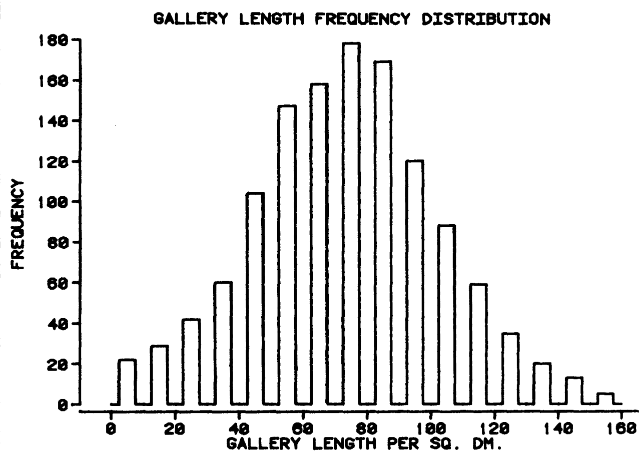


Figure 2.

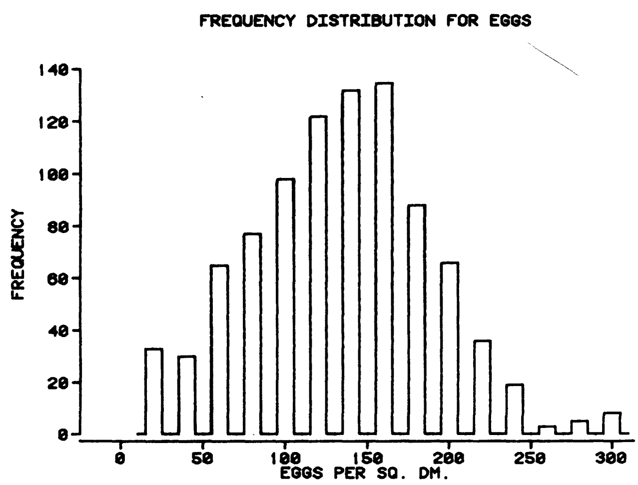


Figure 3.

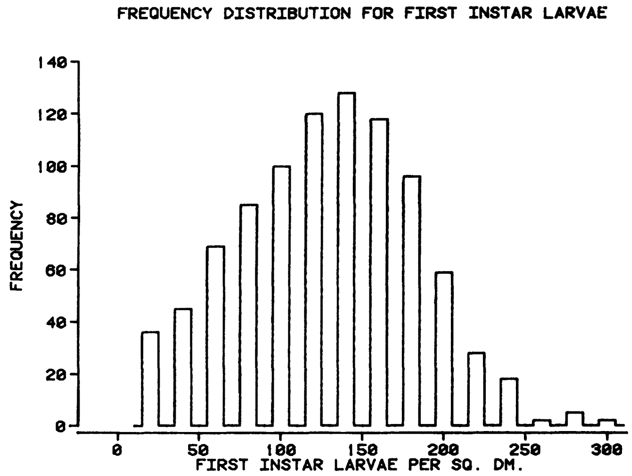


Figure 4.

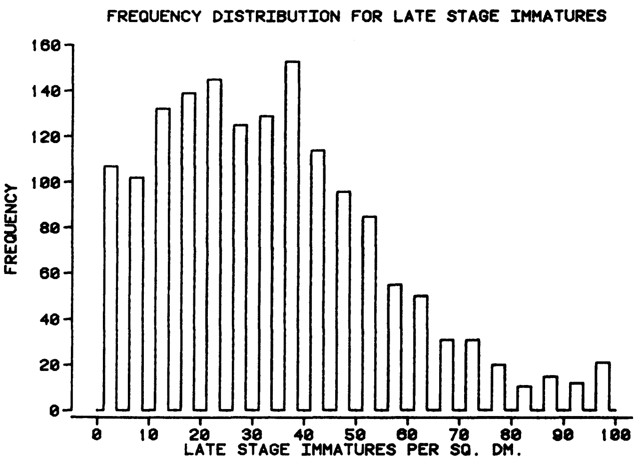


Figure 5.

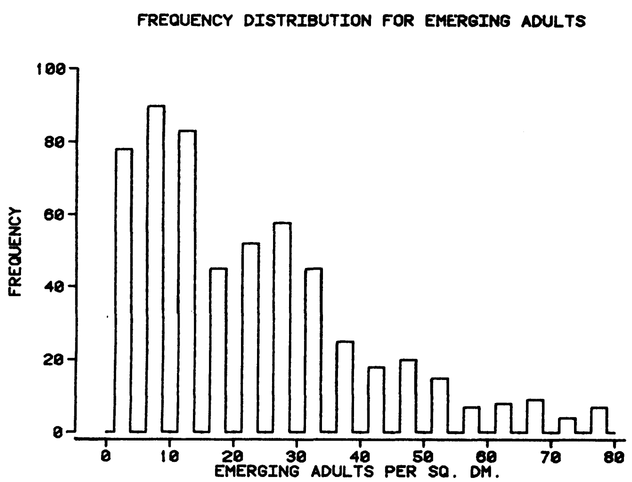


Figure 6.

This procedure was repeated 100 times. The mean and standard deviation of this set of means was then computed. The set of means thus computed must be normally distributed according to the central limit theorem (Snedecor 1967), thus permitting accurate estimates of variance about the mean and calculation of confidence intervals. The mean densities, standard errors of the means, and 95 percent confidence limits are given for each SPB life stage as determined from our data base (table 1).

Infested Bark Area Estimation

Two variables that define the absolute population density of SPB in a particular forest stand are the average beetle density per sample unit and the number of sample units (i.e., the total infested bark area). Much effort has been spent on developing techniques to estimate beetle density accurately, but estimation of infested bark area has received less attention. In part this may reflect the fact that more emphasis has been placed on measuring beetle populations within specific trees that were either climbed or felled when sampled. This procedure yielded measurement of the height and circumference at the top of the infested bole, which, in conjunction with measurements of circumference and height at the base of infestation, provides for accurate determination of the infested bark area (Stephen and Taha 1979). The area of bark (approximately equal to area of phloem) utilized by SPB on each tree varies substantially between spots and by season of the year (Cooper and Stephen 1978). Infestation level (i.e., spot population density), *Ips* species abundance, or other as yet undetermined variables may also influence average infested bark area.

Estimating beetle populations over a large area precludes measuring height and base of infestation on all trees, so predictive techniques are desirable. Using the data base referred to above, we calculated infested bark areas from our equations (Stephen and Taha 1979). Regression analyses were carried out using SAS (Barr et al. 1976). The best single predictor of infested bark area in square decimeters (IBA) is diameter at breast height, in centimeters (d.b.h.). The model IBA = 650.60 + 55.230 d.b.h. was fitted to our data with an F = 612, Pr > F = .0001. The mean square error (MSE) = 113131.70 with 179 d.f. and an R^2 of 0.77. Incorporating total tree height and date at which infestation occurred increased the R^2 to about 0.80.

ERRATA -- Hodges Gardens Symposium

In the Proceedings of the Symposium "Evaluating Control Tactics for the Southern Pine Beetle" the following corrections should be made in the paper by Stephen and Taha (Tree mortality, infested bark area, and beetle population measurements as components of treatment evaluation procedures on discrete forest management units):

1. p. 48, 2nd column, line 57: "The model IBA = - 650.60 + 55.230 d.b.h..." (insert negative symbol).
2. p. 49, 2nd column, line 6: "IBA = -1335.4 + 43.74 (d.b.h. _ Class) + ..." (insert negative symbol).

Table 1.--Mean standard error of the mean and 95 percent confidence limits for estimates of mean density per 100 cm^2 area for different southern pine beetle life stages.

	Lower 95% CL	Mean ± $S_{\bar{x}}$	Upper 95% CL
Attacks	4.39	4.92 ± .27	5.45
Gallery length	69.53	85.01 ± 7.74	100.49
Eggs	123.75	135.66 ± 5.95	147.57
First stage larvae	118.77	129.88 ± 5.55	140.98
Late stage immatures	31.56	34.06 ± 1.25	36.57
Emerging adults	19.64	22.82 ± 1.59	26.00

As particular control measures may themselves have an unexpected effect on the physical limits of the infestation within trees, a predictive equation that does not in any way consider height at top of infestation--a variable also highly correlated with infested bark area--cannot be recommended without more extensive examination. Determination of height at top of infestation (HTI) can at this time be made only by cutting away the bark to actually expose the limits of SPB galleries. This requires either climbing or felling the tree, an effort that is prohibitive if large numbers of trees are to be examined.

We noted some consistency in height at top of infestation within trees sampled in a given plot on about the same date, with the range in HTI not exceeding 5 m in 75 percent of our plots. We also noted an overall trend in increasing HTI with increasing d.b.h. All trees in our data base were thus classed by HTI. A 5-m-wide, overlapping interval was used:

HTI_Class	Limits
10.5	8-13 m
11.5	9-14 m
12.5	10-15 m
etc.	

The rationale for this grouping was to permit the user to measure HTI on a limited number of trees within a plot, and then to choose the single HTI_ Class best fitting the average for the overall plot.

The trees were also classed by d.b.h. at 2-cm intervals from 16 cm to the largest measured d.b.h._Class of 74 cm. The 2-cm width of the d.b.h._Class served only to provide discrete d.b.h. measurements which are more readable in the tables to follow.

Fitting our data with the general linear model procedure in SAS (Barr et al. 1976) yields the equation for predicting infested bark area (IBA) on a given tree:

$$IBA = 1335.4 + 43.74\ (d.b.h.\_Class) + 77.77\ (HTI\_Class) \qquad (1)$$

The F value = 4454.4, Pr > F = 0.0001. The MSE = 27445.58 with 722 d.f. The coefficient of multiple determination (R^2) = 0.93. The intercept and coefficients for both parameters were significantly different from zero (PR > (T) = 0.0001). Examination of the residuals indicated that the model is a good one and does not violate any of the required assumptions for regression analysis.

To simplify the infested bark area estimation procedure, we prepared table 2 containing the d.b.h._Classes and HTI_ Classes covered by our data. This table gives the predicted IBA for specific trees of various d.b.h._Classes for a particular HTI_Class. The estimate is in square decimeters.

To calculate the expected total infested bark area in a discrete area, the following technique would be employed:

(1) In each spot estimate the average HTI_Class by direct measurement from a small random sample of trees. Once computed, the average HTI_Class measurement is used as a constant for all prediction in that particular spot.

(2) Determine the stage of SPB development in each infested tree and measure the d.b.h. (to the nearest 2 cm) for that tree.

(3) Repeat this procedure in each spot.

(4) Using the IBA estimates from table 2, sum these estimates to calculate the total infested bark area of a particular life stage over all plots.

$$\hat{IBA}_i = \sum_{j=1}^{n_i} IBA_{ij} \qquad (2)$$

where *i* is the beetle life stage and *j* is an individual tree from one to the total (n_i) in the *i*th life stage.

The variance of the estimate of IBA for any specific set of d.b.h._Class and HTI_Class variables can be determined using standard techniques for a linear model with two independent variables (Draper and Smith 1966). The variance of a specific IBA estimate can be approxi-

Table 2.--Predicted infested bark area estimates in dm^2, for individual trees with specific sets of d.b.h._Class and HTI_Class measurements.

d.b.h. Class	HTI_Class ≦ 9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	≧ 22.5
≦ 16	103.2	180.9	258.7	336.5	414.3	492.0	569.8	647.6	725.4	803.1	880.9	958.7	1036.4	1114.2
18	190.6	268.4	346.2	424.0	501.7	579.5	657.3	735.1	812.8	890.6	968.4	1046.1	1123.9	1201.7
20	278.1	355.9	433.7	511.4	589.2	667.0	744.8	822.5	900.3	978.1	1055.8	1133.6	1211.4	1289.2
22	365.6	433.4	521.1	598.9	676.7	754.5	832.2	910.0	987.8	1065.5	1143.3	1221.1	1298.9	1376.6
24	453.1	530.8	608.6	686.4	764.2	841.9	919.7	997.5	1075.2	1153.0	1230.8	1308.6	1386.3	1464.1
26	540.5	618.3	696.1	773.9	851.6	929.4	1007.2	1084.9	1162.7	1240.5	1318.3	1396.0	1473.8	1551.6
28	628.0	705.8	783.6	861.3	939.1	1016.9	1094.6	1172.4	1250.2	1328.0	1405.7	1483.5	1561.3	1639.0
30	715.5	793.3	871.0	948.8	1026.6	1104.3	1182.1	1259.9	1337.7	1415.4	1493.2	1571.0	1648.7	1726.5
32	803.0	880.7	958.5	1036.3	1114.0	1191.8	1269.6	1347.4	1425.1	1502.9	1580.7	1658.4	1736.2	1814.0
34	890.4	968.2	1046.0	1123.7	1201.5	1279.3	1357.1	1434.8	1512.6	1590.4	1668.1	1745.9	1823.7	1901.5
36	997.9	1055.7	1133.4	1211.2	1289.0	1366.8	1444.5	1522.3	1600.1	1677.8	1755.6	1833.4	1911.2	1988.9
38	1065.4	1143.1	1220.9	1298.7	1376.5	1454.2	1532.0	1609.8	1687.5	1765.3	1843.1	1920.9	1998.6	2076.4
40	1152.8	1230.6	1308.4	1386.2	1463.9	1541.7	1619.5	1697.2	1775.0	1852.8	1930.6	2008.3	2086.1	2163.9
42	1240.3	1318.1	1395.9	1473.6	1551.4	1629.2	1706.9	1784.7	1862.5	1940.3	2018.0	2095.8	2173.6	2251.3
44	1327.8	1405.6	1483.3	1561.1	1638.9	1716.6	1794.4	1872.2	1950.0	2027.7	2105.5	2183.3	2261.0	2338.8
46	1415.3	1493.0	1570.8	1648.6	1726.3	1804.1	1881.9	1959.7	2037.4	2115.2	2193.0	2270.7	2348.5	2426.3
48	1502.7	1580.5	1658.3	1736.0	1813.8	1891.6	1969.4	2047.1	2124.9	2202.7	2280.4	2358.2	2436.0	2513.8
50	1590.2	1668.0	1745.7	1823.5	1901.3	1979.1	2056.8	2134.6	2212.4	2290.1	2367.9	2445.7	2523.5	2601.2
52	1677.7	1755.4	1833.2	1911.0	1988.8	2066.5	2144.3	2222.1	2299.8	2377.6	2455.4	2533.2	2610.9	2688.7
54	1765.1	1842.9	1920.7	1998.5	2076.2	2154.0	2231.8	2309.5	2387.3	2465.1	2542.9	2620.6	2698.4	2776.2
56	1852.6	1930.4	2008.2	2085.9	2163.7	2241.5	2319.2	2397.0	2474.8	2552.6	2630.3	2708.1	2785.9	2863.7
58	1940.1	2017.9	2095.6	2173.4	2251.2	2328.9	2406.7	2484.5	2562.3	2640.0	2717.8	2795.6	2873.4	2951.1
60	2027.6	2105.3	2183.1	2260.9	2338.6	2416.4	2494.2	2572.0	2649.7	2727.5	2805.3	2883.1	2960.8	3038.6
62	2115.0	2192.8	2270.6	2348.3	2426.1	2503.9	2581.7	2659.4	2737.2	2815.0	2892.8	2970.5	3048.3	3126.1
64	2202.5	2280.3	2358.0	2435.8	2513.6	2591.4	2669.1	2746.9	2824.7	2902.5	2980.2	3058.0	3135.8	3213.5
66	2290.0	2367.7	2445.5	2523.3	2601.1	2678.8	2756.6	2834.4	2912.2	2989.9	3067.7	3145.5	3223.2	3301.0
68	2377.4	2455.2	2533.0	2610.8	2688.5	2766.3	2844.1	2921.9	2999.6	3077.4	3155.2	3232.9	3310.7	3388.5
70	2464.9	2542.7	2620.5	2698.2	2776.0	2853.8	2931.6	3009.3	3087.1	3164.9	3242.6	3320.4	3398.2	3476.0
72	2552.4	2630.2	2707.9	2785.7	2863.5	2941.3	3019.0	3096.8	3174.6	3252.3	3330.1	3407.9	3485.7	3563.4
≧ 74	2639.9	2717.6	2795.4	2873.2	2951.0	3028.7	3106.5	3184.3	3262.0	3339.8	3417.6	3495.4	3573.1	3650.9

Table 3.--Calculated q values as determined for individual trees with particular HTI_Class and d.b.h._Class measurements

d.b.h. Class	HTI_Class ≦ 9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	≧ 22.5
≦ 16	1.0113	1.0107	1.0104	1.0104	1.0106	1.0111	1.0119	1.0130	1.0143	1.0159	1.0177	1.0198	1.0222	1.0249
18	1.0101	1.0095	1.0091	1.0090	1.0092	1.0096	1.0103	1.0113	1.0126	1.0141	1.0159	1.0179	1.0202	1.0228
20	1.0090	1.0083	1.0079	1.0077	1.0079	1.0082	1.0089	1.0098	1.0110	1.0124	1.0141	1.0161	1.0184	1.0209
22	1.0081	1.0073	1.0068	1.0066	1.0067	1.0070	1.0075	1.0084	1.0095	1.0109	1.0126	1.0145	1.0167	1.0191
24	1.0073	1.0065	1.0059	1.0056	1.0056	1.0058	1.0063	1.0071	1.0082	1.0095	1.0111	1.0130	1.0151	1.0175
26	1.0066	1.0057	1.0051	1.0047	1.0047	1.0048	1.0053	1.0060	1.0070	1.0082	1.0098	1.0116	1.0136	1.0160
28	1.0061	1.0051	1.0044	1.0040	1.0038	1.0040	1.0043	1.0050	1.0059	1.0071	1.0086	1.0103	1.0123	1.0146
30	1.0057	1.0046	1.0039	1.0034	1.0032	1.0032	1.0035	1.0041	1.0050	1.0061	1.0075	1.0092	1.0111	1.0133
32	1.0054	1.0043	1.0035	1.0029	1.0026	1.0026	1.0029	1.0034	1.0042	1.0052	1.0066	1.0082	1.0100	1.0122
34	1.0052	1.0041	1.0032	1.0025	1.0022	1.0021	1.0023	1.0028	1.0035	1.0045	1.0057	1.0073	1.0091	1.0112
36	1.0052	1.0040	1.0030	1.0023	1.0019	1.0018	1.0019	1.0023	1.0029	1.0039	1.0051	1.0065	1.0083	1.0103
38	1.0053	1.0040	1.0030	1.0022	1.0017	1.0015	1.0016	1.0019	1.0025	1.0034	1.0045	1.0059	1.0076	1.0095
40	1.0055	1.0042	1.0031	1.0023	1.0017	1.0014	1.0014	1.0017	1.0022	1.0030	1.0041	1.0054	1.0070	1.0089
42	1.0059	1.0045	1.0033	1.0024	1.0018	1.0015	1.0014	1.0016	1.0021	1.0028	1.0038	1.0051	1.0066	1.0084
44	1.0064	1.0049	1.0037	1.0027	1.0020	1.0016	1.0015	1.0016	1.0020	1.0027	1.0036	1.0048	1.0063	1.0080
46	1.0070	1.0054	1.0042	1.0031	1.0024	1.0019	1.0017	1.0018	1.0021	1.0027	1.0036	1.0047	1.0061	1.0078
48	1.0077	1.0061	1.0048	1.0037	1.0029	1.0023	1.0021	1.0021	1.9923	1.0029	1.0037	1.0048	1.0061	1.0077
50	1.0086	1.0069	1.0055	1.0044	1.0035	1.0029	1.0026	1.0025	1.0027	1.0032	1.0039	1.0049	1.0062	1.0077
52	1.0096	1.0079	1.0064	1.0052	1.0042	1.0036	1.0032	1.0030	1.0032	1.0036	1.0042	1.0052	1.0064	1.0079
54	1.0107	1.0089	1.0074	1.0061	1.0051	1.0044	1.0039	1.0037	1.0038	1.0041	1.0047	1.0056	1.0068	1.0082
56	1.0120	1.0101	1.0085	1.0072	1.0061	1.0053	1.0048	1.0045	1.0045	1.0048	1.0053	1.0062	1.0072	1.0086
58	1.0134	1.0115	1.0098	1.0084	1.0072	1.0064	1.0058	1.0054	1.0054	1.0056	1.0061	1.0068	1.0078	1.0091
60	1.0149	1.0129	1.0112	1.0097	1.0085	1.0076	1.0069	1.0065	1.0064	1.0065	1.0069	1.0076	1.0086	1.0098
62	1.0166	1.0145	1.0127	1.0112	1.0099	1.0089	1.0082	1.0077	1.0075	1.0076	1.0079	1.0086	1.0094	1.0106
64	1.0184	1.0162	1.0143	1.0127	1.0114	1.0103	1.0096	1.0090	1.0088	1.0088	1.0091	1.0096	1.0104	1.0115
66	1.0203	1.0181	1.0161	1.0145	1.0131	1.0119	1.0111	1.0105	1.0102	1.0101	1.0103	1.0108	1.0116	1.0126
68	1.0223	1.0200	1.0180	1.0163	1.0148	1.0136	1.0127	1.0121	1.0117	1.0116	1.0117	1.0121	1.0128	1.0138
70	1.0245	1.0221	1.0201	1.0183	1.0167	1.0155	1.0145	1.0138	1.0133	1.0131	1.0132	1.0136	1.0142	1.0151
72	1.0268	1.0244	1.0222	1.0204	1.0188	1.0175	1.0164	1.0156	1.0151	1.0148	1.0149	1.0152	1.0157	1.0165
≧ 74	1.0292	1.0267	1.0245	1.0226	1.0209	1.0196	1.0184	1.0176	1.0170	1.0167	1.0166	1.0169	1.0174	1.0181

mated by the mean square error (MSE_{IBA}) associated with equation (1) (i.e., 27445.58) times a correction factor determined by the distance the specific set of d.b.h._Class and HTI_Class variables deviate from the mean. This can be expressed in matrix notation as: Var (Y) = $S^2 \cdot (1 + \underline{X}_o' (\underline{X}'\underline{X})^{-1} \underline{X}_o)$ (see Draper and Smith 1966, p. 121). For our model this correction factor, representing the number within the parentheses which we will term *q*, has been computed for each d.b.h._Class and HTI_Class set of variables (table 3). It should be noted that *q* approximates 1 and thus does not produce a large increase in the variance of IBA. The user could employ the *q* values from table 3 in the following manner.

$$S^2_{IBA_i} = (MSE_{IBA}) \cdot \sum_{j=1}^{n_i} q_{ij} \qquad (3)$$

However, since from table 3 $q_{ij} \cong 1$ for all ij,

$$\sum_{j=1}^{n_i} q_{ij} \cong n_i$$

As a result the variance for the expected total IBA_i in life stage *i* can be approximated as

$$S^2_{IBA_i} = (MSE_{IBA}) \cdot n_i \qquad (4)$$

Total Population Estimation

Given the estimates of average beetle density for each life stage (table 1) plus an estimate of the total infested bark area containing each life stage, an estimate of the total beetle population can be made:

$$\hat{P}_i = \hat{IBA}_i \ \bar{X}_i \qquad (5)$$

where *P* is an estimate of the total beetle population in the *i*th life stage, IBA_i is an estimate of the total infested bark area from trees containing the *i*th life stage, and $\bar{X}_i$ is the mean density per unit area in the *i*th life stage.

The variance of $\hat{P}_i$ can be estimated as the product of two independent random variables, according to Goodman (1960), as

$$S^2_{\hat{P}_i} = \bar{X}^2_i \ S^2_{\hat{IBA}_i} + \hat{IBA}^2_i \ S^2_{\bar{x}_i} - S^2_{\bar{x}_i} \ S^2_{\hat{IBA}_i} \qquad (6)$$

Table 4.--Infested bark area estimation from 2 plots, based on tree measurement and calculation method versus prediction method

Plot 1 (HTI_Class 22.5)		d.b.h.	d.b.h._ Class	HTI	Calculated IBA	Predicted IBA
Tree	1	45.5	46	23.7	2414.0	2426.3
	2	54.4	54	23.1	3002.4	2776.2
	3	51.5	52	23.5	2878.4	2688.7
	4	53.5	54	22.5	2868.4	2776.2
	5	56.7	56	24.6	3180.3	2863.7
	6	47.1	48	21.0	2373.1	2513.8
	7	44.9	44	25.0	2623.1	2338.8
	8	26.1	26	24.0	1522.8	1551.6
	9	47.4	48	20.5	2538.8	2513.8
Plot 2 (HTI_Class 13.5)						
Tree	1	23.2	24	8.0	548.8	764.2
	2	45.2	46	16.2	2002.1	1726.3
	3	56.0	56	16.9	2636.5	2163.7
	4	46.5	46	19.4	2421.2	1726.3
	5	42.3	42	11.8	1440.0	1551.4
	6	42.0	42	12.9	1562.3	1551.4
	7	39.8	40	12.0	1370.2	1463.9
			Total IBA_i		35382.6	33396.3
			Mean IBA_i		2211.4	2087.3
			*Var IBA_i		534,400.8	441,874.2

*Var IBA_i calculated = $\frac{\Sigma (IBA_i - \overline{IBA})^2}{n-1}$

Var IBA_i from equation $(MSE_{IBA}) \sum_{i=1}^{n} q_{ij} = (27445.60) \times (16.1)$

RESULTS

To test the prediction method, we selected two plots which were intensively sampled for attacking adults during the summer of 1976. The data in table 4 list the actual d.b.h., height at top of infestation, and calculated IBA in square decimeters. In addition the d.b.h._Class, HTI_Class, and predicted IBA are given for each tree. The predictive technique seems to work well in this situation as the calculated total IBA (35382.6) is only about 6 percent greater than the predicted total of 33396.3. This is true despite the fact that the range of HTI in plot 2 is greater than the 5 m which should normally be encountered. The estimated variance is less with the predictive technique than the calculated method, probably because of the wider-than-normal range in HTI in plot 2.

The average attack density, determined from intensive sampling in the two plots in table 4, was 5.32 ± 0.18 standard errors of the mean. The total beetle numbers are then estimated by the product of the mean beetle density and total IBA. Confidence limits can be placed about this estimate following determination of the variance (equation 6). Using the same mathematical procedure with the expected population mean for attacks of 4.92, and the predicted total infested bark area, the total beetle numbers can be estimated from these data. The population totals and 95 percent confidence limits for the two population estimation techniques are given in table 5. Although the population totals of 188,235 and 164,310 differ by 13 percent, an area of overlap does occur between the confidence limits of the two estimates.

Table 5.--Estimation of total and 95% confidence limits for SPB attacks on 16 trees in plots 1 and 2

Sampling and Tree Measurement Method	Prediction Method
188,235 ± 18,929	164,310 ± 14,922

DISCUSSION

The benefits of the population estimation technique we propose may be summarized in the following manner. The method can be used to obtain a pre- and posttreatment SPB population estimate for a particular spot, series of spots, or an entire area. It does not require intensive within-tree sampling of beetle populations, but rather makes use of an existing data base that encompasses variation in season, geographic location, and infestation levels. Compared to methods which do require intensive within-tree sampling, this technique is relatively simple to use and inexpensive. It does not require highly trained entomologists in either the field or the lab, and eliminates much of the need for specialized sampling and X-raying equipment. A further advantage is the reduced time between data collection and population estimation.

By including measurements of such variables as beetle life stage, tree size, and average height at top of infestation, the resulting estimate of infested bark area is much more precise than that derived by simply counting faded trees. Finally, comparison of this method with intensively sampled trees on which the bark surface had been accurately measured provided reasonably similar population estimates.

Although the benefits of using a technique such as this are attractive, there are certain inherent limitations which must be stressed so as to prevent possible misuse of the method. The primary biological drawback is the fact that no *direct* measurements are made of average beetle density within the infested trees. Because of this fact, the procedure cannot be used to measure the effect of any treatment on the density of *within-tree* beetle populations, except as it may influence the infested bark area. It is intended to be used to estimate total population. For example it could be used to compare populations before and after a treatment, when the residual population has reinfested new trees.

Sources of potential error not accounted for by the technique are the assumptions that beetle life stage is constant within a particular tree and that a small random sample used in determination of height at top of infestation will provide a suitably accurate estimate of average HTI Class. In addition, it must be realized that the data used in estimating the mean density of each beetle life stage were from Arkansas and may not be totally applicable to all other Southern States. Although highly trained entomologists are not required, the personnel who do the ground surveys must be trained to the point of being able to determine accurately the predominant SPB life stage for each tree, and able to assess the HTI on a few trees correctly.

LITERATURE CITED

Barr, A. J., J. H. Goodnight, J. P. Sall, and J. T. Helwig. 1976. A user's guide to SAS·76. Sparks Press, Raleigh, N.C.

Cooper, M. E., and F. M. Stephen. 1978. Parent adult reemergence in southern pine beetle population. Environ. Entomol. 7:574-577.

Coulson, R. N., J. L. Foltz, A. M. Mayyasi, and F. P. Hain. 1975a. A quantitative evaluation of frontalure and cacodylic acid treatment effects on within-tree populations of the southern pine beetle. J. Econ. Entomol. 68(5):671-678.

Coulson, R. N., F. P. Hain, J. L. Foltz, and A. M. Mayyasi. 1975b. Techniques for sampling the dynamics of southern pine beetle populations. 19 p. Texas Agric. Exp. Stn. Misc. Publ. 1185. College Station, Tex.

Coulson, R. N., P. E. Pulley, J. L. Foltz, and W. C. Martin. 1976. Procedural guide for quantitatively sampling within-tree populations of *Dendroctonus frontalis.* 26 p. Texas Agric. Exp. Stn. Misc. Publ. 1267. College Station, Tex.

Draper, N. R., and H. Smith. 1966. Applied regression analysis. 407 p. Wiley & Sons, Inc., New York.

Foltz, J. L., P. E. Pulley, R. N. Coulson, and W. C. Martin. 1977. Procedural guide for estimating within-spot populations of *Dendroctonus frontalis.* 27 p. Texas Agric. Exp. Stn. Misc. Publ. 1316.

Goodman, L. A. 1960. On the exact variance of products. J. Am. Stat. Assoc. 55:708-713.

Linit, M. J., and F. M. Stephen. 1978. Comparison of methods for estimation of attacking adult populations of *Dendroctonus frontalis.* J. Econ. Entomol. 71:732-735.

Mayyasi, A. M., R. N. Coulson, J. L. Foltz, and A. E. Harvey. 1975. A quality control approach to the evaluation of survey sampling procedures for the southern pine beetle. J. Econ. Entomol. 68:336-338.

Nebeker, T. E., O. P. Hackney, R. R. Hocking, M. Paz, and J. H. Lashomb. 1978. Methods for and comparison of sampling schemes for estimating within tree southern pine beetle populations (Coleoptera:Scolytidae). Can. Entomol. 110:1015-1022.

Pulley, P. E., R. N. Coulson, J. L. Foltz, W. C. Martin, and C. L. Kelly. 1977a. Sampling intensity, informational content of samples, and precision in estimating within-tree populations of *Dendroctonus frontalis.* Environ. Entomol. 6:607-615.

Pulley, P. E., J. L. Foltz, R. N. Coulson, and W. C. Martin. 1977b. Evaluation of procedures for estimating within-spot populations of attacking adult *Dendroctonus frontalis.* Can. Entomol. 109:1325-1334.

Snedecor, G. W. 1956. Statistical methods (fifth ed.). 534 p. The Iowa State University Press, Ames, Ia.

Stephen, F. M., and H. A. Taha. 1976. Optimization of sampling effort for within-tree populations of southern pine beetle and its natural enemies. Environ. Entomol. 5:1001-1007.

Stephen, F. M., and H. A. Taha. 1979. Area-wide estimation of southern pine beetle populations. (Submitted to Environ. Entomol.)

RELATING TREE MORTALITY TO COLLAPSING BEETLE POPULATIONS

F. P. Hain, C. J. DeMars, W. T. McClelland, and W. D. Mawby[1]

Abstract.--A collapsing southern pine beetle epidemic was monitored by aerial photography and within-tree population sampling in an area comprising 8600 acres. The aerial photographs showed a significant decline in number of faded trees and average spot size by Julian date 266. Brood production per tree and per square decimeter showed a decline by sampling period 221 to 251 (Julian date). However, the decline was not significant until sampling period 282 to 002 of the following year. This decline may have simulated the type of decline that would have occurred after an effective control treatment application.

INTRODUCTION

Certain insecticidal and cultural treatments for the control of southern pine beetle (SPB), *Dendroctonus frontalis* Zimmerman, pose unique problems that require area-wide, rather than tree-to-tree or spot-to-spot, evaluation. This is particularly true of treatments that disrupt or disperse beetle populations rather than kill them directly. For example, a treatment such as cut-and-leave may succeed in eliminating further tree mortality within a given spot due to a pheromone disruption, but beetle mortality may be negligible or minor, resulting in dispersal to new areas and spot proliferation. Since we know little about dispersal mortality, we must evaluate treatments on an area-wide basis. If dispersal mortality is not effective, and area-wide stand conditions are poor, spot proliferation rather than control could result. That is, under certain stand conditions of high tree susceptibility, treatments that rely wholly or partially on dispersal mortality may prove unsatisfactory.

Furthermore, area-wide evaluations are useful--if not necessary--because of the spot-to-spot variations in stand, site, tree, and beetle population parameters. What succeeds in one location may fail or partially fail in another. This is true of treatments that are meant to improve tree resistance, such as stand thinning. Thus the overall or area-wide effects of treatments must be evaluated.

Area-wide treatment evaluations pose logistical problems that can most economically and practically be solved through some type of aerial surveillance. The large number of man-hours that would be required for an on-the-ground surveillance and evaluation makes this approach unfeasible. Even if manpower were available, the problem of detecting SPB trees from the ground would be immense. The heavy underbrush and high stand densities typical of our southeastern forests make detection of infested trees from anywhere but the immediate vicinity or along the roadsides all but impossible.

Thus the question resolves to what is the most efficient means of aerial surveillance. The two general approaches are aerial photography and sketch mapping. The three major advantages of aerial photographs are accuracy, precision, and permanency; sketch mapping, on the other hand, is quick to obtain. Coulson (1975) has demonstrated the inaccuracy of estimating numbers of infested trees within spots by aerial observers. In our own experience, we have found the identification of SPB trees by aerial observers to be extremely inaccurate for the location of endemic trees. We are defining endemic populations as nonexpanding infestations with less than five trees, and frequently only one or two trees. In one area, for example, our aerial surveillance team, consisting of two experienced North Carolina Forest Service spotters and two less experienced North Carolina State University technicians,

---

[1] The authors are, respectively, Associate Professor, Dept. of Entomology, North Carolina State Univ., Raleigh, N.C.; Research Entomologist, Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Berkeley, Cal.; Research Associate, Dept. of Entomology; and Graduate Research Assistant, Biomathematics Program, North Carolina State University, Raleigh, N.C.

in a single-engine Cessna, detected two spots. While a ground crew was searching for the aerially sighted spots later, they discovered six more SPB spots.

Many actual spots were not observed from the air; in fact, the majority of our sample plots (86 percent, or 12 of 14) were spotted by the on-the-ground-roadside survey crew. The aerial surveillance merely served to locate those areas where the greatest number of faders could be found. On the other hand, during the 2-year study (1976-77) in Person County, North Carolina, that we are reporting on now, the only trees detected from the ground that were not detected on the photos were small, suppressed trees whose crowns were not visible from the air, or recently infested trees that had not begun to fade. Thus, although not precise scientific information, these observations led us to believe that aerial photographs are far more reliable.

Of course, aerial photographs are precise in locating spots. The human error of marking the wrong location is eliminated. And the photograph is a permanent record of crown fading at that time and place. If questions arise regarding what was observed, the photographs are available for reexamination.

The disadvantages of aerial photography are costs and time delays. The cost of a flight in Person County which covered the equivalent of 65,000 acres (32,000 covered at two scales), including flight time (40 miles from the study area to the airport), film, film development, and photo interpretation, was approximately $3,000 per flight. This does not include the cost of equipment such as the plane, the camera, and the digitizer and plotter, which we will describe later. Thus the expense of aerial photographs could be prohibitive.

I should add that Garland Mason, at Stephen F. Austin University, has developed a camera mount for a 35-mm camera which can be attached to the outside of most Cessnas. The approximate cost of the mount is probably $200 or $300. This system would greatly reduce the costs and probably be more than adequate for area-wide treatment evaluations. We experimented with the system in North Carolina and found it to be quite operational, but flight time was increased slightly because of the small area covered per photo. At any rate, with this system, cost may not be as prohibitive for treatment evaluations.

The second disadvantage of aerial photographs is the time delay in film processing and photo interpretation. In our work from 1 to 2 weeks elapsed between the photo flight and the first bits of information from the photo interpreter's initial cursory examination. However, for treatment evaluation this time delay should not be an important problem since time is not crucial.

Aerial photos can tell us only what trees are fading and the stage of the fade. The causal agent and, in the case of SPB, its brood stage cannot be determined. Thus ground information on causal agents is required. Measurements of stand, site, tree, and other beetle population parameters on at least a portion of the infested trees may also be useful.

The objective of this paper is to relate tree mortality, as determined from aerial photographs, to parameters of within-tree populations during a declining SPB epidemic and to evaluate which of the on-the-ground parameters may be most useful in future studies of area-wide treatment evaluation. We are assuming that the photo-detected mortality is 100 percent accurate and precise. Reports in the literature (Heller and Wear 1969, DeMars et al. 1973) and our own experience indicate that a 10 percent error may be more accurate.

It is important to keep in mind that the information presented here is an attempt at merging the results of two separate projects. Evaluating treatment effectiveness was not the original objective of either project. The North Carolina objective was to study the population dynamics of SPB. C. J. DeMars' project in California dealt with computer retrieval of photo-interpreted information. As an offshoot of these two projects, certain methodologies were developed that may have a potential utility in area-wide treatment evaluations. Also the populations were declining over the entire area, perhaps simulating the type of decline that might occur after certain control treatments are applied. But the actual evaluation of treatments was not attempted.

METHODS AND MATERIALS

The study area was in Person County, North Carolina. The infrared stereo transparencies covered approximately 32,000 acres with the town of Hurdle Mills as the coverage center. The area in which our population dynamics study plots were located covered approximately 8600 acres. The relationship of this

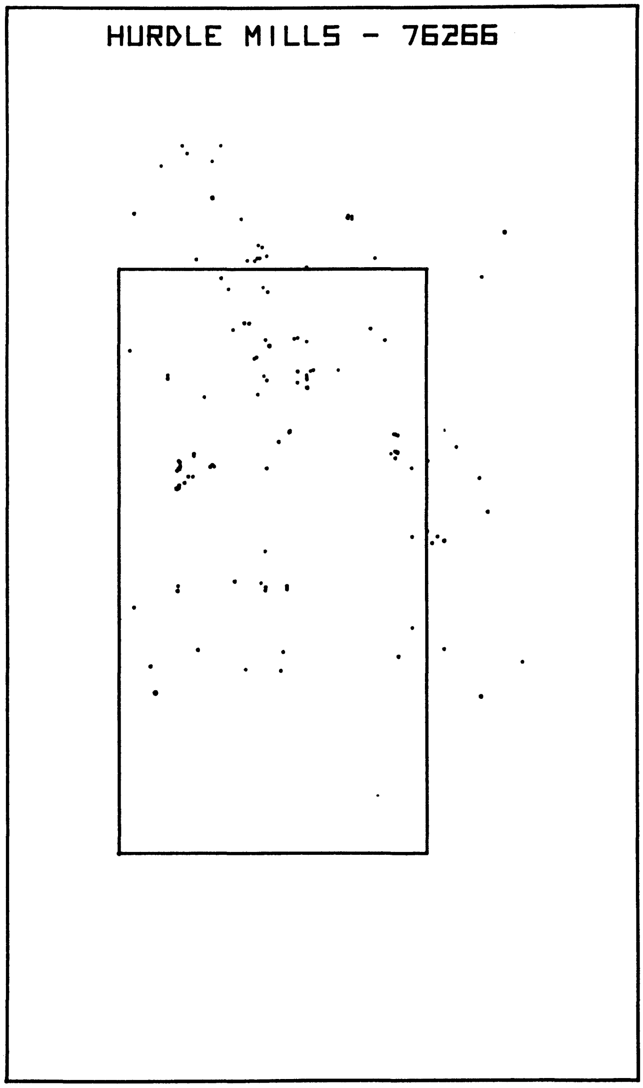


Figure 1.--Southern pine beetle spots in 32,000-acre survey area on J.D. 76266. Smaller rectangle indicates 8600-acre study plot.

smaller area to the total area is shown in figure 1. The dots represent SPB spots detected on Julian date 266 of 1976. The remainder of this paper will deal with information gleaned from the smaller rectangle only. The stands (fig. 2) within the smaller area were classified into pine (90 percent pine or more), mixed pine-hardwood (30 to 89 percent pine), hardwood (1 to 29 percent pine), and agricultural type (0 percent). About 58 percent of the area was classified as agricultural (mainly tobacco), 25 percent as mixed, 15 percent as hardwood, and 1 percent as pure pine. The predominant pine species was shortleaf, with some loblolly and Virginia pine. Tree age, height and d.b.h., and stand density varied greatly from site to site. But most sites were old fields with high stand density and poor radial growth. The dots show the location of our population study plots.

The study was initiated in July 1976. By that time a statewide collapse of SPB was evident. However, the Hurdle Mills population was still fairly active. The first flight flown on July 22 showed 561 trees with red, orange, or yellow-green crowns. However, activity declined throughout the field season, and overwintering survival was very poor (McClelland et al. 1978). No newly infested trees could be sampled in the spring of 1977. The final flight on July 22, 1977, found only two orange-topped trees over the entire study area. The last bark sample was removed on April 15, 1977. After that, no suitable trees for sampling could be found. This collapse was also evident in the statewide population as our efforts to find infested trees in other parts of the State proved fruitless. Thus it is evident from this information that we are dealing with a population in transition from epidemic to endemic status--perhaps not unlike the type of transition that occurs when a control treatment is applied.

The 9 × 9-inch color infrared transparencies were taken from July 22, 1976, to June 22, 1977, at approximately 1-month intervals to coincide with the expected within-tree brood development time. The photos were taken with a Wild Hurbrugg RC-8 at scales of 1:6000 and 1:12,000. The purpose of the small-scale photography was to provide 100-percent coverage of the entire study area. The large-scale photography covered a portion of the study area and was used to obtain more accurate individual tree counts at spots detected on the 1:12,000 photos.

We examined the color infrared positive transparencies stereoscopically using the Abrams four-power model CB-1 stereoscope. The stereoscopic image was scanned for the presence of newly fading pine crowns, which were circled and numbered. Previously mapped faders were excluded by manually back-checking each pine mortality spot detected against the previous set of photos. This ensured that any mortality spot was recorded only once and on the earliest set of photos upon which the crowns appeared faded.

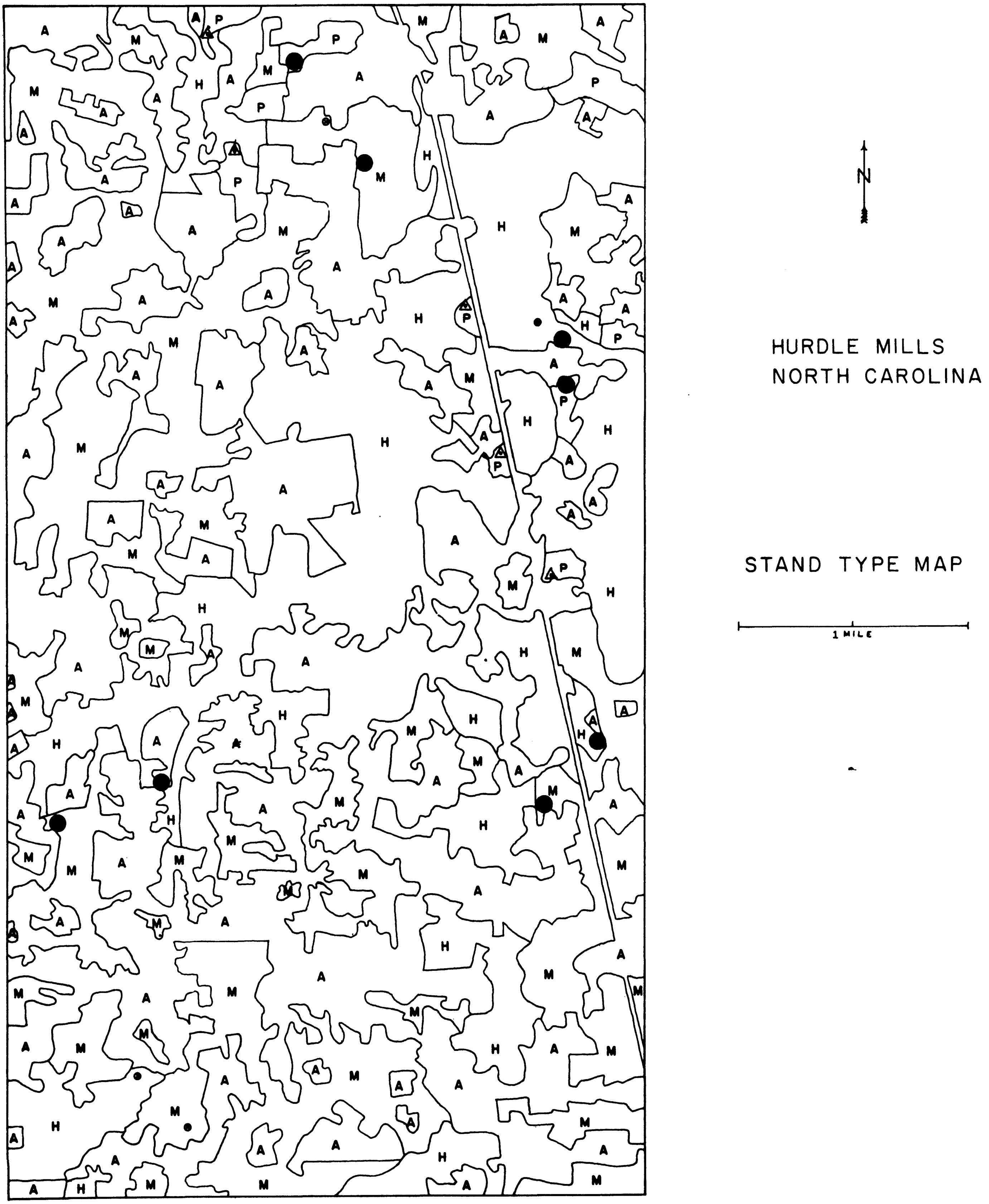


Figure 2.--Stand type map for 8600-acre study plot. P = pine, H = hardwood, M = mixed pine-hardwood, A = agricultural.

In order to prepare tree mortality maps, the Cartesian coordinates of all information annotated on the photo templates were digitized using a Numonics Graphics Calculator. The maps and map overlays were plotted on a Hewlett-Packard plotter.

Some of the mortality spots were ground checked by locating the exact faded trees on the ground and collecting relevant data such as d.b.h., tree height, crown color, and brood stage at breast height. A hand-held field board, with the sun as a light source, allowed stereo viewing of the original photography and greatly facilitated accurate location of the mortality spots.

In addition, more intensive information was subsampled from 57 trees in the eight population study plots. The type of data and collecting procedures have already been described by Coulson et al. (1975). This provided us with very precise information about the stand and site factors within these plots. It also enabled us to accurately estimate within-tree populations of the subsampled trees by using the topological procedures described by Pulley et al. (1976). Population data was collected during the first four photo periods. After that no additional sample trees could be found. Fifteen trees were first sampled from Julian dates 188 to 220, 16 from 221 to 251, 12 from 252 to 281, and 14 from 282 to 322.

RESULTS

Aerial Photo and Ground-Check Information

Information from the aerial photos is depicted in figures 3-10; each shows the number of photo-detected SPB spots for that particular flight date. Once again, photos were taken at approximately 1-month intervals. The black *x*'s represent spots where population data was being collected at that time. This phenomenon cannot be explained solely by the slow fade of trees during the winter months, since the number of spots started declining before cold weather set in and since we did not pick up any significant flush of fading trees in the early summer of 1977.

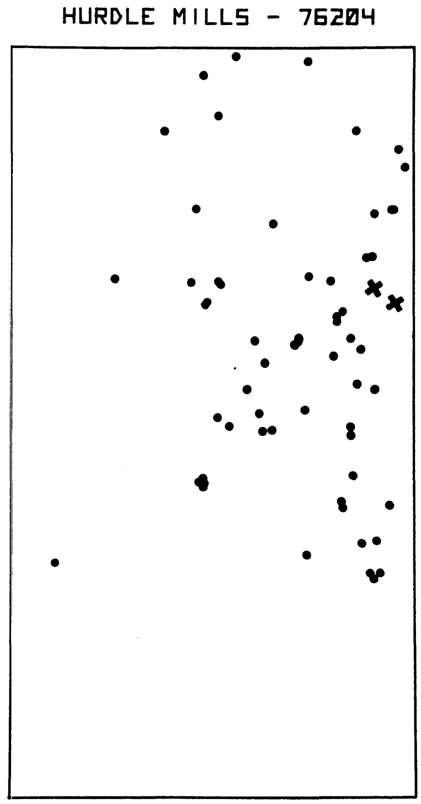


Figure 3.

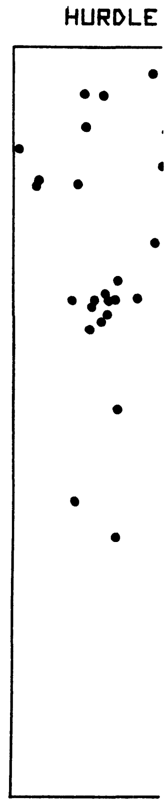


Figure 4.

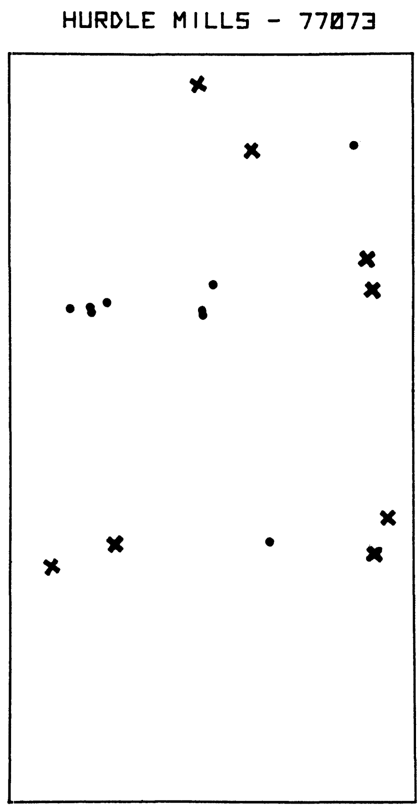


Figure 7.

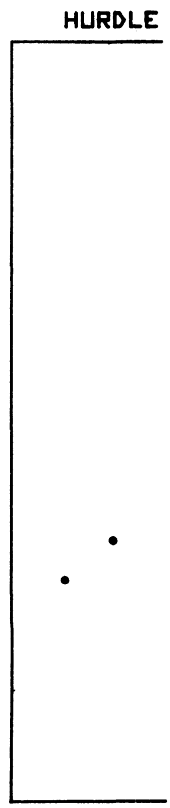
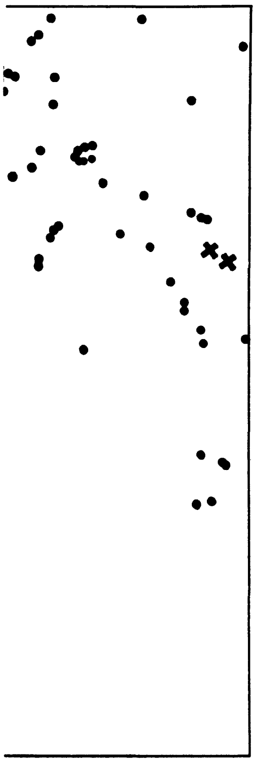


Figure 8.

Figures 3-10.--Photo-detected southern pine beetle spots on various Julian dates. X = spot where population data were being taken at given dates.

MILLS - 76237



HURDLE MILLS - 76266

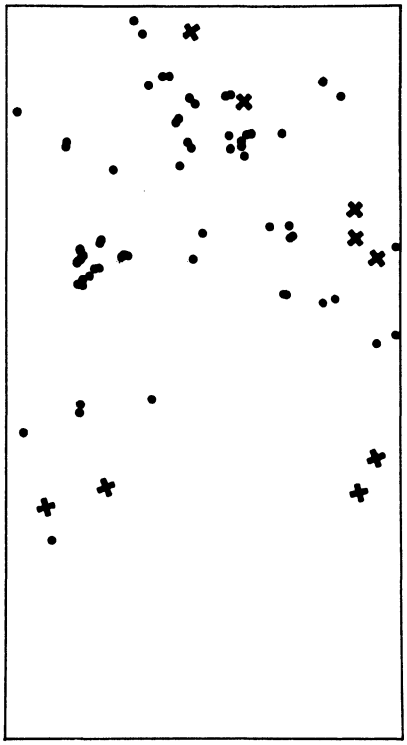


Figure 5.

HURDLE MILLS - 76296

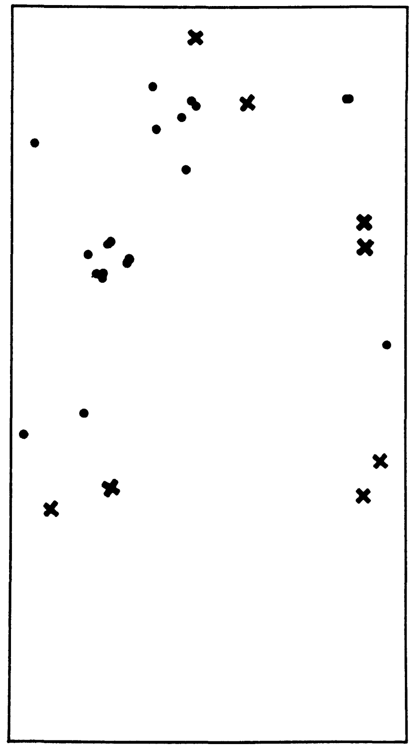
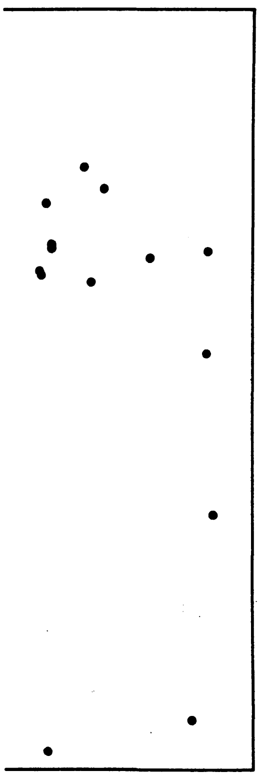


Figure 6.

MILLS - 77118



HURDLE MILLS - 77147

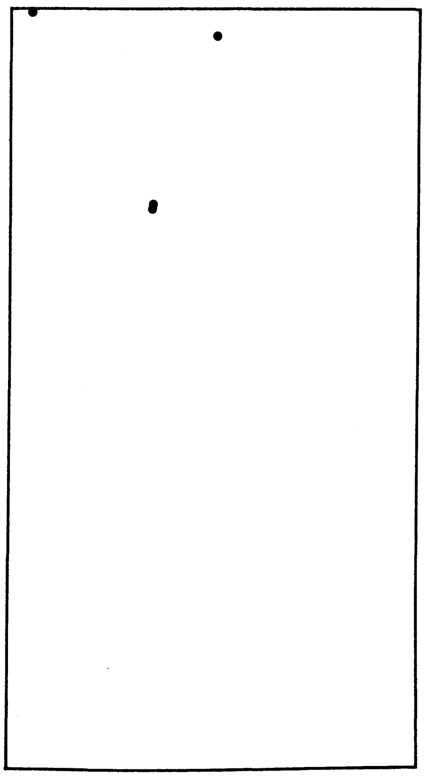


Figure 9.

HURDLE MILLS - 77173

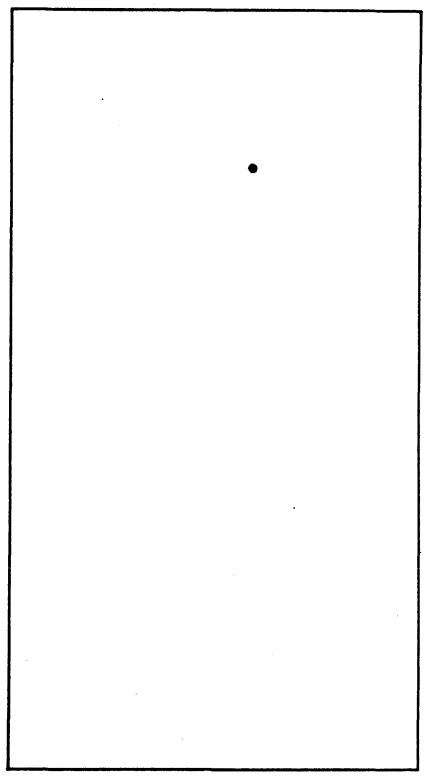


Figure 10.

Figure 11 shows the number of photo-detected trees that have faded during each photo period and dramatically depicts the decline. Both the total number of trees and the average number per spot showed a significant reduction by Julian date 266 (September 22). By this date the rate of crown fade should still be fairly high and not an important factor in the shape of the curve. C. J. DeMars will elaborate on this reduction in spot number and spot size in the next paper. So from this information it is apparent that by September 22 something dramatic was happening to the population in this area.

Also with regard to the aerial information, we attempted to correlate crown color with SPB life stages at breast height during each flight period. If such a correlation were possible, we felt it could be useful in estimating brood stage and area-wide population density from the aerial photographs with a minimum of ground check information. However, figures 12 and 13 show that very little correlation exists even during relatively short time periods. There is so much variation in the rate of crown fade among trees that the best we can do is assume that a certain proportion of orange-top trees will have larvae at breast height and a certain proportion will have brood adults, and so on. This would be based upon our ground survey information. A precise correlation is not possible, nor is a precise statement about proportions possible, as figure 13 shows. This figure illustrates the next flight period (early October to early December), and it shows that the rate of crown fade has probably changed and hence so have the proportions in each crown color class. This information may be useful in estimating beetle stage and population size in this area, but it is unlikely to be useful in other areas or for other tree species.

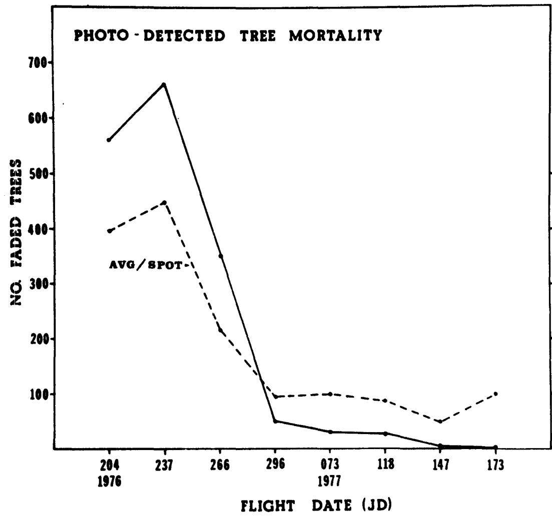


Figure 11.--Decline in numbers of faded trees during each photo period.

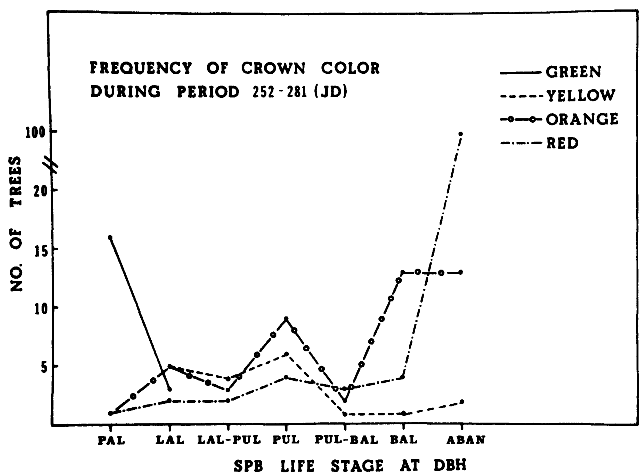


Figure 12.--Correlation of crown color with southern pine beetle life stage at breast height during first flight period.

Population Information

The population data collected during the first four photo flights also indicates a change in population conditions. Figure 14 shows average beetle density per square decimeter as derived from the topological estimates. It is interesting to note that attacking adult densities remained fairly constant during the study, while immature densities seemed to increase but brood adult densities showed a decline. This decline was first evident, although statistically nonsignificant, during the second photo flight when the aerial photographs revealed an increase in tree mortality. It wasn't until the third photo period that the photos showed a decline in tree mortality. The sharp decline in brood production during the fourth photo period was a result of the high overwintering mortality.

Although brood adult density was declining during the study, infested bole height (IBH) was increasing. Thus it is possible that total brood production per tree may have remained unchanged or even increased. However, that is not

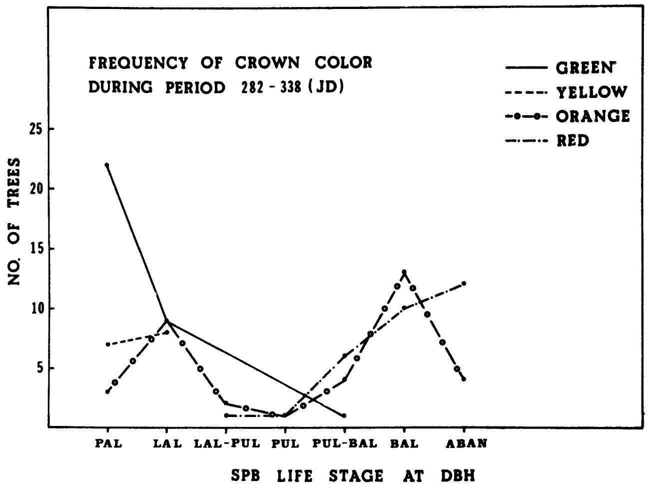


Figure 13.--Correlation of crown color with southern pine beetle life stage at breast height during second flight period.

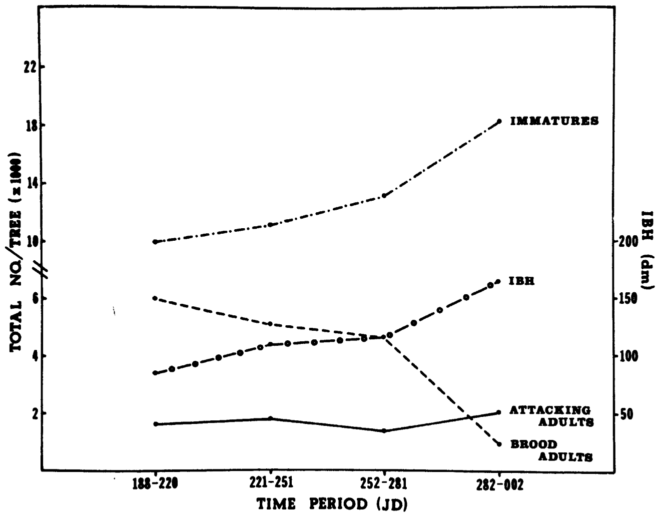


Figure 15.--Average numbers of beetles per tree, in each life stage, over time.

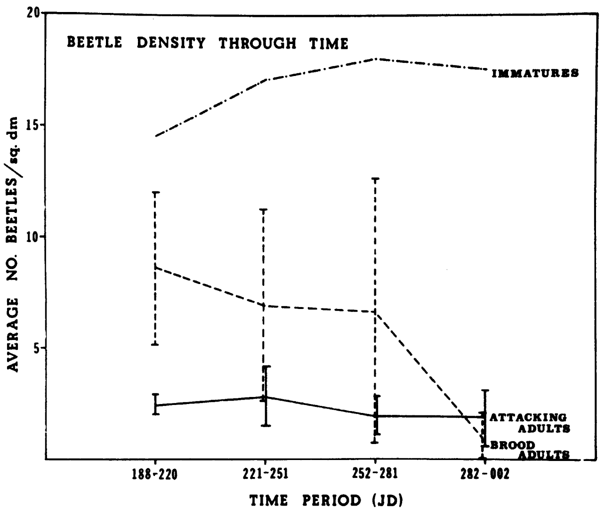


Figure 14.--Average beetle density over time, as derived from topological estimates.

the case, as figure 15 indicates. Total brood adult production per tree follows the same general pattern as the density curve even though immature production per tree was increasing. Although the population data appear to be signalling a change in status by the second photo date (August 24), and that change does not become obvious on the photos until the third photo date, the change in mean number of brood adults per tree from the second to the third photo date is not significant according to Student's *t* test. And by this time the decline was already in progress. Thus a great deal of time and effort was spent in obtaining precise within-tree population data that could show trends, but no statistically significant differences were found until the fourth photo period (when the collapse was obvious). Of course, it is possible that if population data had been taken earlier in the epidemic cycle, a decline in within-tree density would have been more apparent.

We have concluded that the aerial photo information was more sensitive than the within-tree density in detecting the SPB collapse. Therefore, aerial photos would be most useful in evaluating the types of treatments that do not result in direct beetle mortality, such as stand thinning. The within-tree population data would probably be more useful in evaluating treatments that do result in direct beetle mortality, such as insecticides.

We also believe that the most useful ground information for evaluating treatments that do not result in direct beetle mortality would be the number of active trees per spot and their brood stage classes. Since the size of our spots declined as the population declined, the synchrony between beetle emergence and pheromone production was probably lacking, resulting in beetle dispersal and apparent higher mortality.

The number of aerial flights necessary for an effective evaluation is probably no more than two or three--one before treatment to determine the overall status of SPB, one about 2 months after treatment to determine the immediate effects, and one in 6 to 12 months to evaluate the longer-term effects.

LITERATURE CITED

Coulson, R. N. 1974. Southern pine beetle population dynamics. *In* Southern pine beetle symposium. T. L. Payne, R. N. Coulson, and R. C. Thatcher, eds. p. 26-31. Texas A&M University Press, College Station, Tex. [College Station, Tex., Mar. 1974.]

Coulson, R. N., F. P. Hain, J. L. Foltz, and A. M. Mayyasi. 1975. Techniques for sampling the dynamics of southern pine beetle populations. 19 p. Tex. Agric. Exp. Stn. Misc. Publ. 1185. College Station, Tex.

DeMars, C. J., Jr., J. Caylor, B. Erving, and P. Rauch. 1973. Estimating cause and pattern of insect-killed trees from aerial photographs. Int. Union For. Res. Organ. Proc. 4th Conference Adv. Grp. For. Statistics. [Vancouver, B.C., Aug. 1973.]

Heller, R. C., and J. F. Wear. 1969. Sampling forest insect epidemics with color films. *In* Proc. 6th Int. Symp. on Remote Sensing of Environ. p. 1157-1167. Univ. of Michigan Press, Ann Arbor, Mich. [Ann Arbor, Mich., 1969.]

Pulley, P. E., J. L. Foltz, A. M. Mayyasi, and R. N. Coulson. 1976. Topological mapping to estimate numbers of bark-inhabiting insects. Environ. Entomol. 5:640-643.

DISTRIBUTION AND ABUNDANCE

OF PHOTO-DETECTED TREE MORTALITY OVER TIME

C. J. DeMars, F. P. Hain, and G. W. Slaughter[1]

Abstract.--The distribution and abundance of tree mortality caused by the southern pine beetle occurring on an 8568-acre tract at Hurdle Mills, N.C., was measured during summer and fall 1976 and spring 1977. Infrared aerial transparencies were used to detect and count tree mortality at 30-day intervals. Tree mortality was highest in July and August, declined sharply in October, and fell to only two trees the next June. Contingency table analysis of the frequency of tree mortality spots in geometrically increasing size classes gave nonsignificant χ^2 values in comparisons between dates. Significant χ^2 values were obtained for contingency table analysis of the total tree occurrence within the same size classes. The relationships of tree mortality abundance and frequency to stand pine composition suggest a logistic growth equation; however, the R^2 values obtained were not statistically significant.

INTRODUCTION

The southern pine beetle, *Dendroctonus frontalis*, is a consistent killer of trees. These bark beetles express their population statistics through the host trees they kill. Data recorded on the number of trees killed by southern pine beetles (SPB) suggest that these beetle populations and accompanying tree mortality increase and decrease exponentially.

[1] The authors are, respectively, Research Entomologist, Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Berkeley, Ca.; Associate Professor, Dept. of Entomology, North Carolina State University, Raleigh, N.C.; and Staff Research Associate, Dept. of Plant Pathology, University of California, Berkeley, Ca.

Terms used in analysis of population changes over time--distribution and abundance, in particular--have been given various and nonspecific meanings in the literature of several disciplines, including zoology, botany, statistics, and ecology.

This paper provides specific, operational definitions of the terms *distribution* and *abundance*, analyzes data sets of tree mortality for evidence of changes over time, and discusses how the results of this study may apply to the practical problem of measuring treatment effects over wide areas in control experiments of bark beetle populations.

Background of Conflict

Since the publication of *Animal Ecology* by Elton in 1927, the central theme of ecology has been the *distribution* and *abundance* of animals in nature (Andrewartha 1961). Both terms have been used by zoologists, botanists, and statisticians, but often with quite different meanings.

For example, Andrewartha and Birch (1954) state

> The concept of *distribution* is well understood by naturalists. The *distribution* of a species coincides with the broad geographical limits inside which the species may be found more or less permanently established. It has become customary to separate distribution from abundance. . . . However necessary this abstraction may be as a methodological device, the separation should never be allowed to persist in the final synthesis, for distribution and abundance are but the obverse and reverse aspects of the same problem.

Although these authors define *density* as the number of individuals in a particular area, they do not specifically define *abundance*. This concept can be grasped only by examining their illustrations as represented by the area under a density distribution curve. Their definition of abundance, then, is "population total." Southwood (1966) also uses *abundance* in this manner, but again one has to examine his graphics to infer what is meant.

Quantitative studies of bark beetles have usually described the distribution of observed sample densities at one point in time with respect to height on the tree (Hain et al. 1978, Mayyasi et al. 1976, Nebeker et al. 1978, and Stephen and Taha 1976) or over both height and time (Coulson et al. 1979, and DeMars et al. 1970). In a symposium on insect abundance (Richards and Southwood 1967), *abundance* was used to mean multitudes of insects, as in "outbreak" or "epidemic." In summary, entomologists use *distribution* to mean the location of various densities within a habitable range, and *abundance* in an undefined manner but meaning population total or "too many insects for comfort."

From the statistical point of view, Pielou (1969) notes that much confusion exists in the ecological literature because *distribution* is used in both its colloquial sense of "arrangement" or "pattern" and its statistical sense of the way a variate is apportioned. She concisely states the statistical view: "A variate has a distribution, whereas a collection of organisms has a pattern." Note that this use of *pattern* or *arrangement* is the meaning in DeMars (1970) but is different from the definition of species distribution within broad geographical limits of Andrewartha and Birch (op. cit.). Pielou contends that while much work has been done on the arrangement in space of organisms at one moment in time, little headway has been made in combining the accounting for the organisms' pattern in space with tracing how they vary with time. These two topics continue to be somewhat isolated from each other: studies of spatial patterns make little reference to population dynamics, and studies of population dynamics usually ignore pattern.

We contend that because of the bark beetles' habit of only temporarily occupying a tree and then moving to new trees in the next generation, any technique for evaluating a proposed SPB control strategy must incorporate these two elements--pattern and abundance. Since SPB expresses its population characteristics through the host trees that it kills, it is important to review how plant ecologists define *distribution* and *abundance*.

Among botanists, *distribution* has the same variations in usage as were found among zoologists (Greig-Smith 1964, Kerhsaw 1964); however, the definition of *abundance* has been more directly addressed. Since 1927, ecologists in Britain have used five abundance classes: Dominant, Abundant, Frequent, Occasional, and Rare (Kershaw 1964). The Braun-Blanquet approach, used in Europe, is a quantitative expression of the percentage of ground cover provided by a plant species, which can be expressed on a "Domin scale" of 0 to 10.

Greig-Smith (1964) summarized the plant ecologists' view with the following definitions on the basis of area sampling with quadrats:

(1) Abundance is the average number of individuals per occupied quadrat.

(2) Density is the average number of individuals per quadrat.

(3) Frequency is the proportion of quadrats occupied.

These are specific, operational definitions which we shall apply in our analysis.

The question of how to treat *distribution* re mains open. Most appropriate for our purposes is the approach used by C. B. Williams (1964) in his analysis of light trap data describing the number of moth species with different numbers of individuals. Plots of his data take the form of a "hollow curve" with an extremely long tail. Data recording the number of trees killed at SPB spots mapped over a large area has the same form. Encouraged by Williams' comment, "Since order cannot be made out of chaos by mere sampling, we must infer that there is some related order in the relative abundance of the species in the population sampled," we infer that the order in SPB populations is based upon geometric changes in population size. Assuming that SPB populations and concomitant tree mortality increase and decrease exponentially, we propose two hypotheses for testing:

Hypothesis 1

In forested tracts with similar stand mosaics, populations of SPB in the same phase of expansion (outbreak) or contraction (collapse) have similar proportional allocation of killed host trees to successive frequency classes with limits increasing on a geometric scale.

Hypothesis 2

In a forested tract composed of stands varying in pine composition, population expansion (outbreak)and contraction (collapse) will be expressed through geometrically increasing or decreasing use of stands with arithmetically increasing proportions of pine composition.

Statistical Analysis

In selecting the statistical procedure to evaluate the effect of a treatment such as cut-and-leave, we assumed that it would be applied over a very large area in order to reduce the effect of beetles flying into and out of the treated zone. Such an area would be from several thousand to tens of thousands of acres in size. Replication sufficient to apply analysis of variance procedures would be costly on units this large; therefore, we propose that the treatment effect be measured by an analysis of the change in the internal structure of the population of dead trees in a treated area compared to that in an untreated area. This procedure would allow for testing the relative difference between two treatments when there is no check area. The limitation on this method is that without replicates, no general conclusions can be drawn as to the effectiveness of the treatment strategy for other areas.

MATERIALS AND METHODS

Several steps are involved in obtaining useful tree mortality trend information from aerial photographs. The particular specifications vary depending upon the objectives of the study, but there are elements common to every study: (1) photo acquisition, (2) photo interpretation, (3) data capture and verification, (4) data file manipulation, (5) establishing ground truth, and (6) data summary and analysis.

Photo Acquisition

The 8568-acre study area at Hurdle Mills, North Carolina, described in a previous paper (Hain et al. 1979) was also used for this analysis. Color infrared aerial transparencies (Kodak Aerochrome 2443)[2] in a 9 × 9-inch format were taken at approximately 30-day intervals during the summer and fall of 1976 and the spring of 1977. The 30-day interval was chosen to correspond to the anticipated time for SPB broods to complete development. Foliage fading usually became noticeable 2 or 3 weeks after the tree was attacked. This time lag was longer in the cooler months, and photos were taken at longer intervals. The photos were taken by the North Carolina State Highway Department using a Herrbrugg RC-10 aerial camera with a 6-inch focal length lens. On each photo date, the entire study area was mapped at medium scale (1: 12,000) with stereo photography (60 to 75 percent overlap and 25 to 30 percent sidelap) to detect active pine mortality spots and to provide tree counts at each spot.

Photo Interpretation

The photos were interpreted on split-top, fluorescent light tables fitted with a cool white tube, using an Abrams model CB-1® folding stereoscope at 4× magnification. The photos were interpreted to locate the images of trees with recently faded foliage. Images from several dates were compared to determine the earliest date on which fading was apparent. On infrared photographs, healthy pine foliage appears red-brown, off-color green foliage appears pink, yellow-to-orange foliage appears white, reddish-brown foliage appears yellow to yellow-orange, and completely defoliated trees appear blue-gray to gray.

Data Capture and Verification

A clear acetate overlay was prepared for each stereo photo pair and annotated to record the center of detected tree mortality locations, the count of visible trees, the stand type, and a sequential spot identification number. Nine easily recognized points were selected on each detection photo to control the geometry of the mapping. The same points were also located on a U-2 photo that covered the entire study area on a single photograph.

---

[2] Mention of a proprietary or commercial product does not constitute recommendation or endorsement of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that also may be suitable.

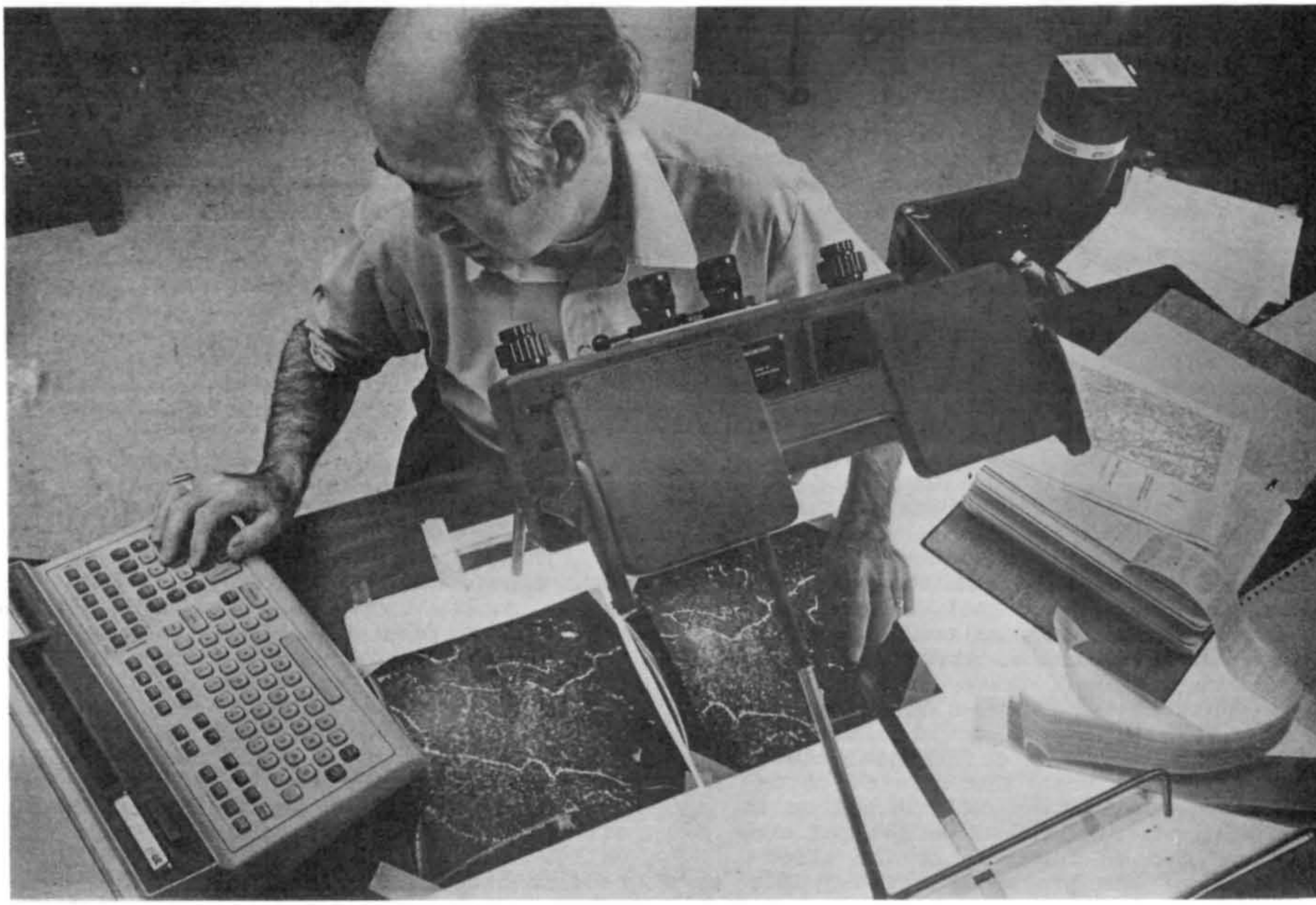


Figure 1.--Operator using Old Delph stereoscope and Numonics Graphics Calculator to digitize the Cartesian coordinates of control points and tree mortality spots. Digitizer is interfaced to the Hewlett-Packard 9825A desk-top calculator used to store and manipulate data files. (Photo credit: Dennis Galloway.)

The data were captured by digitizing the Cartesian coordinates using a Numonics Graphic Calculator® interfaced to a Hewlett-Packard 9825A® desk-top calculator (fig. 1). True scale photo overlays were plotted from the stored digitized data using an HP 9862A® calculator plotter. These graphics were visually compared to the acetate templates and photos to verify the point locations. The tabulated data were verified by comparing them to listings of the stored data.

Data File Manipulation

Tree mortality maps for each occasion were prepared by digitizing the control point net from the small-scale reference photo (U-2 photo) and then relating the control point locations on the detection photos to the corresponding locations on the reference photo. This was done by estimating the coefficients for two bivariate linear equations using a least squares procedure. The coefficients calculated were applied to the coordinates of tree mortality spot locations on the detection photos to compute their reference map locations. Mapping was achieved with an accuracy corresponding to 50 to 75 ft on the ground. The maps were reduced to a scale of 1:37,782.

An integer arithmetic algorithm was used to accumulate the spot locations and associated tree counts into 1-acre grid cells. We also identified the stand type code for each cell.

Establishing Ground Truth

Ground-check data were taken to relate the crown foliage color to the SPB brood stage. However, the distribution of ground-checked spots was inadequate to make a corrected estimate of total tree mortality. Because the detection rates were expected to be 85 to 90 percent of the total tree mortality

Table 1.--Average pine mortality (number) per spot by date and stand type, Hurdle Mills, N. C.

Julian date	Pine $\bar{X}$	Pine SD	Mixed $\bar{X}$	Mixed SD	Hardwood $\bar{X}$	Hardwood SD	All Stands $\bar{X}$	All Stands SD
76204	17.83	33.92	7.05	7.05	3.76	9.62	7.90	16.32
76237	14.85	24.18	6.11	6.11	9.89	13.72	8.93	15.01
76266	9.67	10.82	3.31	3.31	2.46	2.44	4.34	6.53
76296	1.75	.96	1.94	1.94	2.00	1.41	1.92	1.44
77073	1.43	.79	1.29	1.29	5.50	.71	1.88	1.52
77118	2.33	1.51	1.29	1.29	1.67	1.15	1.75	1.13
77147	1.00	0.00	1.00	0.00	0.00	-	1.00	.00
77173	0.00	-	2.00	-	0.00	-	2.00	-

Table 2.--Average pine mortality (number) per 1-acre cell (abundance) by date and stand type, Hurdle Mills, N.C.

Julian date	Pine $\bar{X}$	Pine SD	Mixed $\bar{X}$	Mixed SD	Hardwood $\bar{X}$	Hardwood SD	All Stands $\bar{X}$	All Stands SD
76204	17.83	33.92	8.93	12.28	4.16	10.07	9.20	18.36
76237	16.50	25.12	6.25	7.95	9.89	13.72	9.31	15.26
76266	11.15	12.49	3.69	5.00	2.83	2.48	4.88	7.21
76296	2.33	1.53	2.19	1.72	2.00	1.41	2.17	1.59
77073	2.00	1.00	1.29	.76	5.50	.71	2.14	1.66
77118	2.33	1.51	1.29	.49	1.67	1.15	1.75	1.13
77147	1.00	.00	1.00	.00	.00	-	1.00	0.00
77173	.00	-	2.00	-	.00	-	2.00	-

(Caylor and Thorley 1970, DeMars et al. 1973, and Heller 1974), for purposes of our analysis the photo-detected data were treated as a total enumeration.

Data Summary and Analysis

Means and standard deviations for the number of dead trees per unit were calculated within each stand type (pine, mixed, hardwood, and total) for two unit definitions--spots and occupied 1-acre cells *(abundance)*. The percentage of cells with tree mortality within each stand type *(frequency)* and the percentage of spots and trees within each stand type were calculated.

The tree mortality within each cell was summarized as the number of spots and the total number of dead trees. These data were then organized into frequency *distribution* classes using a ×3 geometric scale. Limits for each succeeding interval were set three times the width of the preceding interval. The class limits were I (1), II (2-4), III (5-13), IV (14-40), V (41-121), and VI (122-364) (Williams 1964).

Differences between populations of tree mortality from different dates were tested by two-way contingency table analysis using the χ^2 values computed on the *distribution* of both the frequency of dead tree spots and the total occurrence of dead trees by spot size class intervals.

The relationships between *abundance* for each stand type and total tree mortality and between *frequency* for each stand type and total tree mortality were investigated by linear regression. The slopes (rates) from these linear regressions were fitted to an exponential nonlinear model using the percent pine composition as the independent variable.

RESULTS

Trends in Tree Mortality

In July 1976, there were 561 recently faded trees visible on the photos at 71 spot locations (fig. 2A). Tree mortality peaked in late August at 661 trees at 74 spots (fig. 2B). Thereafter it declined through the fall and winter to a low of two trees at a single spot by late spring of 1977 (figs. 2C-2H).

The average number of trees per spot varied with stand type with spots in pine>mixed>hardwood stands (table 1). The declining trend in total tree mortality was also reflected in a decline in the average spot size. Variability about the means was very high, however, considering that it did not include a sampling error component but only the variance of a fully enumerated population. The combined data reflected the following: with eight to nine trees per spot, the standard deviation was nearly twice the mean; with four trees per spot, the standard deviation was half again as large as the mean and was not less than the mean until the average spot size declined to two trees per spot.

Tree mortality data organized by 1-acre cells to express *abundance* (table 2) followed the pattern of tree mortality in spots. Tree mortality per acre was greater in the pine stands than elsewhere, and the standard deviation exceeded the mean per cell by a wider margin. This result demonstrated the inappropriateness of testing for differences between two populations by comparison of the mean

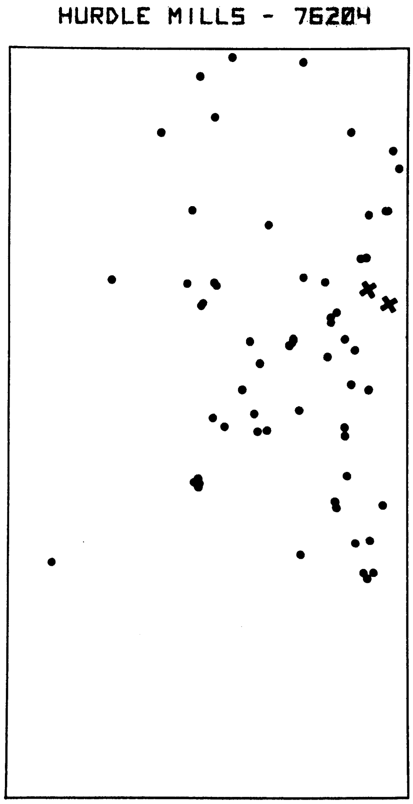


Figure 2A

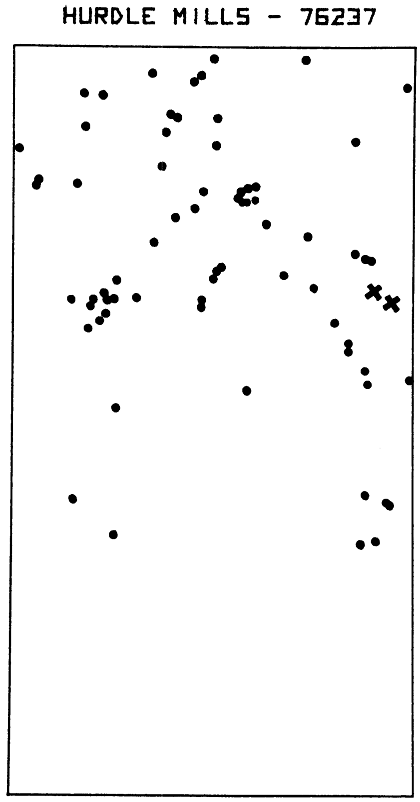


Figure 2B

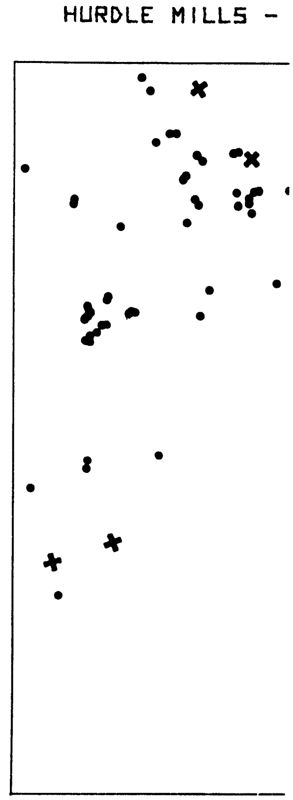


Figure 2C

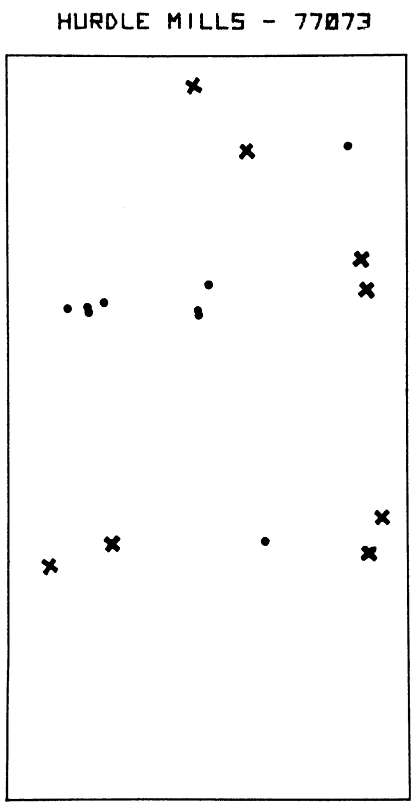


Figure 2E

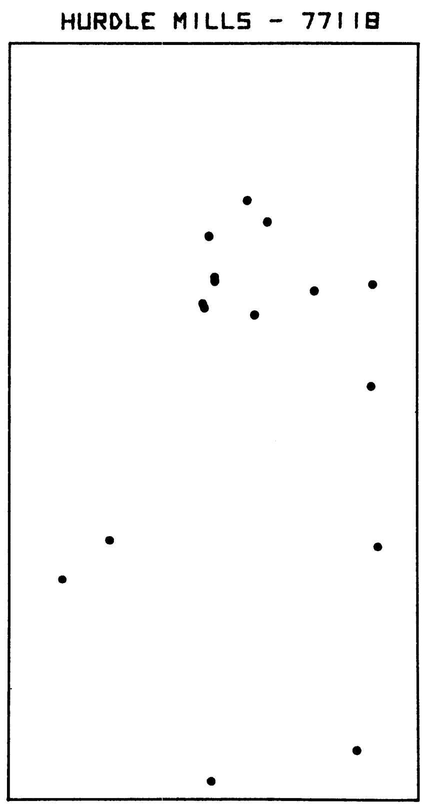


Figure 2F

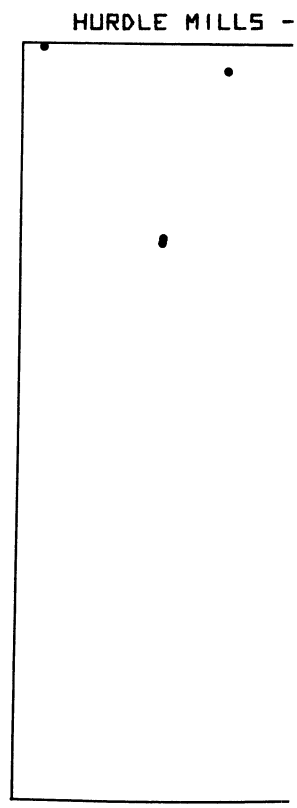


Figure 2G

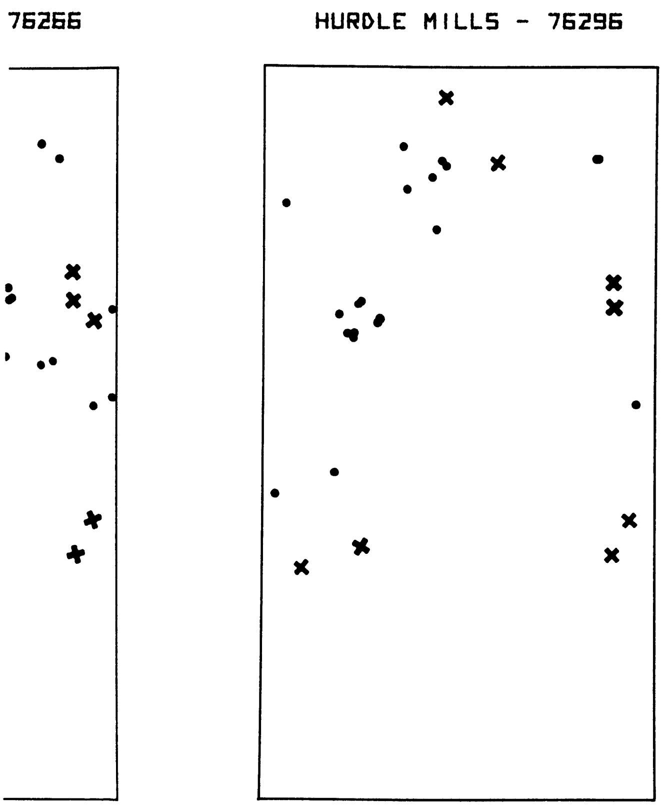


Figure 2D

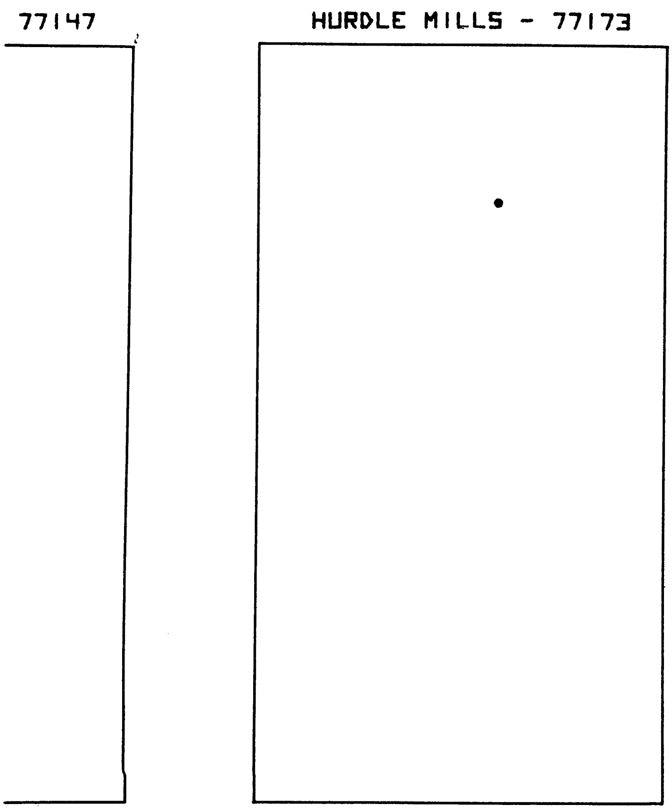


Figure 2H

Table 3.--Frequencies of tree mortality spot size classes on a ×3 geometric scale and χ^2 tests of paired totals, for Hurdle Mills, N.C.

		Julian dates							
	Inter-	1976				1977			
Class	val	204	237	266	296	073	118	147	173
I	1	30	25	42	14	11	9	3	0
II	2-4	17	19	18	10	3	6		1
III	5-13	11	17	16	2	2	1		
IV	14-40	11	10	6					
V	41-121	1	3						
VI	122-364	1							
Total Spots		71	74	82	26	16	16	3	1

Totals paired	χ^2	df	sig.	Totals paired	χ^2	df	sig.
71 74	1.79	3		74 16	2.82	1	ns
71 82	4.77	3		82 26	.05	1	ns
71 26	1.03	1		82 16	1.66	1	ns
71 16	3.68	1		82 16	.14	1	ns
71 16	1.03	1		26 16	.91	1	ns
74 82	6.56	3		26 16	.02	1	ns
74 26	3.26	1		16 16	.53	1	ns
74 16	6.70	1	**				

** Significantly different at P = .01.

number of trees per tree mortality spot. Data on the total number of trees and the total number of spots should be used. The ratio of the standard deviation to the mean supported the use of the geometric scale frequency classes in the *distribution* analysis.

Frequency and Occurrence Analysis

The frequency of spots within spot size classes I through VI shifted over time with the decline of the population of tree mortality (table 3). There were 13 spots with 14 or more trees on Julian dates 76204 and 76237, six on day 76266, and none thereafter. In spite of this large shift in frequencies, the χ^2 values from the contingency table analysis comparing the spot frequency distributions between the several dates showed nonsignificant differences in the proportional allocations, except between the 74 spots on day 76237 and the 16 spots on day 77073.

Figure 2.--Photo-detected tree mortality spot map for Hurdle Mills, N.C., for various Julian dates.

Table 4.--Distribution of tree mortality counts in spots by ×3 geometric spot size classes and χ^2 tests of paired totals, Hurdle Mills, N.C.

Class	Interval	1976 204	1976 237	1976 266	1976 296	1977 073	1977 118	1977 147	1977 173
		Julian dates							
I	1	30	25	42	14	11	9	3	1
II	2-4	45	49	50	24	8	14		2
III	5-13	84	144	116	12	11	5		
IV	14-40	235	252	148					
V	41-121	45	191						
VI	122-364	122							
Total Trees		561	661	356	50	30	28	3	2

Totals paired	χ^2	df	sig.	Totals paired	χ^2	df	sig.
561 661	10.50	4	*	661 28	120.00	2	**
561 356	83.00	3	**	356 50	52.30	2	**
561 50	155.70	2	**	356 30	22.96	2	**
561 30	70.60	2	**	356 28	44.96	2	**
561 28	116.41	2	**	50 30	3.63	2	
661 356	69.36	3	**	50 28	1.09	2	
661 50	154.63	2	**	30 28	4.02	2	
661 30	74.23	2	**				

* Significant at P = .05.
** Significant at P = .01.

Table 5.--Frequencies of tree mortality cell size classes on a ×3 geometric scale and χ^2 tests of paired totals, Hurdle Mills, N.C.

Class	Interval	1976 204	1976 237	1976 266	1976 296	1977 073	1977 118	1977 147	1977 173
		Julian dates							
I	1	25	22	32	11	8	9	3	0
II	2-4	13	19	19	10	4	6		1
III	5-13	11	16	16	2	2	1		
IV	14-40	9	11	6					
V	41-121	2	3						
VI	122-236	1							
Total Cells		61	71	73	23	14	16	3	1

Totals paired	χ^2	df	sig.	Totals paired	χ^2	df	sig.
61 71	1.65	3		71 16	3.63	1	
61 73	3.87	3		73 23	.11	1	
61 23	.32	1		73 14	.84	1	
61 14	1.21	1		73 16	.81	1	
61 16	1.20	1		23 14	.30	1	
71 73	5.03	3		23 16	.27	1	
71 23	2.16	1		14 16	.00	1	
71 14	3.50	1					

Table 6.--Distribution of tree mortality counts in cells by ×3 geometric scale cell size classes and χ^2 tests of paired totals, Hurdle Mills, N.C.

Class	Interval	1976 204	1976 237	1976 266	1976 296	1977 073	1977 118	1977 147	1977 173
		Julian dates							
I	1	25	22	32	11	8	9	3	0
II	2-4	33	48	51	27	11	14		2
III	5-13	85	131	119	12	11	5		
IV	14-40	193	269	154					
V	41-121	103	191						
VI	122-364	122							
Total Trees		561	661	356	50	30	28	3	2

Totals paired	χ^2	df	sig.	Totals paired	χ^2	df	sig.
561 661	20.00	4	*	661 28	120.00	2	**
561 356	90.95	3	**	356 50	60.26	2	**
561 50	155.70	2	**	356 30	22.96	2	**
561 30	70.60	2	**	356 28	44.96	2	**
561 28	116.41	2	**	50 30	2.40	2	ns
661 356	69.83	3	**	50 28	1.09	2	ns
661 50	154.63	2	**	30 28	2.60	2	ns
661 30	74.23	2	**				

* Significantly different at P = .05.
** Significantly different at P = .01.

When tree counts within the same spot size classes were accumulated, however, a stronger measure of the shift in tree mortality distribution was apparent (table 4). χ^2 values for contingency table analyses showed significant differences for all contrasts except for those that included only data taken after October 1976. By then, the population had collapsed and no differences would be expected. These analyses all support the first hypothesis.

The close-to-marginal χ^2 value for the difference between 561 and 661 trees suggested that it should be possible to find areas with nonidentical tree mortality totals but which are not significantly different and could be used as equivalent plots in experimental designs. The highly significant differences between 561 and 356 and between 561 and 50 suggested that treatment-related reductions in tree mortality, varying from 50 to 90 percent, could be demonstrated to be statistically significant.

The frequency of 1-acre cells within the class intervals 1, 2-4, 5-13, 14-40, 41-121, and 122-364 trees per cell (table 5) followed the pattern estab-

Table 7.--Percentage of SPB-caused mortality spots, cells, and trees by stand types for eight dates, Hurdle Mills, N. C.

Julian date	Pine			Mixed			Hardwoods		
	Spots	Cells	Trees	Spots	Cells	Trees	Spots	Cells	Trees
76204	16.90	19.67	38.15	53.52	49.18	47.77	29.58	31.15	14.08
76237	27.03	25.35	44.93	60.81	61.97	41.61	12.16	12.68	13.46
76266	18.29	17.81	40.73	65.85	65.75	50.28	15.85	16.44	8.99
76296	15.38	13.04	14.00	69.23	69.57	70.00	15.38	17.39	16.00
77073	43.75	35.71	33.00	43.75	50.00	30.00	12.50	14.29	36.67
77118	35.29	37.50	50.00	41.18	43.75	32.14	17.65	18.75	14.29
77147	33.00	33.33	33.00	67.00	66.67	67.00	0.00	0.00	0.00
77173	0.00	0.00	0.00	100.00	100.00	100.00	0.00	0.00	0.00

lished by the spots. In most cases there was only one spot per cell, but in a few cases several spots were combined and the total number of trees in the cell caused a shift to another cell size class. These changes did not result in any changes in the contingency tests that compared the total number of occupied cells on the several dates.

When the tree mortality count by cells was accumulated for each class interval to obtain the distribution of the occurrence of tree mortality, significant χ^2 values were obtained for most comparisons (table 6). The similarity between the results for analyses based upon spot and cell data suggested that either variable could be used to compare two areas for treatment effect. The choice of spot or cell approach is dictated by balancing the simplicity of the spot method with no digitization against the utility of the cell method that permits analysis of underlying covariables of explanatory and predictive value. The cell method does introduce a possible bias, though, since some orientation must be introduced. This could cause some different results but seems insignificant here.

Distribution of Tree Mortality by Stand Type

When total tree mortality was greater than 350 trees (Julian dates 76204, 76237, and 76266), more than 38 percent of the tree mortality was found in the pine type (table 7). This figure represents a high proportion of the total tree mortality when we consider that pure pine stands (≧90 percent pine) make up only 2 percent of the total forested area. Mixed stands (31 to 89 percent pine), occurring on 61 percent of the 3513 forested acres, contained from 42 to 50 percent of the tree mortality on those dates. At the low tree mortality levels found on Julian dates 77147 and 77173, nearly all the dead trees were found in mixed stands. Hardwood stands (≦30 percent pine), occurring on 37 percent of the forested acres, contained less than half that percentage of the trees except in one instance. The mortality in hardwood stands probably occurred in patches of pine that were too small to delineate as separate stands.

The percentage of trees killed by SPB was greater than the *frequency* (percentage of cells infested) in the pine stands, and less than the *frequency* in the mixed or hardwood stands. This condition reflects the obvious fact that large tree mortality spots occurred only in pure pine stands. This phenomenon may be analyzed quantitatively by regression analysis of the *abundance* for each date (table 2) on the tree mortality totals for that date (table 4). The slope of the regression line for *abundance* in pine stand was significantly different from the slopes for mixed and hardwood stands, but the latter were not different from each other (fig. 3). From this we conclude that average spot size was not different in mixed and hardwood stands, but the total number of spots was much greater in the mixed stands.

The three slopes were fitted to an exponential equation having the percentage of pine in the stand as the independent variable (fig. 4). Class midpoints for pine percentage in the three stand types were used. This fit is based upon only three points and the r^2 value of .72 is not significant. The curve does suggest an exponential relationship that would be more sensitively tested if data were available for tree mortality rates for smaller intervals of pine percentage in the stand.

A test of the second hypothesis was derived from a regression analysis of *frequency* data for each date by stand

Table 8.--Frequency of 1-acre cells occupied by dead pines by date and stand type, Hurdle Mills, N. C.

Julian date	(Percent)			
	Pine	Mixed	Hardwood	Total
76204	13.95	1.40	1.48	1.74
76237	20.93	2.05	.70	2.02
76266	15.12	2.24	.93	2.08
76296	3.49	.75	.31	.65
77073	5.81	.33	.16	.40
77118	6.98	.33	.23	.46
77147	1.16	.09	.00	.09
77133	0.00	.05	.00	.03

type (table 8) as a function of the total tree mortality on that date (fig. 5). The slopes of these linear regressions for mixed and hardwood stands were again different from the slope for pine stands, but not from each other. The nonzero intercepts were an artifact of data because all should have passed through the origins. This analysis demonstrated that the percentage of pine acres infested by SPB increased as a linear function of the total tree mortality. A similar relationship held in the other stand types but the rates of infestation were not equal. A nonlinear, exponential model of these rates as a function of the percent of pine in the stand (fig. 6) suggests some support for the second hypothesis, although the r^2 value of .85 and the paucity of the data do not provide a statistically significant test.

DISCUSSION

The results of this study indicate that tree mortality resulting from SPB infestation in two populations may be compared on the basis of the total occurrence of dead trees in geometrically increasing class size spot or grid cell counts. But because this comparison involves the contrast between two unreplicated areas, one cannot infer from a single trial the general applicability of the treatment that resulted in the difference. We may conclude from a single contrast whether cut-and-leave had an effect in a particular instance, but without replication we cannot conclude how likely we are to be able to repeat the results.

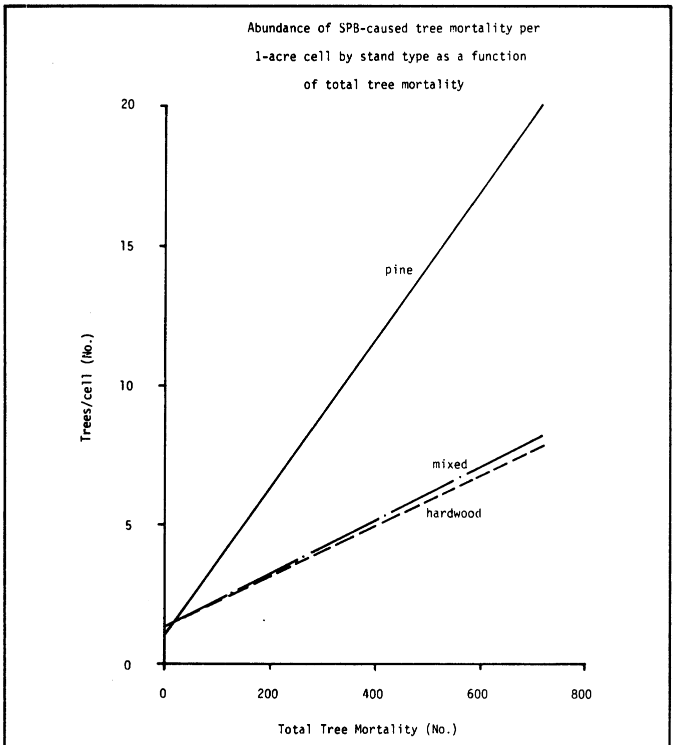


Figure 3.--Abundance of SPB-caused tree mortality per 1-acre cell by stand type as a function of total tree mortality.

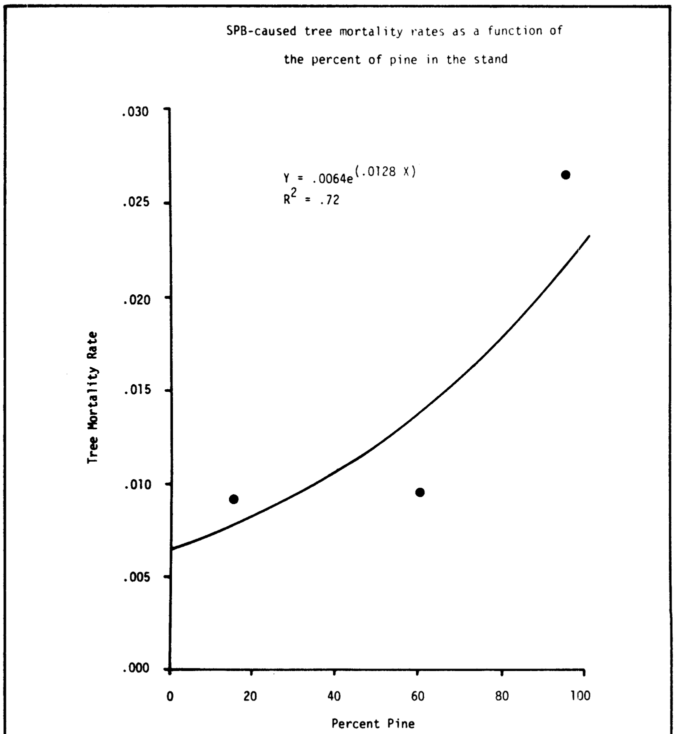


Figure 4.--SPB-caused tree mortality rates as a function of the percent of pine in the stand.

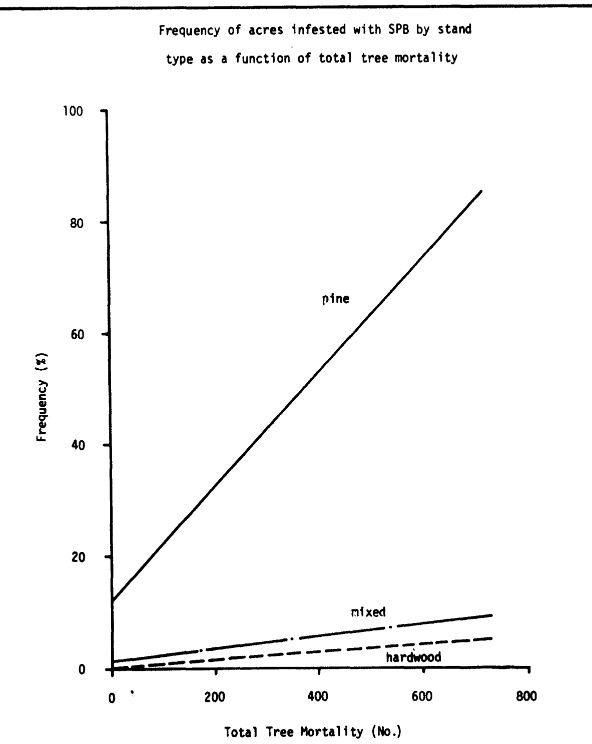


Figure 5.--Frequency of acres infested with SPB by stand type as a function of total tree mortality.

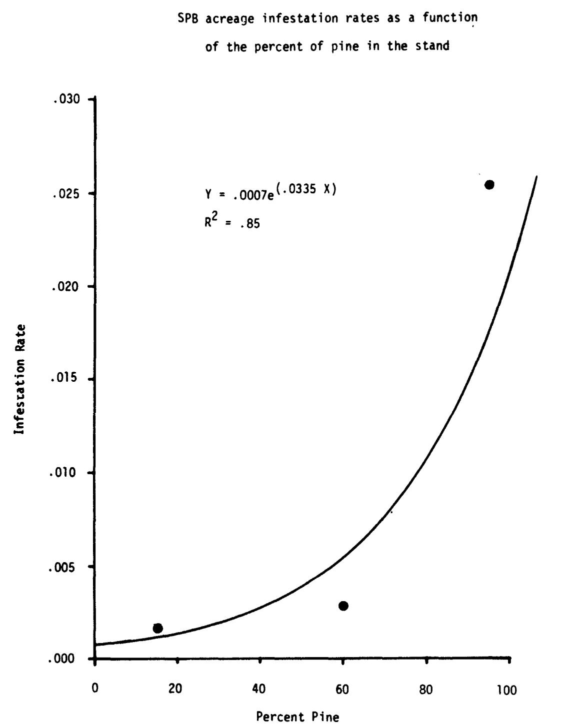


Figure 6.--SPB acreage infestation rates as a function of the percent of pine in the stand.

A suggestion of conformance to the hypotheses concerning geometric rates of population change was found, but statistical tests gave nonsignificant results. The χ^2 tests performed upon spot count data are simpler to obtain because no digitization of the data is required. However, digitization permits a higher degree of quality control in data collection and an integrated analysis of both population trend and pattern. We have identified digitization as a necessary requirement for evaluating bark beetle treatment tactics.

ACKNOWLEDGMENTS

The authors thank Mr. Chester Gray of the Photogrammetry Unit, North Carolina State Highway Department, for his assistance in obtaining the aerial photographs. We thank Drs. R. N. Coulson, G. T. Ferrell, and F. M. Stephen, and Mr. W. D. Mawby for helpful reviews of the manuscript.

This work was funded in part by a USDA-sponsored program entitled the "Expanded Southern Pine Beetle Research and Applications Program." The findings, opinions, and recommendations are those of the authors and not necessarily those of the USDA.

LITERATURE CITED

Andrewartha, H. G. 1961. Introduction to the study of animal populations. 281 p. Univ. of Chicago Press, Chicago.

Andrewartha, H. G., and L. C. Birch. 1954. The distribution and abundance of animals. 782 p. Univ. of Chicago Press, Chicago.

Caylor, J. A., and G. A. Thorley. 1970. Sequential aerial photography as an aid in the evaluation of bark beetle population trends in westside Sierra forests. *In* Studies on the population dynamics of the western pine beetle, *Dendroctonus brevicomis* LeConte (Coleoptera:Scolytidae). p. 8-32. R. W. Stark and D. L. Dahlsten, eds. Univ. of California, Div. Agri. Sci., Berkeley, Cal.

Coulson, R. N., W. S. Fargo, P. E. Pulley, D. N. Pope, J. L. Foltz, and A. M. Bunting. 1979. Spatial and temporal patterns of emergence for within-tree populations of *Dendroctonus frontalis*. (Coleoptera:Scolytidae). Can. Entomol. 3:273-287.

DeMars, C. J., Jr. 1970. Frequency distributions, data transformations and analysis of variations used in determination of optimal sample size and effort for broods of the western pine beetle. *In* Studies on the population dynamics of the western pine beetle, *Dendroctonus brevicomis* LeConte. p. 42-65. R. W. Stark and D. L. Dahlsten, eds. Univ. of California, Div. Agri. Sci., Berkeley, Cal.

DeMars, C. J., Jr., A. A. Berryman, D. L. Dahlsten, I. S. Otvos, and R. W. Stark. 1970. Spatial and temporal variations in the distribution of the western pine beetle, its predators and parasites, and woodpecker activity in infested trees. *In* Studies on the population dynamics of the western pine beetle, *Dendroctonus brevicomis* LeConte. p. 80-101. R. W. Stark and D. L. Dahlsten, eds. Univ. of California, Div. Agri. Sci., Berkeley, Cal.

DeMars, C. J., Jr., J. Caylor, B. Ewing, and P. Rauch. 1973. Estimating cause and pattern of insect-killed trees from aerial photographs. *In* Statistics in forestry research. Int. Union. For. Res. Organ. Fourth Conference of Advisory Group on Forest Statistics. Subj. Group S6.02, p. 37-47. Can. For. Serv., Ottawa. [Vancouver, B.C., Aug. 1973.]

Elton, C. 1927. Animal ecology. Sidgwick and Jackson, London.

Greig-Smith, P. 1964. Quantitative plant ecology. 2nd ed. 256 p. Butterworths, Washington, D.C.

Hain, F. P., C. J. DeMars, W. T. McClelland, and W. D. Mawby. 1979. Relating tree mortality to collapsing beetle populations. *In* Evaluating control tactics for southern pine beetle: symposium proceedings. p.54. J. E. Coster and J. L. Searcy, eds. [Many, La., January/February 1979.] USDA For. Serv., Tech. Bull. .

Hain, F. P., W. T. McClelland, D. N. Pope, P. E. Pulley, J. L. Foltz, and R. N. Coulson. 1978. Standardized within-tree sampling for populations of *Dendroctonus frontalis*. Environ. Entomol. 7:157-64.

Heller, R. C. 1974. Remote sensing as an inventory tool for forest insect surveys. *In* Monitoring forest environment through successive sampling. Proc. p. 321-343. State University of New York, Syracuse, N.Y. [Syracuse, N.Y., June 1974.]

Kershaw, K. A. 1964. Quantitative and dynamic ecology. 183 p. Edward Arnold (Publishers) Ltd., London.

Mayyasi, A. M., P. E. Pulley, R. N. Coulson, D. W. DeMichele, and J. L. Foltz. 1976. Mathematical description of within-tree distributions of the various developmental stages of *Dendroctonus frontalis* Zimm. Res. Popul. Ecol. 18:135-145.

Nebeker, T. E., R. R. Hocking, O. P. Hackney, and J. H. Lashomb. 1978. A comparison of non-linear and linear models for describing gallery length distribution of *Dendroctonus frontalis* Zimm. attacking shortleaf pine. Environ. Entomol. 7:636-640.

Peilou, E. C. 1969. An introduction to mathematical ecology. 286 p. Wiley-Interscience (Div. of John Wiley and Sons), New York.

Richard, O. W., and T.R.E. Southwood. 1967. The abundance of insects: Introduction. *In* Insect abundance symposia of the Royal Entomological Society of London, No. 4. T.R.E. Southwood, ed. p. 1-7. Blackwell Scientific Publications, Oxford, Gr. Brit.

Southwood, T.R.E. 1966. Ecological methods with particular reference to the study of insect populations. 391 p. Barnes and Noble, London.

Stephen, F. M., and H. A. Taha. 1976. Optimization of sampling effort for within-tree populations of southern pine beetle and its natural enemies. Environ. Entomol. 5:1001-1007.

Williams, C. B. 1964. Patterns in the balance of nature. 324 p. Academic Press, New York.

ESTIMATING TREE MORTALITY OVER EXTENSIVE AREAS

William H. Clerke and James D. Ward[1]

Abstract.--Evaluation of tree mortality caused by southern pine beetles (SPB) is an important component in impact surveys, biological evaluations, and the development and evaluation of suppression projects. The objectives of the survey, characteristics of the study area, and insect/host tree interactions must be considered in developing procedures to estimate SPB-caused tree mortality over extensive areas. A flexible three-stage sampling design for mortality estimation and a sampling design for periodic mortality estimation currently being conducted by Ghent and Ward are presented.

INTRODUCTION

Procedures to estimate tree mortality caused by the southern pine beetle (SPB) over extensive areas are essential for the development and implementation of a pest management system. Under the Expanded Suthern Pine Beetle Research and Applications Program, Southeastern Area State and Private Forestry is developing such procedures. They must be based on a sound knowledge of the environment in which the outbreak is occurring, the interactions between insect and host trees, and the evaluation objectives. The limitations of aerial photography and sketch mapping techniques have made it difficult to develop cost-effective estimates of SPB-caused tree mortality at the required levels of precision.

The multistage sampling design for point-in-time estimates of tree mortality and procedures for developing periodic tree mortality estimates for impact surveys presented here represent new approaches to this problem. The multistage sampling design developed by Schreuder, Clerke, and Barry (1977) is flexible enough to permit its application under a wide variety of situations by research investigators and pest managers. The investigation now being conducted by Clerke and Ward[2] is the first attempt to develop a procedure to provide periodic estimates of SPB-caused timber mortality for impact surveys.

DEVELOPMENT OF TREE MORTALITY ESTIMATES FOR EXTENSIVE AREAS

Realistic and effective procedures to estimate beetle-caused tree mortality must be developed within the constraints of survey objectives, characteristics of the survey area, and SPB/host tree interactions. Procedures for general use should be flexible enough to allow practitioners to adapt them to local conditions. An "extensive area" may be defined as a group of counties or a National Forest covering no more than 500,000 areas, or an area as large as a State or region encompassing from 20 to 30 million acres. Forest Insect and Disease Management, State forestry organizations, and National Forests may be responsible for estimating tree mortality over extensive areas. These estimates must (1) evaluate the effectiveness of a proposed control procedure, (2) assess the operational effectiveness of a suppression project, (3) estimate current mortality in preparing a biological evaluation, and (4) determine the impact of SPB infestations.

The data needed to develop mortality estimates can be acquired during operational surveys to locate groups of attacked trees for suppression and salvage, or through special studies designed specifically for this purpose. Billings (1979) has demonstrated the use of operational survey data, employing the Texas Forest Service Informational System.

---

[1] Survey Improvement Specialist, USDA Forest Service, Southeastern Area, State and Private Forestry, Atlanta, Ga.; and Survey Team Leader, USDA Forest Service, Southeastern Area, State and Private Forestry, Doraville, Ga.

[2] Ghent, J. H., and J. D. Ward. Determination of annual timber mortality: Impact of the southern pine beetle. 10 p. Unpublished study plan (1977). USDA For. Serv. Expanded Southern Pine Beetle Res. and Appl. Progr. Pineville, La.

Sharing data collection activities with operational surveys can substantially reduce the cost of developing tree mortality estimates. To obtain useful, cost-effective estimates of tree mortality for impact studies and biological evaluations where costs cannot be shared, innovative approaches to survey design are called for.

Defining Survey Objectives

The objectives of a survey must be clearly defined before effective estimation procedures and data collection techniques can be developed. The objectives should clearly state the data requirements, including the units of measure, level of precision, and time span of the data collection, as well as costs and organizational constraints under which the procedure will be implemented.

Southern pine beetle mortality estimates fall into two general classes, point-in-time and periodic estimates. Point-in-time procedures provide an estimate of the extent of mortality at the date of the aerial phase of the survey. Periodic extimates of mortality provide an estimate of the cumulative volume of timber killed over a period of time, generally one year.

Almost all procedures developed to estimate SPB-caused tree mortality provide point-in-time estimates. These estimates have been used to provide an index of the severity of outbreaks for biological evaluations and to rank outbreaks for allocation of suppression funds. Point-in-time estimates have also been used to calculate periodic mortality using empirically derived expansion factors.

Southern pine beetle impact surveys require a series of annual estimates of tree mortality. Periodic estimates of tree mortality may also be useful for establishing the efficacy of a suppression technique or evaluating suppression projects. Estimates of periodic mortality necessitate two measurements on each sample unit: initial mortality and subsequent mortality. The periodic mortality estimate is derived by subtracting the initial baseline estimate from the mortality present at the end of the period.

The series of annual mortality estimates required for impact evaluations may be derived from samples drawn independently for each year of the evaluation. Sample plot locations selected independently for each year of an impact study provide maximum flexibility for adjusting the sampling for changes in the intensity and distribution of infestations. A series of independent estimates, however, may not be consistent or comparable. Conversely, dependent estimates based on a set of plots utilized throughout the study yield consistent estimates but little flexibility. The sampling with partial replacement approach presented by Cunia (1974) is a flexible compromise in this situation.

The number of trees killed or acres of timber killed are the simplest ways of describing mortality. Estimates expressed in this manner, however, do not provide the tree volume information for relating mortality to economic impact. Converting these measures to volume estimates using a average-per-tree volume can introduce substantial errors that may not be readily estimated. Procedures using aerial photographs or ground measurements to estimate volume are potentially more accurate but also more expensive.

Incorporating the collection of detailed stand measurements into the mortality estimation procedure permits estimation of mortality by hazard classes. Recent studies (Sader 1976, Matthews 1978) have shown that stands may be divided into risk or hazard classes on the basis of parameters measured on aerial photographs. While useful inferences could be drawn from such estimates, they would generally be of less precision than aggregated estimates of mortality per acre of host type.

Characteristics of the Study Area

Once the objectives of the study have been determined, the characteristics of the study area itself must be considered in developing mortality estimation procedures. Patterns of vegetation over extensive areas reflect interactions between physiography, climate, and the activities of man. Variations in the vegetation patterns affect selection of the sampling method and the number, size, and distribution of the sampling units.

Extensive areas are rarely spatially homogeneous in terms of vegetation patterns or the distirbution of pest populations. Stratification[3] will generally improve the precision and utility of mortality estimates over extensive areas. Stratification can also provide a proce-

---

[3]Stratification is the process of dividing a heterogeneous population into subpopulations, each of which is usually internally more homogeneous than the whole (Cochran 1963).

dure for (1) improving the precision of estimates for specific subdivisions of the survey area, (2) conducting the survey and displaying the results by administrative units, and (3) accounting for different sampling problems in segments of the population. Summaries of pine-type acreage from forest survey reports or management data bases such as the Forest Service Continuous Inventory of Stand Conditions can be displayed on maps for setting stratum boundaries. Cover maps based on remote sensing data are becoming increasingly available for extensive areas. A regional stratification based on (1) division of the loblolly pine ecosystem provinces related to timber production potential (Boyce, McClure, and Sternitzke 1975), and (2) an appropriate degree day measure of SPB biological potential would be extremely valuable in siting study areas and interpreting the results of surveys and research studies.

Insect/Host Interactions

Biological characteristics of the southern pine beetle population and its interaction with the host species are the final factors that must be considered in procedures to estimate SPB-caused tree mortality over extensive areas. In the Southeast, all species of yellow pine are susceptible to SPB attack (Bennett and Ciesla 1971). However, the beetle prefers to attack loblolly and shortleaf pines. Spatial distribution of stands of host species is generally nonrandom and determined by a variety of factors, including physiographic characteristics of the area, site requirements of the species, and management practices of the landowners. In addition, individual stands of a susceptible species may be differentially susceptible to initial attack or increase in the number of attacked trees (Moore and Thatcher 1973). From a sampling standpoint, it is important to recognize that the most susceptible stands generally represent a spatially nonrandom, clumped distribution.

Southern pine beetle behavior patterns, coupled with the variability of host susceptibility, result in a clumped spatial distribution of attacked trees. Attacked trees occur singly, distributed more or less at random within susceptible host type, as well as in groups (spots) that may contain up to several thousand trees. The clumping of attacked trees into spots results from the aggregation behavior of the beetle in response to pheromones emitted by attacking adults. Current evidence indicates that spot infestations will continue to increase within the limits of susceptible host type as long a continuous source of pheromone and responding beetles are present within the spot (Gara 1967).

Disruption of the pheromone source leads to dispersal of newly emerging beetles. While the distance that dispersing beetles can travel and still initiate successful attack is yet unknown, new infestations are more likely to be initiated in the vicinity of active or recently active spots.

The degree of clumping of SPB spots within areas of susceptible host type appears to be directly related to the intensity of the outbreak. Under endemic conditions spots are generally small and more or less randomly distributed within host type. Under epidemic conditions, the clumping of spot locations generally increases and the distribution of spot sizes is extremely skewed. Spots in the smaller size classes generally predominate. Large spots, while relatively rare, represent a substantial proportion of the trees and volume attacked.

Aerial observers or photo interpreters cannot detect SPB-attacked trees until the crowns start to lose their normal green color. On the ground, green attacked trees may be detected by the presence of pitch tubes and boring dust on the stem. But at any point in time, a portion of the SPB spots will contain only green attacked trees not detectable with currently operational survey techniques. Similarly, some of the infested trees within spots that can be detected by aerial methods will have green crowns.

Southern pine beetles produce up to seven generations per year (Bennett and Ciesla 1971). Each generation attacks and kills additional trees. Attacked trees can be detected and separated from trees killed in previous years only during the period between the onset of crown fading and the time when they lose most of their needles. In North Carolina, Doggett (1971) reported this period to be between 5 and 9 weeks, depending on the season. Because of the multiple generations and rate of tree fading, the total losses for any one year cannot be reliably estimated by a single survey.

Aerial Photography *v.* Sketch Mapping

Limitations in our current aerial observation techniques compound the problems described earlier. Spot location and estimates of the number of trees per spot are based on data from the aerial phase of the survey. Spot locations and size estimates are plotted directly onto maps by observers in the aircraft (sketch mapping) or plotted by photo interpreters on aerial photographs taken during the aerial phase of the survey.

The accuracy of sketch mapping depends on the experience of the observers, the density of the spots, and the width of the strip they are observing (Aldrich et al. 1958). For each suspect group of trees the observer must (1) determine if the suspect trees have been attacked by SPB, (2) estimate the number of trees in the spot, (3) determine the map location of the spot, and (4) assess the probable accuracy of his plotting of map location. During one minute the observer must plot all the spots in an area one-half mile wide and 2 miles long, covering 640 acres. The observer in a sketch map survey must be able to perform these procedures for up to 4 hours in a light aircraft flying at 1500 feet above the terrain. It is difficult to design a sketch mapping procedure that will correct for errors of omission.

Aerial photography provides more flexilibity in specifying the scale and sampling unit and lends itself to procedures for evaluating errors of omission. In addition aerial photography provides a permanent record that can be used in directing ground checking. Also, it permits comparisons with images taken at a later date and permits reinterpretation of the photographs if necessary. The accuracy of photo interpretation depends on the skill of the interpreter, the interpretation equipment available, and the scale, emulsion, and quality of the photographic image. Aerial photographic sampling, however, is more expensive than sketch mapping, requires specialized equipment, is suitable only in a narrow range of weather conditions, and has a relatively long delay between the initial flight and ground checking.

Southern Pine Beetle Survey Techniques

The techniques used to estimate SPB mortality have been summarized (Schreuder, Clerke, and Barry 1977). Heller and coworkers (1955) developed a two-stage sampling procedure in which spots detected along sample flight lines were plotted on aerial photographs. Applications of this technique provided mortality estimates for areas up to 15 million acres.

In 1956, Aldrich, Heller, and Bailey (1958) conducted the classic study of the observational limitations of aerial sketch mapping. Their results indicated that detectability decreased with (1) increase in width of the strip used, (2) increase in the density of spots observed, and (3) decrease in spot size.

Operations recorder equipment for bark beetle surveys was developed at the Beltsville Forest Insect Laboratories in the 1950's (Bailey 1958) to improve the consistency of sketchmap surveys. The equipment restricted the observer's field of view to the flight strip and provided mechanical equipment for recording spots, sizes, and locations, as well as the presence of host type. The system was effective but could only be used under a restricted set of conditions with a highly trained flight crew.

Dr. J. E. Clutter developed a new survey plan utilizing the operations recorder (Ketcham 1964). In the multistage sampling procedure, a sample of flight strips running the length of the survey unit was the basic sampling unit. The system provided reliable estimates of the parameters of interest.

The first study to provide a quantitative evaluation of the applicability of aerial photography for evaluating SPB infestations was conducted by Heller, Aldrich, and Bailey (1959) during 1955. They found that the number of infested trees per spot could be reliably estimated from photo counts of red and fading trees by means of a linear regression. They recommended the use of aerial photography at a scale of 1:7920 with one flight line every 6 miles (16 percent) in conjunction with the regression developed in the study to provide satisfactory estimates at reasonable cost.

A pilot study employing aerial photography to evaluate SPB infestations was conducted by Forest Pest Control in 1965 (Ciesla, Bell, and Curlin 1967). The study was based on systematically distributed 50-acre plots. Clutter's survey design (Ketcham 1964) for operations recorder surveys, rather than Heller's regression procedure, was used to analyze the data. Photo plots were substituted for flight strips in the data analysis. The Southeastern Area adopted this approach, utilizing a 200-acre plot and 1:6000 scale photography for operational surveys (U. S. Dept. of Agriculture, Forest Service 1970).

Two factors tended to produce unacceptable errors when this sampling scheme was utilized with the 200-acre aerial photographic plots: (1) the 200-acre photo plots were smaller and more variable than the original flight strips, and (2) substantially fewer than the recommended 30 to 50 spots were ground checked. Confidence intervals (90 percent) of 60 to 80 percent of the population estimate were not uncommon. Efforts to overcome these deficiencies by increasing the number of photo plots were generally unsuccessful. Using an inappropriate sampling plan with the 200-acre plots tended to discredit aerial photography as a survey tool.

A FLEXIBLE THREE-STAGE SAMPLING DESIGN FOR MORTALITY ESTIMATION

Introduction

Multistage sampling designs are a common tool in resource evaluation applications. They have been used to evaluate mortality caused by SPB (Ketcham 1964), Douglas-fir tussock moth (Wert and Wickman 1970), Douglas-fir beetle (Wert and Roettgering 1968), and air pollution effects (Wert 1969). The emphasis has been on the development of designs that provide efficient, unbiased estimators through the use of unequal probability sampling (P.P.S.) at each stage with standard ratio estimators usually associated with P.P.S. sampling. In this approach, the probability of a spot being selected for ground checking is proportional to the size of the spot. The allocation of samples to the larger spot will be true on the average for a large number of surveys, though not for an individual survey. Schreuder (1975) showed the superiority of stratified sampling over unequal probability sampling (3-P sampling) in situations where unequal probability sampling had been advocated. Schreuder's studies also emphasized the use of appropriate estimators. Consistent estimators are a class of biased estimators whose bias goes to zero as a function of sample size. Consistent estimators may increase sampling efficiency and be superior to unbiased estimators for both stratified and unequal probability sampling.

The sampling procedure developed by Schreuder, Clerke, and Barry (1977) was designed to incorporate an understanding of biological characteristics of SPB infestations with efficient approaches to sampling. In their sampling procedure, the stratification variables are generally correlated with the variables of interest. Consistent, but not necessarily unbiased, estimators based on the relationships between the data collected in the aerial and ground phases of the survey provide reliable estimates of mortality. Unlike most of the sampling plans previously cited, this procedure, implemented for computer computation by David Holland, gives the investigator considerable flexibility in application and data analysis. The procedure may be used with either sketch mapping or aerial photography. Both types of data collection were incorporated into the pilot study.

Methods

Development of the multistage sampling plan consisted of four phases. Schreuder developed the preliminary plan. A pilot test of the sampling plan was conducted on the Chattahoochee National Forest during the second phase of the study. At the same time, the third phase--development of a computer program to implement the sampling plan--was initiated through a contract with the School of Forest Resources of North Carolina State University. During the final stage, the computer program was tested with the pilot study data and modifications were made to meet the remaining objectives of the study. Since formal completion of the study, the computer program has been substantially modified to facilitate its operational use.

Description of the Pilot Study Area

The study area consisted of three Ranger Districts on the Chattahoochee National Forest in northeast Georgia. The area is part of the southern Appalachian mountain chain and ranges in elevation from 1200 to 5000 feet. There is a total of 732,527 acres within the administrative boundaries of the three districts--Chattooga, Tallulah, and Brasstown. Approximately 83 percent of the land is in commercial forest (USDA Forest Service 1976). The forest is composed of oak-hickory (48 percent), oak-pine (20 percent), pine types (20 percent), and miscellaneous (4 percent).

Stratification of the Survey Area

Stratification of the survey area is the initial step in applying the proposed sampling plan. In the pilot study, stratum boundaries were developed on the basis of current occurrence of aerially observable timber mortality and the distribution of host pine type within the study area. A four-level mortality intensity map, generalized from a reconnaissance sketch map of the area, provided mortality data for stratification. A six-level host type proportion map was developed from the Region 8 Continuous Inventory of Stand Conditions (CISC) data base. The host type proportion and mortality intensity maps were utilized to delineate six strata within the forest

Table 1.--Spot size distribution and sample size allocation by strata and substrata as determined from aerial photography or sketch mapping

Stratum (Acres of NF land)	Infestation intensity	Sub-stratum	Aerial information	Percent survey	Spot size	No. spots photo detected	No. spots sketch map detected	No. spots ground checked
1A (43,093)	Heavy	1	Photo	100	1-49	263		7
		2	Photo	100	50-250	50		11
		3	Photo	100	> 250	6		6
						319		24
1B (50,188)	Heavy	1	Photo/Sketch	100	1-7	231	28	5
		2	Photo/Sketch	100	8-19	114	32	5
		3	Photo/Sketch	100	20-49	61	32	5
		4	Photo/Sketch	100	50-200	52	39	8
		5	Photo/Sketch	100	201-2000	3	3	3
						461	134	26
2 (3,802)	Medium	1	Photo	90	1-10	36		5
		2	Photo	90	11-35	34		7
						70		12
3A (14,936)	Light	1	Sketch	50	1-15		38	6
		2	Sketch	50	16-50		8	3
							46	9
3B (39,834)	Light	1	Sketch	50	1-50		5	4
4 (216,684)	Very Light	1	Sketch	25	1-9		39	6
		2	Sketch	25	10-150		38	7
							77	13

boundary. Operational limitations of the aerial survey techniques, statistical analysis problems, pilot test objectives, and survey efficiency were secondary conditions in delineating stratum boundaries.

The aerial stage of the pilot test was conducted in September 1975, utilizing the primary and secondary procedures shown in table 1. The primary procedures simulated those that might be used in an operational survey. Additional data were collected for the technique evaluation activities of the investigation.

Photo Interpretation and Data Preparation

Each spot detected during the aerial phase of the evaluation was assigned a unique number. Mechanical problems precluded interpreting the imagery with the Huston Fearless Variscan Film Viewer originally scheduled for this project. An Agfa Lupe 8× magnifier was used for most of the photo interpretation.

The second stage of the design consisted of subdividing the strata into subpopulations on the basis of the estimated number of red and fading trees. From one to five substrata were defined in each of the primary strata. In the pilot study, the distribution of spot sizes was subdivided for two reasons: (1) to insure that large spots were selected for sampling with a higher probability than the small spots, and (2) to provide subdivisions of the spot size population for which there was more likely to be a strong relationship between the number of aerially observed red and fading trees than for the population as a whole.

At least six spots were randomly selected for ground checking in each substratum to permit computation of substratum regressions. The substrata containing the largest spots were censused. The division of the primary stratum into substrata and the allocation of samples will depend on the circumstances and resources available for each survey. The division of stratum into substratum based on spot size should be made, utilizing the investigator's best judgment after examination of the array of spot sizes aerially detected in each stratum.

Ground Checking

Ground checking of 88 previously selected spots was accomplished from September through November 1975. Each attacked tree within the spot was examined and the species, d.b.h., crown color, and beetle status (infested or emerged) were recorded. Tree heights were measured on at least two large, two medium, and two small trees in each spot unless the spot contained fewer trees.

The third stage of the sampling procedure permits the collection of information on ground variables from a subsample of trees in larger spots. In the pilot study, spots containing over 500 trees were sampled.

Data Analysis

The sample design and associated estimation procedures are presented in the final report of the investigation (Schreuder, Clerke, and Barry 1977). The computer program developed to implement the sampling design is ANSI FORTRAN, with versions available for the Univac 1100 series and IBM 370 computers. The main objective of the Program is to provide estimates and standard errors of the estimate of specified parameters of interest. The regressions of variables of interest against the number of red and fading trees per spot from the aerial stage are developed for each substratum. The estimates of the variables of interest are then summarized from the substratum estimates for each stratum and for the area as a whole.

Estimates can also be developed from combined regressions based on the data from several substrata or strata. These regressions are obtained utilizing the combined stratified regression equation as explained in Cochran (1963). Some or all of the substrata or strata can be combined to estimate the coefficients of a common regression line. Since points along the combined regression line have different probabilities of selection, the procedure does not lend itself readily to computing R^2 or other measures of goodness of fit.

The program also permits computation of combined stratified random sampling estimates. These--along with the option of plotting variables of interest against the substratification variable and computation of sample linear regression statistics--serve as a useful check on the stratified regression estimates. The program will handle up to 10 strata with 10 substrata per stratum with a maximum of 10 ground-measured variables. Up to 5 separate combined regressions can be computed as a basis for stratum and area estimates.

Measured variables correlated with the number of red and fading trees estimated in the aerial phase of the study included six classes of attacked and/or infested trees, the total basal area, and total Scribner board-foot volume per spot.

RESULTS AND DISCUSSION

Eighty spots were included in the ground check. The probability of a spot being selected for ground checking depended on the substratum defined, the number of spots in the stratum, and the number of spots selected for ground checking. In the pilot study spot selection, probability ranged from certainty for large spots in the censused substratum to a probability of .04 for small spots in stratum four.

The variables of interest were plotted against the number of red and fading trees from the aerial phase of the study separated by strata, by substrata, and for all spots ignoring strata and substrata. These results showed that the regressions were linear and that logical ones were obtained only when substrata were ignored. Combined regressions were used in deriving the final estimates. Censused substrata are treated separately because their estimates have no error associated with them.

In four of the six strata, regression estimates were clearly superior to stratified random sampling estimates. The results show that regression estimates should be used for all evaluations with conditions similar to those encountered in the pilot study. The regressions, however, were not as strong as expected. While satisfactory estimates were obtained for the important variables of interest, the precision of the estimates varied widely. The standard errors for the combined stratum estimates of red and fading trees and total affected trees were approximately 10 percent of the estimate. The standard errors of estimates of basal area and board-foot volume were 12 and 16 percent of the estimates, respectively.

In terms of R^2 values, the regressions developed for the sketch-map strata were stronger than those of the aerial photographic strata. The apparently better correlation between sketch mapping and ground check should be viewed with considerable caution. First of all, the sketch mapper was highly experienced; the photo interpreter was not. In the second place, the sketch-map strata generally contained fewer and smaller spots. In stratum 1B, a heavy stratum, where regressions were developed for both photographic and sketch-map data, the regressions were stronger for the sketch-map data. Examination of the data indicates that sketch mapping may have provided a stronger regression in 1-B only because the sketch mapper did a better job estimating one large spot than the photo interpreter. Skilled and careful interpretation is essential to the use of aerial photography.

The most significant problem of the sketch-map procedure is the high proportion of spots that are not detected or plotted. This problem is especially significant in the areas similar to stratum 1-B, with a high level of mortality. In this stratum, sketch mapping detected only 134 of the 461 spots detected on the photographs, or 29 percent of the total spots detected. Sketch-map detection accuracy in this stratum ranged from 12 percent for spots of seven or fewer trees to 100 percent for spots over 200 trees. Sketch mapping should probably be considered for strata with relatively low mortality. In the lightly infested stratum that represented approximately 50 percent of the study area, estimates could have been considerably improved if 100 percent rather than 25 percent sketch mapping had been used.

The sampling design and the computer program through which it is implemented provide an effective procedure for developing point-in-time estimates of SPB mortality. The procedure is sufficiently flexible to permit its application in a variety of conditions encountered in making mortality assessments.

A SAMPLING DESIGN FOR PERIODIC MORTALITY ESTIMATION

Introduction

Another approach to estimating annual timber mortality caused by southern pine beetle is being tested in central Mississippi (Ghent and Ward op. cit.). This investigation is designed to evaluate a sampling method that could meet several requirements. It must

(1) Be practical for use by a State or Federal agency over an extensive area where there is not an established control operations information system,
(2) Provide an annual estimate of volume loss,
(3) Require little or no ground checking, and
(4) Estimate losses at a satisfactory level of precision (sampling error of ±20 percent).

To meet these requirements a system that incorporates sequential aerial photographic sampling was selected.

Special problems had to be considered in this study. The sampling plan had to deal with large variations in population density throughout the proposed study area. Accurate rephotographing of the plots during successive flights was required, and qualified personnel and satisfactory aerial volume tables were needed in order to interpret the photos.

Table 2.--Number of plots established per county for estimating timber losses caused by southern pine beetle in central Mississippi, 1978.

County	Gross Area (M Acres)	Vol. Pine[1] MMBF	No. of Plots
Rankin	512.0	297	6
Simpson	375.7	182	4
Scott	393.6	370	8
Smith	410.9	270	5
Jasper	437.1	502	10
Newton	371.2	100	2
Copiah	500.0	479	10
Total	3,000.2	2,200	45

[1] USDA For. Serv. 1973. Forest area statistics for mid-South counties. USDA For. Serv. Resource Bull. SO-40. USDA For. Serv. South. Stn., New Orleans, La.

Methods

A 3,000,000-acre area in central Mississippi was chosen for the study (table 2). Both high and low levels of beetle-caused tree mortality occurred within the area, and a cross section of ownership classes was represented, including National Forests, timber industry, and small forest landowners. The area was representative of SPB outbreak areas throughout most of the South. Three photo missions were conducted in 1978 (two are planned for 1979). The volume and acreage of timber killed by the SPB during a 12-month period will be determined from the aerial photographs.

A modified random sampling plan was employed. Forty-five photo sampling points, randomly selected in seven counties, served as starting points for photos. Plots were oriented in an east-west direction and were 4000 ft wide. The lengths of the plots were different because each plot was extended until 500 acres of pine were photographed. Plots were allocated to each county on the basis of the proportion of the total pine type in the study area within the county. Plots were initially located on land-use maps compiled from high-altitude NASA photography. From these maps estimates were made of the length that each flight line needed to be to acquire photos of 500 acres of pine type.

The aerial photography was accomplished in an Aero Commander aircraft equipped with a Wild RC-10 aerial camera. The plots were photographed at a scale of 1:8000 (6-in lens, 4000 ft above the terrain). Ektachrome color infrared 2443 film was used to obtain positive infrared transparencies of the plots. Aerial film was processed by Precision Photo Lab in Dayton, Ohio.

The aircraft was equipped with a LORAN-C navigation system developed by Teledyne Corporation in California. The LORAN-C navigation system enables the tracker to (1) locate predetermined sampling points, (2) assist the pilot in flying a straight line, and (3) relocate the exact same sampling point on subsequent photo missions. In order to rephotograph the exact plot, the plane was not allowed to deviate more than 900 ft north or south of the center of the plot, which was 4000 ft wide and unmarked on the ground. The difficulty of accomplishing this without the navigation equipment is apparent considering that some of the photo plots extend for 6 miles.

Photographs were taken in April, July, and September. The initial photo mission served to establish a base from which determination of subsequent timber mortality and on which delineation of susceptible host stands on the plot were made. Stands with an area of at least 10 acres containing 25 percent pine stems were delineated as susceptible stands.

Photographs were sent to Virginia Polytechnic Institute and State University in Blacksburg, Virginia, for interpretation. Photo interpretation was done using an Old Delft stereoscope to view the plots. Timber mortality visible on the photos was recorded on a transparent overlay after the flight made in April. Both the number of affected trees in and the acreage of each spot were determined. The overlay was updated after each flight. Spots appearing on each set of photos were cross referenced with those plotted from previous and subsequent photo missions to monitor spot occurrence and growth (volume, acreage).

Tree height and crown closure were measured in 30 stands to develop an aerial volume table.

In the final analysis, the amount of timber killed will be computed in both volume and acreage and expressed as a ratio compared to the acreage of host type occurring on the photo plots.

Discussion

Although the study will not be completed until the fall of 1979, it has enhanced our understanding in three major areas related to the practical and operational aspects of procedures for determining periodic volume loss.

First, the sample plan, which is probably the most important consideration in this project, may have to be modified if the test is continued for more than 2 years. Stratifying by outbreak intensity may be necessary to improve the accuracy of statistics derived from a short-term project. For longer periods, selecting new sample plots may be necessary since the locations of beetle activity usually change drastically. As additional information becomes available from other studies funded by ESPBRAP, stratification of an area by hazard classes could prove more accurate statistically.

Second, the results from using Avery's (1968) composite aerial volume tables for southern pines and hardwoods were unsatisfactory. His volume tables include hardwoods and pines, while our need was for pine species only. However, his table provided a basis for constructing a new aerial volume table. This table will be refined after collecting additio nal data from both natural and planted pine stands in central Mississippi. Aerial volume tables will also be constructed for other areas of the South.

Improvement in a third area can best be appreciated by people with experience in aerial surveys. The LORAN-C navigation equipment proved to be almost a necessity for conducting this project. The LORAN equipment has applications for aerial surveys, fire control, and aerial spraying.

The project has provided a good opportunity to bring together for the first time the technology needed to determine timber losses caused by southern pine beetle. Procedures developed from this work will be used on an operational basis throughout the South. While this study will not provide all the needed answers, it will provide a sound basis for future SPB impact surveys.

LITERATURE CITED

Aldrich, R. C., R. C. Heller, and W. F. Bailey. 1958. Observation limits for aerial sketch mapping southern pine beetle damage in the Southern Appalachians. J. For. 56:200-202.

Avery, T. E. 1968. Interpretation of aerial photographs. Burgess Publishing Company, Minneapolis, Minn.

Bailey, W. F. 1958. An oblique strip viewer for aerial sampling in forest insect surveys. USDA For. Serv., Beltsville Forest Insect Laboratory.

Bennett, W. H., and W. M. Ciesla. 1971. Southern pine beetle. USDA For. Serv., Forest Pest Leaflet No. 49.

Billings, R. F. 1979. Spot proliferation as a measure of the operational effectiveness of southern pine beetle control tactics in East Texas. Evaluating Control Tactics for Southern Pine Beetle, symposium proceedings. USDA For. Serv., Expanded Southern Pine Beetle Research and Applications Program, Pineville, La.

Boyce, S. G., J. P. McClure, and H. S. Sternitzke. 1975. Biological potentials for the loblolly pine ecosystem east of the Mississippi. USDA For. Serv. Research Paper SE-142. USDA For. Serv., Southeastern For. Expt. Stn., Atlanta, Ga.

Ciesla, W. M., J. C. Bell, Jr., and J. W. Curlin. 1967. Color photos and the southern pine beetle. Photogrammetric Engineering 33:883-888.

Cochran, W. G. 1963. Sampling techniques. Second ed. John Wiley and Sons, New York.

Cunia, T. 1974. Independent versus dependent measurements. *In* Monitoring forest environment through successive sampling. Symposium cosponsored by Int. Union For. Res. Org., Soc. Amer. For., and State Univ. of New York, Syracuse, NY. pp. 1-18.

Doggett, C. A. 1971. Foliage coloration changes in loblolly pine during southern pine beetle attack. J. Econ. Entomol. 65:1298-1299.

Gara, R. I. 1967. Studies on the attack behaviour of the southern pine beetle. I. The spreading and collapse of outbreaks. Contrib. Boyce Thompson Inst. 23:349-354.

Heller, R. C., J. F. Coyne, and J. L. Bean. 1955. Airplanes increase the effectiveness of southern pine beetle surveys. J. For. 53:483-487.

Heller, R. C., R. C. Aldrich, and W. F. Bailey. 1959. An evaluation of aerial photography for detecting southern pine beetle damage. Photogrammetric Engineering 25:595-606.

Ketcham, D. C. 1964. Aerial survey plan for sampling pine bark beetle populations. 3rd Ann. Work Conf. 1964, Proc. USDA For. Serv., State and Private Forestry, Southeastern Area, Forest Insect and Disease Control. Atlanta, Ga. pp. 82-101.

Matthews, M. L. 1978. Forest stand mapping from LANDSAT and aircraft imagery to assess southern pine beetle susceptibility. M. S. thesis, Stephen F. Austin State Univ. Nacogdoches, Tex. 53 p.

Moore, G. C., and R. C. Thatcher. 1973. Epidemic and endemic populations of the southern pine beetle USDA For. Serv., Southeastern Forest Expt. Stn., Asheville, NC. Res. Paper SE-111.

Sader, S. A. 1976. Development of a risk rating system for southern pine beetle infestations in Copiah County, Mississippi. M. S. thesis, Mississippi State Univ., Mississippi State, Miss. 61 p.

Schreuder, H. T. 1975. Two stratified sampling alternatives to 3-P sampling. *In* Monitoring forest environment through successive sampling. Symposium cosponsored by Int. Union For. Res. Org., Soc. Amer. For., and State Univ. of New York, College of Environmental Sciences and Forestry, Syracuse, NY. pp. 55-58.

Schreuder, H. T., W. H. Clerke, and P. J. Barry. 1977. A flexible three-stage sampling design with double sampling at the second stage in estimating southern pine beetle spot characteristics. Unpublished final report of USDA For. Serv., Expanded Southern Pine Beetle Research and Applications Program. Pineville, La. 64 p.

USDA For. Serv. 1970. Evaluating southern pine beetle infestations. USDA For. Serv., State and Private Forestry, Southeastern Area, Division of Forest Pest Control, Atlanta, Ga.

USDA For. Serv. 1976. Customized forest information retrieval--6 county area in North Georgia. 44 p. USDA For. Serv., Southeastern Forest Expt. Stn., Atlanta, Ga.

Wert, S. L. 1969. A system for using remote sensing techniques to detect and evaluate air pollution effects on forest stands. Proc., 6th Int. Symp. on Remote Sensing of Environment. Inst. of Science and Technology, Univ. of Michigan, Ann Arbor, Mich. 2:1169-1177.

Wert, S. L., and B. Roettgering. 1968. Douglas-fir beetle survey with color photos. Photogrammetric Engineering: 1243-48.

Wert, S. L., and B. E. Wickman. 1970. Impact of Douglas-fir tussock moth: color aerial photography evaluates mortality. 6 p. USDA For. Serv. Res. Pap. PSW-60. USDA For. Serv., Pacific Southwest Expt. Stn., Berkeley, Cal.

SPOT PROLIFERATION PATTERNS AS A MEASURE OF THE AREA-WIDE EFFECTIVENESS OF SOUTHERN PINE BEETLE CONTROL TACTICS

Ronald F. Billings and Herbert A. Pase III[1]

Abstract.--The apparent effeciveness of operational tactics now in use to control infestations (spots) of the southern pine beetle, *Dendroctonus frontalis* Zimmerman, in east Texas was measured with use of Statewide detection and control records. Treatment efficacy was based on observed changes in the temporal pattern of new spot proliferation in proximity to all controlled and uncontrolled infestations present during 1974. We developed a methodology which simultaneously accounted for variations due to season of control and influencing factors other than control treatment. Results showed that salvage or cut-and-leave applied to active spots during the summer months was associated with a short-term reduction in subsequent levels of new spot proliferation in surrounding stands. In contrast, increased proliferation attributable to treatment occurred in proximity to uncontrolled, active spots or spots controlled after September.

INTRODUCTION

To date, measurements of the area-wide impact of forest pest control strategies have been largely neglected due to the numerous problems involved: (1) Between-stand relations are difficult to treat experimentally, particularly in the South, a region characterized by a multitude of small land holdings and diverse stand conditions. (2) Replications of treatments are exceedingly difficult and expensive. (3) Sampling forest pest populations rather than pest-related damage is time consuming and costly. (4) Methods for analyzing data from extensive arrays of stands are lacking (Stage and Long 1976). With a few notable exceptions (Lorio and Bennett 1974, Morris and Copony 1974), efficacy data supporting tactics to control the southern pine beetle, *Dendroctonus frontalis* Zimmerman (Coleoptera:Scolytidae) have been limited to estimates of brood reduction within treated trees (Bennett and Pickard 1966, Copony and Morris 1972, Coulson et al. 1973 and 1975, Ollieu 1969). This type of information is insufficient for assessing current spot disruption tactics such as salvage or cut-and-leave (Texas Forest Service 1975, 1976), which conceivably may reduce survival of adult beetles after they emerge.

The availability of computerized spatial and temporal records of southern pine beetle (SPB) infestations for several consecutive years in east Texas provided an opportunity to evaluate the relative effectiveness of cut-and-leave, salvage, and other control alternatives applied under operational conditions on an area-wide basis. In this nonexperimental approach, temporal patterns of new spot occurrence (proliferation) in the vicinity of controlled and uncontrolled infestations provided the measure of treatment efficacy.

PROCEDURES AND RESULTS

Data Source and Content

Since 1973, the Texas Forest Service has maintained computerized records of each SPB spot detected by aerial sketch-map survey on State and private lands in east Texas (about 8 million acres). Data on each spot include grid location to within 5 acres, method of control, number of currently infested trees, and dates of detection, ground check, and control. On most spots reported as controlled or inactive (uncontrolled spots vacated by beetles), the volume of infested trees, classified as either pulpwood or sawtimber, also is recorded. Operational records are collected by a variety of field personnel representing 15 major industrial landowners and four Texas Forest Service districts as part of the Operations Informational System (Texas Forest Service 1974).

The present analysis utilized detection and control records for the period January 1974 through July 1975, an interval during which about 5000 multiple-tree SPB infestations were detected. All spot records identified as duplicates, spots containing less than 10 trees at

[1] Principal Entomologist and Entomologist II, Texas Forest Service, Lufkin, Tex.

Table 1.--Distribution of SPB control tactics during 1974 and 1975 in east Texas by spot size and stand class

Treatment	Total spots	Percent of total by spot size (number of brood trees) ≦ 10	11-25	26-50	> 50	Total spots with volume data	Percent of total by stand class Pure pulpwood	Mostly pulpwood	Mostly sawtimber	Pure sawtimber
Salvage	948	18.4	22.4	24.8	34.4	632	31.6	8.4	45.1	14.9
Cut-and-leave	436	31.9	23.9	19.0	25.2	345	15.9	13.6	58.0	12.5
Other control	211	21.8	28.4	11.8	38.0	162	11.7	6.8	74.7	6.8
Inactive (uncontrolled	1391	100	----	----	----	1020	47.2	11.6	29.1	12.2
Active (uncontrolled)	205	22.0	20.0	27.8	30.2	42	23.8	11.9	52.4	11.9
Total	3190	56.3	13.1	12.5	18.1	2201	34.8	10.6	42.0	12.6

detection, and those representing mortality agents other than SPB were removed prior to analysis.

The data bank consisted of 3190 SPB treatment spots during 1974. For purposes of this analysis, treatment spots were defined as all SPB spots with ≧ 10 infested trees that were ground-checked during 1974 on State and private lands. Table 1 shows distribution of control treatments by spot size and stand class. During 1974, salvage was the primary control tactic, being applied to 30 percent of the treatment spots. Cut-and-leave, a tactic aimed at disrupting spot expansion, was applied to 14 percent of the spots, while 7 percent were controlled by other methods. Inactive and active spots accounted for 44 percent and 6 percent of the treatment spots, respectively. As indicated in figure 1, area-wide SPB populations occurred at relatively high levels throughout the duration of this study (1974-75).

Computer Program to Measure Frequency of Peripheral Spots

A computer program was developed to record the frequency of SPB spots reported in operational records within 605 acres (about ½-mile radius) of the coordinate position of each 1974 treatment spot during six consecutive intervals of detection (fig. 2). The detection intervals were (1) January-May 1974, (2) June-July 1974, (3) August-September 1974, (4) October-December 1974, (5) January-May 1975, (6) June-July 1975. In cases where a spot was found to occur within the scan boundaries of more than one treatment spot, the former was counted once for each treatment spot. (Preliminary analysis showed that exclusion of such cases did not materially influence the final results.) To avoid errors due to comparing

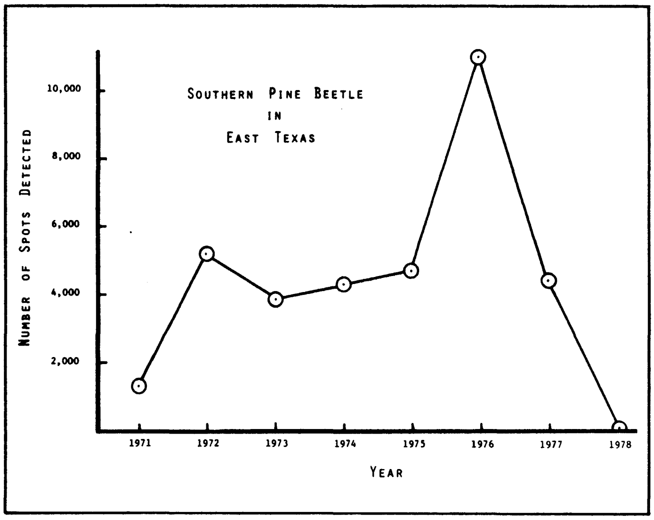


Figure 1.--Number of southern pine beetle spots detected in east Texas 1971-78.

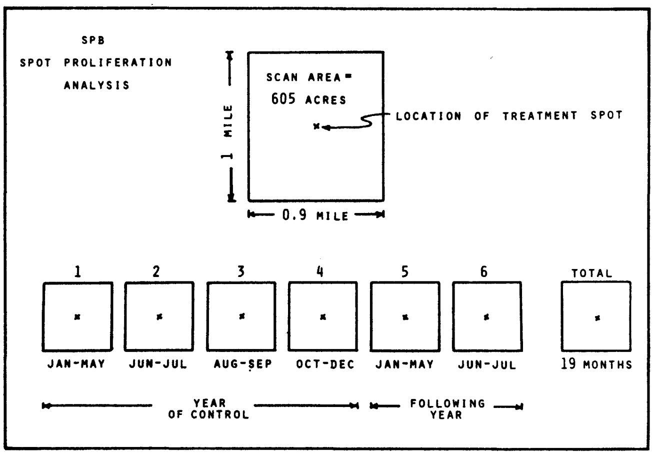


Figure 2.--Scan dimensions and consecutive detection intervals selected for use in monitoring the temporal occurrence of peripheral spots in proximity to each 1974 treatment spot.

a treatment spot to itself and to preclude duplicate spot records, we did not count spots having the same coordinate locations (e.g., within 5 acres). As the final output, one summary file card per treatment spot was generated listing the number of peripheral spots[2] by season of detection together with data for various descriptive variables to be used in subsequent analysis.

Six descriptive variables were used to categorize each 1974 treatment spot:

(1) Spot Size at Detection--estimated number of currently infested trees from the detection flight, in categories as follows: 10 trees; 11-25 trees; 26-50 trees; > 50 trees.

(2) Spot Size at Ground Check--estimated number of currently infested trees at time of last ground visit, in categories as follows: 0 trees; 1-25 trees; 26-50 trees; > 50 trees.

(3) Stand Class--spots for which volume data were available were assigned to one of four stand classes:

All pulpwood--spots in which volumes of ininfested trees were reported exclusively as pulpwood

Mostly pulpwood--spots in which the volume of pulpwood equaled or exceeded the volume of sawtimber

Mostly sawtimber--spots in which the volume of sawtimber exceeded the volume of pulpwood

All sawtimber--spots in which all volumes were reported as sawtimber.

(4) Geographical Area--the general location of the spot, as defined by the following counties in east Texas:

North Central--Cherokee, Anderson, Houston, Trinity, Angelina, Nacogdoches, Shelby, San Augustine, Sabine

South Central--Polk, San Jacinto, Tyler, Hardin, Liberty, Jefferson

Southeast--Jasper, Newton, Orange

Southwest--Madison, Grimes, Walker, Montgomery, Harris, Waller.

(5) Season of Last Action--the season during which the spot was controlled, declared inactive, or, in the case of active spots, was last visited on the ground. The four seasonal categories were January through May, June or July, August or September, October through December.

(6) Control Tactic--the control method applied to the spot. Possible alternatives were (1) salvage, (2) cut-and-leave, (3) other controls (cut-and-top, insecticide, combination of control tactics), (4) inactive (uncontrolled, with no currently infested trees on last ground visit), and (5) active (uncontrolled, with currently infested trees on last ground visit).

Rationale and Approach to Analysis

As initially conceived, the goal of this study was to measure the relative effectiveness of various control alternatives by comparing the frequencies with which new spots were reported in the vicinity of established infestations following control treatment. Assuming that beetles disperse from controlled spots to initiate new infestations (proliferations) nearby, one would expect the number of new spots to be fewer in the vicinity of spots controlled by methods that minimize survival of resident beetle populations than that observed about spots controlled by less effective methods. Proliferation about spots that remained uncontrolled would provide an additional basis for comparison.

Several major problems confronted our early attempts to directly compare new spot frequencies among control tactics as a measure of treatment efficacy, however. Direct comparison of new spot densities necessarily rests upon one of two assumptions--that control treatment is the only factor which significantly influences the frequency of new spots in the vicinity of controls, or that if one or more covariables do exist, control treatments are applied at random with respect to these other variables. Neither assumption is likely to be valid in the case of operational records.

Preliminary analysis indicated a direct relationship between long-term frequencies of new spots and single factors measurable from operational records, such as spot size, stand class, and geographical area (table 2). Furthermore, we knew that the proportion of the 605-acre scan area covered by suitable host

---

[2] To avoid confusion with "treatment spots" and to facilitate discussion, the term "peripheral spots" will be used to refer to all spots found within the scan boundaries (605 acres) of a particular set of treatment spots.

Table 2.--Mean number of peripheral spots within 605 acres of treatment spots over a 19-month period in relation to spot size, geographical area, and stand class

Spot size	Frequency of treatment spots	Mean number of peripheral spots per treatment spot[2]
Flight[1]		
10	1483	1.67 ± 2.24[3]
11-25	1160	1.67 ± 2.01
26-50	360	2.42 ± 2.68
> 50	187	3.44 ± 2.82
Mean	3190	1.86 ± 2.32
Ground check[1]		
Inactive	1501	1.41 ± 1.79
2-25	711	2.17 ± 2.68
26-50	400	2.17 ± 2.53
> 50	578	2.46 ± 2.46
Mean	3190	1.86 ± 2.32
Geographical area		
North central	1049	1.21 ± 1.45
Southeast	289	1.81 ± 2.56
Southwest	878	1.99 ± 2.18
South central	974	2.45 ± 2.89
Mean	3190	1.86 ± 2.32
Stand class		
Pure pulpwood	765	1.47 ± 2.11
Mostly pulpwood	234	1.76 ± 2.42
Mostly sawtimber	925	2.19 ± 2.64
Pure sawtimber	277	1.51 ± 1.71
Mean	2201	1.81 ± 2.36

[1]Estimated number of active trees
[2]January 1974 through July 1975
[3]Standard error of mean

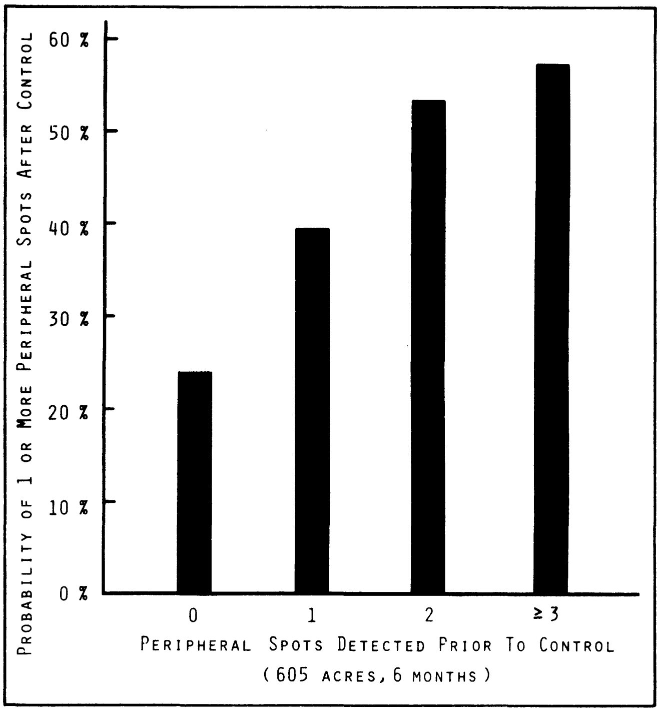


Figure 3.--The probability of one or more peripheral spots occurring within 6 months after control treatment as influenced by the frequency of peripheral spot occurrence during the 6-month period prior to the date of control (based on 1585 controlled spots).

material varied from spot to spot and, conceivably, among treatments. Although no measure of stand uniformity within the scan areas is available from operational records, this variable undoubtedly influences the number of new spots detected in an area over the long term.

To illustrate more clearly the combined effect of variables other than treatment on new spot frequencies, we documented the probability of encountering one or more new spots during a 6-month period after control was applied to a spot, based on the number of spots detected in the same area (605 acres) prior to control (fig. 3). Clearly, whether or not a new spot developed following control action was directly correlated with the recent history of beetle activity or proximity to the controlled spot. The latter, in turn, is largely dependent upon the uniformity and susceptibility of stand conditions present in the area (Lorio and Bennett 1974). Biases in the distribution of control treatments with respect to spot size and site/stand variables (table 1) thus preclude direct comparison of new spot frequencies among treatments as well as the use of most analytical statistical techniques in evaluating the data.

Another problem was determining how to identify the time interval following date of control during which proliferations due to treatment would be detected. Treatment effects could be recorded as soon as 6 to 8 weeks after date of control or be delayed as much as 6 to 12 months, depending upon rates of spot development, rates of foliage fade (Billings and Kibbe 1978), and the frequency of detection flights. Detection of SPB spots also is seasonally dependent (Coulson et al. 1972); from 45 to 75 percent of all new spots are reported during the 3-month period from May through July. Thus, the probability of encountering a new spot due to chance alone would be greater during the summer months than during any other season.

To overcome these obstacles, we used descriptive statistical techniques, common in social science research where a large volume of enumeration data is available (Blalock 1964), to evaluate the data. The assumption was made that the 1974-75 data bank represented the entire population of interest for this time period (controllable-sized infestations, not necessarily the entire SPB population). Accordingly, the analysis consisted of identifying the major variables other than treatment that influence the frequency of peripheral spots, and accounting for their effects in order to ascertain the true treatment effects.

Identifying Factors That Influence Peripheral Spot Occurrence

We divided factors suspected to influence the frequency of peripheral spot occurrence in a given area into two categories: fixed (long-term) factors and temporary (short-term) factors. Fixed factors were defined for purposes of this analysis as all variables that, in combination, determine the spatial pattern and frequency of spot occurrence to be expected in an area over an extended period of time. In this study, fixed factors of primary importance included percent of scan area covered by host type, density and uniformity of stands within the scan areas, and geographical area (since beetle population levels varied among geographic regions of east Texas). Short-term fluctuations in the temporal pattern of new spot occurrence in a given area can be caused by other factors having temporary effects, including type of control treatment, season of control, and number of currently infested trees per treatment spot (a measure of the beetle population within the spot at the time of control).

Measurement of Treatment Effects

By monitoring the frequency of new spot occurrence associated with each set of treatment spots over a sufficient period of time (in this case 19 months or about 10 SPB generations), we were able to account for variations among treatments due to fixed factors. Deviations between observed and expected levels of peripheral spots over time (temporal patterns) in proximity to a set of treatment spots provided a measure of treatment efficacy. To delineate treatment effects, data on the temporal distribution of peripheral spots about 1974 treatment spots were assigned to an R × C contingency table (Steel and Torrie 1960), with R = 20 treatments (rows) and C = 6 seasonal detection intervals (columns). The 20 treatment categories consisted of five types of control options (salvage, cut-and-leave, other control, active, and inactive) stratified by four seasonal periods of application (January-May, June-July, August-September, October-December). In this analysis, controlled spots were assigned to a season by the month of control, active spots by the month of last ground check, and inactive spots by the month they were reported inactive. The six detection intervals refer to the season during which peripheral spots were detected.

Table 3.--Format of 20 × 6 contingency table used to test for effects of control treatment

1974 Treatments Control × Season	No. of treatment spots	Number of peripheral spots: 1 Jan-May	2 Jun-Jul	3 Aug-Sept	4 Oct-Dec	5 Jan-May	6 Jun-Jul	Row Totals
Salvage		O E χ^2						
1. Jan-May	24							71
2. June-July	284	For each cell: O = Observed value						589
3. Aug-Sept	449	E = Computed expected value; χ^2 = Chi-square						956
4. Oct-Dec	190							561
Cut-and-Leave								
5. : 8.								
Other control		20 × 6 Contingency Table						
9. : 12.								
Inactive								
13. : 16.								
Active								
17. : 20.								
	3190	799	2242	465	200	892	1333	5931
		Column Totals						Grand Total

In the contingency table, the row total equaled the total number of peripheral spots occurring about all 1974 spots of a given treatment (control × season) during the 19-month period of observation. The column total represented the total number of peripheral spots encountered about all treatments during a given seasonal interval of detection, while the grand total equaled the sum of all column or all row totals. The format is shown in table 3.

The test for treatment effects consisted of four steps: (1) generation of expected values for each observed value in the contingency table, (2) classification of treatment effects in terms of magnitude and duration, (3) statistical comparison of observed levels of peripheral spots with corresponding expected levels for each treatment to document the significance of treatment effects, (4) statistical comparison of peripheral spot frequencies about controlled spots throughout the duration of treatment effect to corresponding values for active (uncontrolled) spots during the same scan interval.

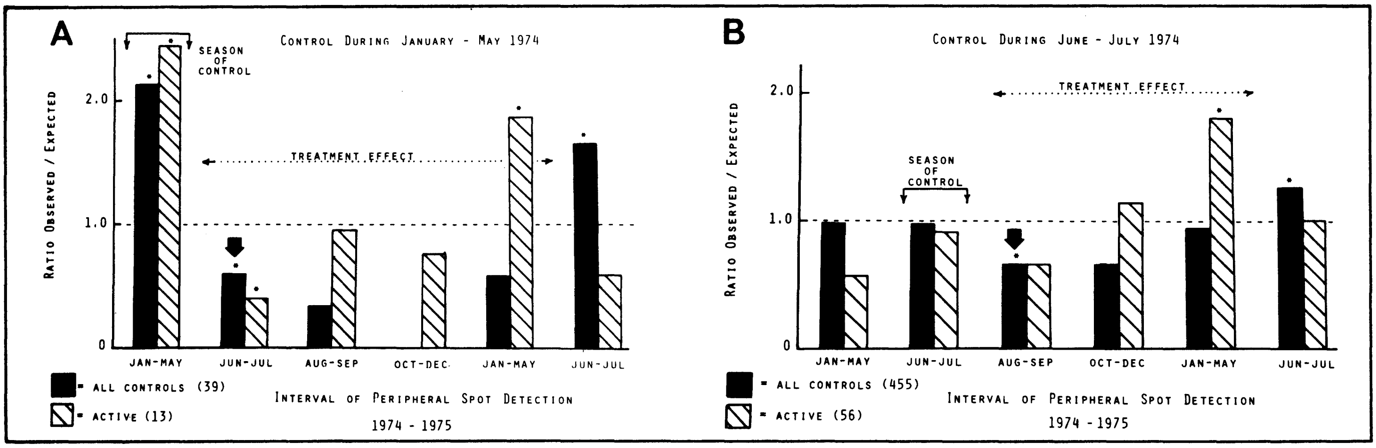


Figure 4.--Temporal patterns of peripheral spots occurring in proximity to treatment spots controlled by all methods combined during January-May (A) and June-July (B) compared to active (uncontrolled) spots. The baseline level of 1.0 represents the level of peripheral spots to be expected if no treatment effects occur. Vertical arrows (↓———↓) encompass the season of control or season of last ground check for active spots. Horizontal dotted lines (←·····→) represent the probable interval of treatment effect. Differences between the observed level of peripheral spots and the expected level that were statistically significant at $P < 0.05$ are indicated by a star (*). The detection interval of maximum treatment effect is indicated by a broad arrow (⬇).

Expected values were generated for each cell of the 20 × 6 contingency table by multiplying each row total by each column total and dividing the product by the grand total. Expected values generated by this procedure were assumed to account for variations due to seasonal detection patterns (column adjustments) as well as long-term "fixed" factors (row adjustments). Accordingly, these values provide an estimate of the frequency of peripheral spots to be expected during a specific scan interval if control treatment had no effect on new spot proliferation (null hypothesis). For seasonal intervals that occur after the date of control, observed values that were significantly different ($P < 0.05$) were interpreted as treatment effects. Deviations were tested for significance by computing χ^2 values, using a formula that corrects for continuity (appendix 1). The χ^2 comparison tested whether the ratio of the observed value within a given cell(s) pertaining to Treatment A, for example, to the observed values combined for all remaining Treatment A cells was independent of the corresponding ratio for all other treatments combined. It was hypothesized that these two ratios should be comparable if the treatment had no effect on levels of proliferation.

Delineation of Treatment Effects

The ratios of observed frequencies of peripheral spots to expected frequencies for six consecutive detection intervals about treatment spots controlled at different seasons by all methods combined in 1974 (figs. 4 and 5) provide an *a posteriori* basis for identifying the extent of treatment effects. For example, consecutive detection intervals following the date of control for which observed values were either consistently higher or consistently lower than expected served to delineate the duration of treatment effect (horizontal dotted lines) for each season of control. In turn, the individual detection interval following date of control which exhibited the most significant deviation of expected to observed values (cell with the largest χ^2 value) was interpreted as the interval of maximum treatment effect (broad inverted arrows). For purposes of discussion, peripheral spots occurring throughout the duration of treatment effect will be referred to as "proliferations" about the corresponding set of treatment spots.

Effects of Control Versus No Control

Temporal patterns of peripheral spot occurrence about controlled spots were found to vary with season of control. For spots controlled (all methods combined) from January through September, proliferation levels were found to decrease significantly ($P < 0.05$) below expected levels following the control date, returning to or exceeding expected levels during the June-July 1975 detection interval. In contrast, spots controlled in late fall and winter (October-December) of 1974

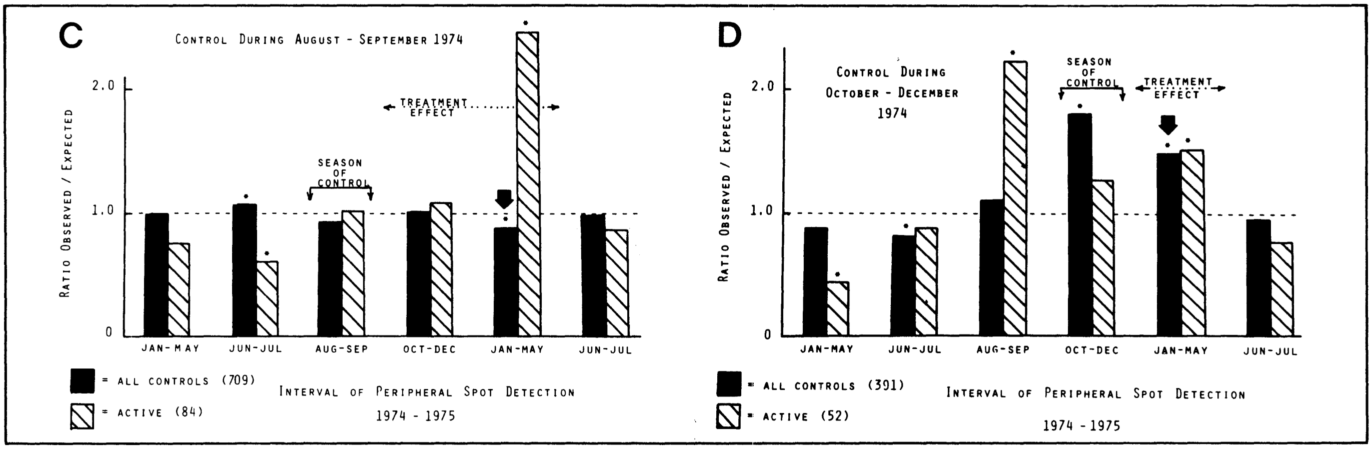


Figure 5.--Temporal patterns of proliferation occurring in proximity to 1974 treatment spots controlled by all methods combined during August-September (C) and October-December (D) compared to active (uncontrolled) spots.

were associated with significantly high levels of proliferation during the following January-May period, compared to all other treatments combined.

During 1974, the period of maximum treatment effect occurred in June and July for spots controlled in January through May; in August-September for spots controlled in June and July; and in January-May 1975 for spots controlled during both August-September and October-December. In each case, treatment effects were expressed at realistic periods following control action, considering inherent delays due to seasonal rates of foliage discoloration (Billings and Kibbe 1978) and the frequency of detection flights.

Spots remaining active during 1974 within each of the four seasonal periods were associated with proliferation significantly higher than expected during the interval January through May 1975, regardless of the season during which active spots were last ground checked. Only controlled spots treated during October-December exhibited similar levels of proliferation that were significantly higher than expected during this detection interval.

The apparent duration of control effectiveness (horizontal dotted lines in figures 4 and 5) characteristically decreased as the season progressed. The temporal pattern associated with inactive spots was similar to that for all controls combined; by the following June, the relative levels of proliferation about inactive spots had increased to expected levels. This relationship reflects the fact that the distribution of new spots had become relatively uniform about all treatments by the following June and July (the season of peak new spot detection), regardless of the season of control the year before.

Effectiveness of Individual Control Tactics

To evaluate the efficacy of individual control tactics, observed values in the contingency table for a given treatment were grouped for all seasonal periods included within the duration of treatment effect and compared statistically to expected values by means of χ^2 (appendix 1). In a final test, deviations in observed versus expected values about spots controlled by a given treatment were compared by χ^2 analysis to corresponding values for active (uncontrolled) spots last ground checked during the season control was applied.

Of the various control methods in use throughout east Texas, salvage removal of infested trees was associated with the least proliferation attributed to treatment (table 4). The frequency of proliferation was significantly reduced below expected values following salvage prior to October. Salvage from October-December 1974, however, was associated with significantly high levels of proliferation during the following January-May.

Cut-and-leave applied prior to August appeared to reduce levels of proliferation that occurred before the following June. The same control tactic had no apparent influence on subsequent levels of proliferation when applied in August and September (table 4). Like salvage, cut-and-leave during October-December 1974 was associated with high proliferation during the spring of 1975.

Table 4.--Observed and expected numbers of peripheral spots encountered within 605 acres of 1974 controlled and uncontrolled spots during interval of treatment effect

Season of control (1974)	Treatment	No. of treatment spots	Numbers of peripheral spots: Obs.	Exp.	Deviation from expected	χ^2 [1] (1 df)	χ^2 [2] (1 df)
Jan.-May[3]	Salvage	24	25	45.5	-20.5	24.71**	2.87
	Cut-and-leave	13	14	23.0	- 9.0	8.89**	1.14
	Other	2	0	4.4	- 4.4	9.86**	4.94*
	Inactive	73	58	83.9	-25.9	21.89**	0.76
	Active	13	21	25.0	- 4.0	1.36	-----
June-July[4]	Salvage	284	110	154.7	-44.7	18.96**	11.42**
	Cut-and-leave	117	44	58.9	-14.9	4.90*	7.55**
	Other	54	48	35.4	+12.6	5.69*	0.01
	Inactive	393	70	124.6	-54.6	34.72**	19.15**
	Active	56	28	20.4	+ 7.6	3.31	-----
Aug-Sept[5]	Salvage	449	129	176.0	-47.0	17.96**	59.80**
	Cut-and-leave	203	56	56.5	- 0.5	1.32	23.57**
	Other	57	56	33.3	+22.7	18.65**	2.68
	Inactive	532	82	119.4	-37.4	15.63**	58.27**
	Active	84	55	25.1	+29.9	43.48**	-----
Oct-Dec[6]	Salvage	190	113	84.4	+28.6	12.19**	0.21
	Cut-and-leave	103	51	30.5	+20.5	15.92**	0.16
	Other	98	83	54.4	+28.6	18.12**	0.00
	Inactive	393	78	101.1	-23.1	6.69**	9.58**
	Active	52	27	18.0	+ 9.0	4.76*	-----

[1] χ^2 Comparison of single treatment to all other treatments combined. (* Probability < 0.05; ** Probability < 0.01).
[2] χ^2 Comparison of single treatment to active spots last ground checked during season of control.
[3] Interval of treatment effect = June 1974 through May 1975.
[4] Interval of treatment effect = August 1974 through May 1975.
[5] Interval of treatment effect = October 1974 through May 1975.
[6] Interval of treatment effect = January 1975 through May 1975.

Control methods other than salvage or cut-and-leave exhibited subsequent levels of proliferation that were significantly greater than expected when applied during June-July, August-September, and October-December 1974.

Unlike spots controlled during the spring and summer months, active spots in all four seasons exhibited levels of proliferation that were comparable to or significantly higher than expected levels during the corresponding interval of treatment effect. A direct comparison of proliferation levels about controlled spots during the interval of treatment effect with levels about active spots ground checked during the same season provided an additional measure of treatment effectiveness. Relative levels of proliferation during the specified intervals of treatment effect were significantly greater about active (uncontrolled) spots than about comparable spots that were controlled by salvage or cut-and-leave from June through September (table 4). No significant differences were observed between spots controlled during the remainder of the year by these tactics and active spots. Spots controlled by methods other than salvage or cut-and-leave exhibited subsequent levels of proliferation that were comparable to that observed about active spots.

DISCUSSION AND CONCLUSIONS

The nonexperimental approach described herein for comparing the effectiveness of individual SPB control tactics overcomes many of the obstacles that have prevented the measurement of control efficacy on an area-wide basis by more conventional, experimental methods. For example, the analysis evaluates control tactics applied under operational conditions throughout the entire infestation area (8 million acres) and is not limited to a few sample plots treated under experimental conditions. The methodology is applicable to any large SPB infestation area for which suitable detection and control records are available for electronic data processing. Specific data collection, often an extremely time-consuming and expensive phase of postsuppression evaluations, is unnecessary; our approach requires only detection and control dates and spot locations--information generated as part of routine pest control operations.

The use of new spot proliferation as a measure of treatment efficacy has certain limitations that also warrant mention. For example, in heavily infested areas, beetles dispersing from controlled spots may join uncontrolled spots nearby rather than initiate new infestations. (In this case, however, it seems reasonable to assume that this tendency would be independent of the control tactic applied). The evaluation provides only a relative measure of treatment efficacy, without providing information on why certain control tactics appear more effective than others. Another limitation is that the Texas Forest Service operations data bank excludes all spots that contained less than 10 trees. Although a sizable portion of the total spot population may be overlooked as a result (Leuschner et al. 1977), a majority of the beetle population during outbreak years occurs in the large infestations. Spots with less than 10 trees at detection seldom expand in size or require control (Billings 1979, Hedden and Billings 1979) and are more likely to involve bark beetles other than SPB. Accordingly, this censorship of the data is not expected to influence the results materially. Despite these shortcomings, results of this analysis represent the most comprehensive efficacy data currently available for at least three options the pest manager can now use: salvage, cut-and-leave, and no control.

Perhaps the most significant contribution of the present study is the evidence that spot disruption during summer months is a control strategy with merit, not only for preventing additional timber losses from spot expansion but also as a means to reduce new spot proliferation that is likely to occur if spots remain active into the fall. Presumably, the effectiveness of cut-and-leave results primarily from losses suffered by summer-reared beetles after they emerge from treated trees, since complete brood mortality within trees is not assured (Hodges and Thatcher 1976, Palmer and Coster 1978). With aggregation pheromones no longer present in the spot to guide emerging beetles to new hosts, beetles are forced to disperse from controlled spots under adverse environmental conditions (Gara 1967). Degeneration in the size and physiological condition (fat content) of summer-reared beetles (Hedden and Billings 1977) also may limit the beetle's capacity for long-distance flight and/or ability to initiate new infestations.

In contrast to summer treatments, spots controlled in late fall and winter (October-December) were associated with significantly high levels of proliferation during the following January-May. In these cases, however, levels of proliferation were not significantly different from that observed about active, uncontrolled spots. Apparently, beetles were in the process of leaving established infestations in large numbers when fall controls were applied. That spots controlled prior to October were associated with low levels of proliferation during the October-May period, however, clearly emphasizes the merits of summer control.

The high levels of proliferation observed during January-May 1975 about 1974 active spots (fig. 4) is of particular interest. These winter proliferations provide the nucleus from which beetle populations again may increase to outbreak proportions by the following summer (Thatcher and Pickard 1967).

The reduced levels of proliferation about early spring controls in this study need to be interpreted with caution; this pattern may have resulted from the tendency of surviving beetles to fly to active infestations nearby or to disperse to areas distant from brood sources during this time of year. Although new spot proliferation in the immediate area is reduced, mortality of beetle populations due to dispersal losses may be far less in spring-treated spots than in spots controlled during the summer, when beetles are less capable of long-range dispersal. Since relatively few spots are detected prior to May in east Texas, though, the efficacy of spring controls is of less practical interest.

Summer control will not assure protection from new spot proliferation beyond the next spring if nothing is done to reduce the susceptibility of surrounding stands. During the spring dispersal period, susceptible stands apparently may be reinvaded by beetles from outside sources despite direct suppression efforts in the immediate area the year before. The elimination of stand conditions known to promote perennial beetle problems (Lorio and Bennet 1974, Coulson et al. 1974) appears to offer the best long-term solution to the SPB problem (Hedden 1978).

We believe this evaluation has given us important insight into the seasonal behavior of SPB populations in east Texas in addition to providing a means to compare the impact of various control tactics. The results support the hypothesis that new spot proliferation and spot growth--the two distinct phases of SPB attack behavior--are largely seasonally dependent phenomena. Detection records indicate that most new multiple-tree spots in east Texas are initiated during the spring (March-May) and usually detected 4 to 8 weeks later when crowns of infested trees discolor (Billings 1979). The fact that new spots detected in June and July tend to be uniformly distributed with respect to sources of brood the year before (figs.

4 and 5) provides evidence that spring-emerging beetles tend to disperse longer distances than those emerging at other seasons. This dispersal flight apparently serves to redistribute the population throughout the infestation area and to carry beetles into previously uninfested stands remote from brood sources. Furthermore, the observation that spots reported in August and September 1974 were not aggregated around spots controlled earlier in the year suggests that new spot initiation may be even more seasonally dependent than area-wide detection records indicate. Conceivably, many of the spots reported during late summer months were initiated in the spring and overlooked during June and July surveys.

Spots which are initiated during the spring dispersal period and remain active apparently serve as sources of attraction for beetles entering the area later. Immigration of large numbers of beetles into newly initiated spots during the latter part of the spring dispersal period would account for the rapid increase in the number of active trees often observed in areas of high beetle populations during May and June (Texas Forest Service, unpublished data). This activity is later reflected in the wide range of spot sizes at detection as well as the reduced frequency of new spot proliferation shown to occur during the June and July detection interval about active spots (fig. 4).

The expansion of established infestations by beetles emerging from within the spot (Hedden and Billings 1979) appears to be the primary mode of activity for most of the SPB population during the summer. Continual production of population-aggregating pheromones in active, uncontrolled spots (Gara 1967) would serve to keep emerging beetles within the spot and also to attract beetles from other sources that are flying in the area. This would effectively reduce the occurrence of new spots in proximity to active infestations during summer months, accounting for the temporal pattern evident about active spots in figures 4 and 5. As winter approaches, however, an increasing proportion of the beetle population disperses out of active or controlled infestations from which they emerged (Thatcher and Pickard 1967, Billings 1979), contributing to nearby proliferations that become detectable prior to May of the following year. In turn, by the time these winter proliferations are detected, another generation of SPB broods apparently is emerging to participate in long-range spring dispersal prior to initiating the many randomly distributed spots that appear each year during June and July (Billings 1979).

The evidence that large, active SPB infestations can be controlled during the summer months solely by physically disrupting the production of population-aggregating pheromones without producing increased proliferation has implications for developing new control tactics. At least in the case of southern pine beetle in east Texas, methods designed to capitalize on seasonal limitations in the insect's dispersal and attack behavior may prove more effective and practical for direct suppression than earlier attempts to destroy within-tree populations with insecticides. Indeed, the aerial application of species-specific inhibitors (Payne, Coster, and Johnson 1977) to summer infestations to chemically disrupt spot growth processes and reduce eventual new spot proliferation offers considerable promise as a future control strategy.

LITERATURE CITED

Bennett, W. H., and L. S. Pickard. 1966. Benzene hexachloride emulsion as a summer control of the southern pine beetle. J. Econ. Entomol. 59:484.

Billings, R. F. 1979. Detecting and aerially evaluating southern pine beetle outbreaks--operational guides. South. J. Appl. For. [In press.]

Billings, R. F., and C. A. Kibbe. 1978. Seasonal relationships between southern pine beetle brood development and loblolly pine foliage color in East Texas. Southwest. Entomol. 3: 89-95.

Blalock, H. M. 1964. Casual inference in non-experimental research. 166 p. Univ. of North Carolina Press, Raleigh, N.C.

Copony, J. A., and C. L. Morris. 1972. Southern pine beetle suppression with frontalure and cacodylic acid treatments. J. Econ. Entomol. 65:754-757.

Coulson, R. N., J. L. Foltz, A. M. Mayyasi, and F. P. Hain. 1975. Quantitative evaluation of frontalure and cacodylic acid treatment effects on within-tree populations of the southern pine beetle. J. Econ. Entomol. 68:671678.

Coulson, R. N., F. P. Hain, and T. L. Payne. 1974. Radial growth characteristics and stand density of loblolly pine in relation to the occurrence of the southern pine beetle. Environ. Entomol. 3:425428.

Coulson, R. N., F. L. Oliveria, T. L. Payne, and M. W. Houseweart. 1973. Variables associated with use of frontalure and cacodylic acid in suppression of the southern pine beetle. II. Brood reduction in trees treated with cacodylic acid. J. Econ. Entomol. 6:897-899.

Coulson, R. N., T. L. Payne, J. E. Coster, and M. W. Houseweart. 1972. The southern pine beetle *Dendroctonus frontalis* Zimm. (Coleoptera:Scoltidae) 1961-1971. Texas For. Serv. Publ. 108. 39 p. Texas For. Serv., College Station, Tex.

Gara, R. I. 1967. Studies on the attack behavior of the southern pine beetle. I. The spreading and collapse of outbreaks. Contrib. Boyce Thompson Inst. 23:349-354.

Hedden, R. L. 1978. The need for intensive forest management to reduce southern pine beetle activity in East Texas. South. J. Appl. For. 2:19-22.

Hedden, R. L., and R. F. Billings. 1977. Seasonal variations in fat content and size of the southern pine beetle in East Texas. Ann. Entomol. Soc. Amer. 70:876-880.

Hedden, R. L., and R. F. Billings. 1979. Southern pine beetle: factors influencing the growth and decline of summer infestations in East Texas. For. Sci. [In press.]

Hodges, J. D., and R. C. Thatcher. 1976. Southern pine beetle survival in trees felled by the cut and top--cut and leave method. 5 p. USDA For. Serv. Res. Note SO-219. South. For. Expt. Stn., New Orleans, La.

Leuschner, W. A., H. E. Burkhart, G. D. Spittle, I. R. Ragenovich, and R. N. Coulson. 1976. A descriptive study of host and site variables associated with the occurrence of *Dendroctonus frontalis* Zimm. in East Texas. Southeast. Entomol. 1:141-149.

Lorio, P. L., and W. H. Bennett. 1974. Recurring southern pine beetle infestations near Oakdale, Louisiana. 6 p. USDA For. Serv. Res. Pap. SO-95. South. For. Expt. Stn., New Orleans, La.

Morris, C. L., and J. A. Copony. 1974. Effectiveness of intensive salvage in reducing southern pine beetles in Virginia. J. For. 72:572.

Ollieu, M. M. 1969. Evaluation of alternative southern pine beetle control techniques. Texas For. Serv. Publ. 104. 6 p. Texas For. Serv., College Station, Tex.

Palmer, H. C., and J. E. Coster. 1978. Survival of southern pine beetles in felled and standing loblolly pines. J. Ga. Entomol. Soc. 13:1-7.

Payne, T. L., J. E. Coster, and P. C. Johnson. 1977. Effects of slow-release formulation of synthetic *endo-* and *exo-*brevicomin on southern pine beetle flight and landing behaviour. J. Chem. Ecol. 3:133-141.

Snedecor, G. W., and W. G. Cochran. 1967. Statistical methods. 593 p. Iowa State Univ. Press, Ames, Iowa.

Stage, A. R., and G. E. Long. 1967. Forest stand dynamics as a basis for integrated pest managment of forest pests. Int. Union For. Res. Organ. 16th Congr. Proc., p. 19-27. [Oslo, Norway].

Steel, R.G.D., and J. H. Torrie. 1960. Principles and procedures of statistics with special reference to the biological sciences. 481 p. McGraw-Hill Book Co., Inc., New York.

Texas For. Serv. 1974. Texas forest pest activity 1972-73 and Forest Pest Control Section annual report. 16 p. Texas For. Serv. Circ. 219. Texas For. Serv., College Station, Tex.

Texas For. Serv. 1975. Cut and leave--a method to reduce losses from the southern pine beetle. 4 p. Texas For. Serv. Circ. 223. Texas For. Serv., College Station, Tex.

Texas For. Serv. 1976. Salvage--the preferred method to reduce losses from the southern pine beetle. 5 p. Texas For. Serv. Circ. 225. Texas For. Serv., College Station, Tex.

Thatcher, R. C., and L. S. Pickard. 1967. Seasonal development of the southern pine beetle in East Texas. J. Econ. Entomol. 60:656-658.

APPENDIX 1

To test for significant differences between observed and expected values of interest, a χ^2 value was computed from a 2×2 contingency table using a formula that corrects for continuity (Snedecor and Cochran 1967, p. 217). In this analysis, the ratio a/b was compared for independence to the ratio c/d using the formula

$$\chi^2 = \frac{N([ad-bc]-N/2)^2}{(a+b)(c+d)(a+c)(b+d)}$$ in which

a = observed number of peripheral spots within cell (i, j) located within row (i) and column (j) of the contingency table in which i = 1,20 treatments (control × season combinations) and j = 1,6 detection intervals.

b = observed number of peripheral spots in all other cells combined within row (i), excluding cell (i, j).

c = observed number of peripheral spots in all other cells combined within column (j), excluding cell (i, j).

d = observed number of peripheral spots in all other cells combined excluding cells within row (i) and column (j).

N = a + b + c + d

χ^2 values exceeding 3.84 and 6.63 with 1 df were considered significant at $P < 0.05$ and $P < 0.01$, respectively.

ADDITIONAL CONSIDERATIONS IN EVALUATING TACTICS FOR SOUTHERN PINE BEETLE CONTROL

T. Evan Nebeker[1]

Abstract.--Given the fact that southern pine beetle density estimates will be used in evaluating control tactics, I present a hierarchy of absolute within-tree estimators with considerations of cost, precision, and accuracy. Also discussed are factors that need to be considered in a total evaluation of the control tactic, such as the influence of the physical properties of a tree, site and stand conditions, and the impact on the system as a whole.

INTRODUCTION

The objective of the control tactic for southern pine beetle (SPB), *Dendroctonus frontalis* Zimmerman, has to be clearly stated in view of the management objectives. It might be biological, economic, or ecological. From the biological point of view, a reduction in beetle density in space and time may be the goal, or a reduction in active basal area. From the economic point of view, the objective may be to increase net return. The ecological point of view is much broader and the considerations are more systems oriented. Here, the effects may be either direct or indirect on the parasite and predator community, wildlife populations, and so forth.

The particular point of view one takes in evaluating control tactics will determine the type of information necessary to evaluate the tactic or tactics in combination. For example, the economic point of view is currently being utilized in research validation programs (Parvin 1978). The data needed to make comparisons from this point of view are income or other measurable benefits, direct expenses such as labor (function of hourly rate and time required to complete the operations), materials, and equipment (costs of operation and maintenance). In short, a total accounting of everything that goes into the production of the commodity of interest is required. The economic factor has to be considered eventually in our evaluation of control tactics.

It is the assumption in this paper that the biological point of view will be taken, and further that the change in SPB density will be part of the measure for evaluating the control tactic. It is also assumed that the observed change (increase or decrease in SPB density) is a direct or indirect function of the treatment and can be determined analytically via variance partitioning or holding as many parameters as possible constant through analytical or experimental means.

The reasoning for restricting the number of variables may be illustrated by an example from Cochran and Cox (1957). It was experimentally determined that each of the following three treatments, whiskey and water, gin and water, and rum and water, taken orally in sufficient quantities, produces some degree of intoxication. By itself the experiment provides no information as to whether the intoxication is due to the water, the ingredients, or the fact that the two are mixed. A more extensive experiment with additional treatments would be necessary to throw some light on this question.

We are studying a similar problem at this symposium. Is the change in SPB density, for example, due to the control tactic utilized or due to other conditions associated with the treated area? In order to address this question, we must consider at least four areas. The first area is the estimation procedure used to measure the density of the SPB in time and space. Previous papers in this symposium have covered this topic, so I will address only the question of within-tree absolute population estimators. Second, the influence of the individual tree on SPB success will be considered. Third, the factors (site and stand) that have been found in common with SPB infes-

[1] Associate Professor, Dept. of Entomology, Mississippi Agricultural and Forestry Expt. Stn., Mississippi State Univ., Mississippi State, Miss.

tations should be considered in evaluating control tactics. The fourth area is the impact of the treatment on other populations in the forest system. It is not the purpose of this paper to treat each of these topics in total but simply to present the idea that before an actual experiment is conducted, some consideration of these elements, and possibly many others, needs to take place.

ABSOLUTE WITHIN-TREE POPULATION ESTIMATION PROCEDURES

In order to evaluate (measure) changes in population density, researchers must choose an estimation procedure. In selecting the procedure, they should consider precision, accuracy, cost, and so forth. Of course, the most precise estimate is a complete census of the population or parameter of interest. However, this is obviously too costly and totally unacceptable in evaluating a control tactic because the censustaking becomes the control.

Several investigators have addressed themselves to the problem of sampling and estimating bark beetle populations (Berryman 1968, Carlson and Cole 1965, DeMars 1970, Dudley 1971, Safranyik and Graham 1971). Coulson et al. (1975, 1976), Pulley et al. (1977a and b), Stephen and Taha (1976), McClelland et al. (1978), and Nebeker et al. (1978a) have specifically examined the problem of sampling SPB populations. It is not my intention here to review each in detail but to present a view of the hierarchy of the various estimation procedures that have been developed with precision, accuracy, and cost as criteria for ranking.

As indicated earlier, the most precise estimator would be a complete census where the true population values μ and σ for given sample dimensions can be obtained. However, this is too costly and would obscure information concerning evaluation of the control tactic. The next level of sampling that can yield precise estimators I will call direct intensive sampling. Here the estimators are developed from simple random sampling or stratified random sampling theory. On this subject Pulley et al. (1977a) concluded that simple random sampling requires far too many sample units to be considered in an operational sampling program. This conclusion was supported by Nebeker et al. (1978a). Concerning stratified sampling, Pulley at al. (1977a) concluded that as this technique is generally employed it would concentrate data collection at the extremes of the infested bole, where within-tree variation of life stages is greater; therefore, data requirements again exceed those of other techniques. While this is generally true, it is our position (Nebeker et al. 1978a) that the most precise estimators are obtained via stratified sampling. We recommend unequal stratification with optimal allocation. Through unequal stratification we can reduce the sample intensity at the extremes of the infested bole, hence increasing the relative efficiency of the estimation procedure. If extremely precise estimators are required, cost will have to be ignored to a degree.

The next grouping of estimators is what I call a blend of direct and indirect sampling. The estimators are developed first from current sample information concerning a given tree and then in combination with other analytical tools. Pulley et al. (1977a and b) identified the most precise of these types of estimation techniques as the TG-PDF procedure. Basically the procedure identifies that the optimal sample levels (location within the infested bole) vary with the life stages being sampled. Generally, two or three levels provide an adequate estimate for most sampling requirements. At each level four 100-cm^2 disks are removed and processed as described by Coulson et al. (1976). This information is then utilized in the TG-PDF estimation procedure.

The precision of the estimator is a function of the model used to describe the data that forms the bases of the indirect portion of the estimator. We (Nebeker et al. 1978b) compared a few models used in this manner and presented a model that increases the amount of variation explained and reduces the mean square error through the inclusion of three variables that are a function of individual tree characteristics. That model is as follows:

$$y = a + bx + cx^2 + d_1 IBT_m + d_2 R + d_3 A \qquad (1)$$

where

- y = estimated centimeters of gallery per 100 cm^2
- x = normalized height of the infested bole ranging from 0 to 100
- 0 = base of the infestation
- 100 = top of the infestation
- a, b, c, d_1, d_2, and d_3 are coefficients of the model
- IBT_m = the average inner bark thickness at the middle of the infested bole in millimeters
- R = IBH/TRH, where IBH is the infested bole length and TRH is the tree height, in meters

A = (d.b.h.)(IBH), where d.b.h. is diameter at breast height. Note that A is proportional to an approximate measure of the total infested surface area in units of square meters.

The point I would like to note here is the result of the development of this model and the extension of this model into an absolute population estimator that is very inexpensive, fairly high in accuracy, but less precise than other estimators.

Utilizing this basic model (1) we developed a more general model for seasons and species attacked. The model takes the following general form:

$$y = a_1 + a_2A^1 + a_3R + a_4C. \qquad (2)$$

The point that is important to remember concerning this technique is that *no* samples are taken from the tree, only information concerning (1) d.b.h., (2) total tree height (TH), (3) length of the infestation (L), and (4) inner bark thickness at the middle of infested bole (C) or an estimate based on models describing this variable in relation to species, d.b.h., tree height, taper, and so forth.

Our data set was divided as follows: (1) species attacked (shortleaf or loblolly pine), and (2) time of year that the trees were attacked. For shortleaf, season 1 (S1) is defined as being between Julian dates 01 and 182 and season 2 (S2) between 183 and 365. For loblolly, S1 represents days 01 through 117 and S2 represents days 118 through 365.

The methods and materials for collecting the data on loblolly are the same as for shortleaf as presented by Nebeker et al. (1978b). The complete data set was utilized to obtain the coefficients (a_1, a_2, a_3, and a_4) for S1 and S2, species attacked, and time of sample. The sample time corresponds to the first, second, and third samples described by Coulson et al. (1975), and sample four as described by Nebeker et al. (1978b). The range of the data used to develop the estimators in table 1 is presented in table 2.

The following intensively sampled trees were selected to illustrate the technique because the total gallery length within each tree was known. (D.b.h. measured 15.3 cm in all three trees.)

Table 1.--Models for estimating total gallery length during two time periods and species attacked in relation to 1st, 2nd, 3rd, or 4th samples

Season	Species	Estimate $(\hat{T}) = y$ (DL)	90% C.I. (DL)
1st Sample			
S1	SL	$y=136.921+0.377(A^1)+147.30(R)-85.8(C)$	±64.68
S2	SL	$y=19.670-39.300(A^1)+483.70(R)-0.6(C)$	±72.15
S1	LOB	$y=319.770-16.590(A^1)+159.22(R)-179.4(C)$	±99.61
S2	LOB	$y=206.810-6.314(A^1)+73.51(R)-62.5(C)$	±117.87
2nd Sample			
S1	SL	$y=105.330+10.620(A^1)-18.25(R)+43.4(C)$	±63.17
S2	SL	$y=371.220-16.120(A^1)-200.75(R)-107.8(C)$	±91.46
S1	LOB	$y=511.490-33.500(A^1)-13.32(R)-216.5(C)$	±89.95
S2	LOB	$y=22.630+2.479(A^1)+287.61(R)+4.7(C)$	±96.95
3rd Sample			
S1	SL	$y=194.280+4.710(A^1)-48.16(R)-10.1(C)$	±64.29
S2	SL	$y=79.420-27.000(A^1)+93.62(R)+34.5(C)$	±63.66
S1	LOB	$y=211.060+1.477(A^1)-32.67(R)-51.2(C)$	±100.91
S2	LOB	$y=52.460+4.730(A^1)+123.78(R)+7.6(C)$	±84.67
4th Sample			
S1	SL	$y=149.270+7.760(A^1)+63.74(R)+23.5(C)$	±63.91
S2	SL	$y=128.390-34.700(A^1)=117.90(R)+25.6(C)$	±55.44
S1	LOB	$y=496.120-27.000(A^1)-115.00(R)-172.2(C)$	±64.30
S2	LOB	$y=126.200+2.959(A^1)-100.10(R)+35.2(C)$	±82.20

S1 = days 01 through 182 for shortleaf (SL) and 01 through 117 for loblolly (LOB)

S2 = days 183 through 365 for SL and 118 through 365 for LOB

1st Sample, 2nd, etc., as defined (Nebeker et al. 1978b).

$\hat{T}$ = Estimated total gallery length

D = d.b.h. - 2C

C = Inner bark thickness at middle of infested bole in mm

A^1 = (d.b.h.)(L)/100

R = L/TH

L = Length of infestation

TH = Tree height

C.I. = Confidence interval

Tree species, number, and sampling date	Tree height (m)	Length of infestation (m)	Inner bark thickness (mm)
Loblolly 1101 Oct-Dec	27.4	13.44	1.0
Shortleaf 1301 Oct-Dec	12.3	5.76	1.2
Loblolly 1912 Apr-June	21.8	7.60	0.9

To illustrate the use of this new estimator, the following example is presented. If one needs an estimate of total gallery length within a tree (shortleaf or loblolly) at a particular time of the year,

Table 2.--Range of A^1, R and C utilized in the indirect estimating procedure

		A^1		R		C	
		min	max	min	max	min	max
1st Sample							
S1	SL	1.20	5.55	.34	.77	.6	1.5
S2	SL	2.63	4.47	.44	.59	.5	1.1
S1	LOB	2.46	5.78	.30	.72	.7	1.5
S2	LOB	2.06	6.37	.35	.49	.8	1.4
2nd Sample							
S1	SL	1.20	5.55	.34	.77	.6	1.5
S2	SL	0.88	4.46	.44	.65	.5	1.3
S1	LOB	1.16	5.78	.30	.72	.7	1.5
S2	LOB	3.69	6.37	.35	.68	.8	1.4
3rd Sample							
S1	SL	1.20	5.55	.34	.77	.6	1.5
S2	SL	2.63	4.47	.44	.59	.5	1.1
S1	LOB	0.62	5.78	.30	.72	.7	1.5
S2	LOB	3.70	6.37	.35	.53	.8	1.4
4th Sample							
S1	SL	1.20	5.55	.34	.77	.6	1.5
S2	SL	2.63	4.47	.44	.59	.5	1.1
S1	LOB	1.26	5.78	.30	.72	.7	1.5
S2	LOB	3.69	6.37	.35	.53	.8	1.4

Note--Difference between samples is a function of the inclusion of additional intensively sampled trees during that period.

the proper model can be selected from table 1. Similar models can be generated for the various life stages or parameters of interest; however, gallery length illustrates the estimating procedure here. Tree 1101 was sampled during the attacking adult phase, equaling the first sample. Trees 1301 and 1912 were sampled during the larval stage, equaling the second sample. Trees 1101 and 1301 fall in S2, and 1912 in S1. Based on this information, the appropriate model can be selected from table 1 for estimating total gallery length. The appropriate model for tree 1101 is

$$y = 206.810 - 6.314(A^1) + 73.51(R) - 62.5(C),$$

for tree 1301

$$y = 371.220 - 16.120(A^1) - 200.75(R) - 107.8(C),$$

and for tree 1912

$$y = 511.490 - 33.50(A^1) - 13.32(R) - 216.5(C).$$

Using the definitions of A^1, R and C from table 1, we obtain for tree 1912

$$A^1 = \frac{(15.3)(7.6)}{100} = 1.16$$

$$R = 7.6/21.8 = 0.35$$

$$C = 0.9$$

hence

$$y = 511.49 - 33.5(1.16) - 13.32(0.35) - 216.5(0.9) = 273.12.$$

An absolute estimate of total gallery length ($\hat{T}_{GL}$) is obtained from

$$\hat{T}_{GL} = yDL$$

where D = d.b.h. 2C or 15.3 2(0.9) = 13.5 and L = 7.6.

Hence

$$\hat{T}_{GL} = (273.12)(13.5)(7.6) = 28{,}022 \text{ cm of gallery within tree 1912.}$$

The 90 percent confidence interval is

$$C.I. = 89.95(D)(L) = 89.95(13.5)(7.6) = \pm 9229.$$

The final estimate and C.I. is

$$\hat{T}_{GL} = 28{,}022 \pm 9229$$

with the true value being 25,649 cm of gallery for tree 1912.

These results and those for trees 1101 and 1301 are compared with the estimations of various estimators discussed above in tables 3, 4, and 5.

From the results it appears that this method can give reasonable estimates in comparison with other estimating procedures. It is evident that if an extremely precise estimate is needed, this is not the estimator to use (because of extremely wide confidence intervals). The level of precision is the real question and will dictate in part the utility of any proposed absolute population estimator.

CONSIDERATIONS OF THE INDIVIDUAL TREE

The reduction in SPB density in certain cases may be a function of the species attacked and the physical properties of those trees, and not entirely the control tactic. Hodges et al. (1979) have approached the question concerning

Table 3.--Comparison of various estimation procedures for tree 1912

Procedure	Estimate ($\hat{T}_{GL}$)	90% C.I.
TAMU Methods[1]		
(Long cylinder)		
Single level (n=4)		
2.0 m	20,454	±7,743
3.5 m	21,964	±4,137
5.0 m	14,995	±4,430
6.5 m	25,584	±5,455
Two levels (n=8)		
2.0 m, 5.0 m	17,725	±4,417
3.5 m, 6.5 m	23,774	±3,743
MSU Methods		
$y = a_1+a_2A^1+a_3R+a_4C$	28,022	±9,229
Stratified sampling[2]		
1[3]	30,843	±3,549
2	24,899	±3,870
3	27,611	±6,686
Absolute gallery length (100 cm² sample units)	25,649	±3,928

[1] Methods described by Coulson et al. (1976).
[2] Three equal strata, n = 10, distributed according to optimal allocation after Nebeker et al. (1978a), with two samples from lower strata, six from middle, and two from upper strata.
[3] This procedure repeated three times with new samples being selected at random each time.

the oleoresin characteristics and susceptibility of four southern pines (loblolly, shortleaf, slash, and longleaf) to SPB attack. Data obtained in their study demonstrate that it is possible to predict relative susceptibility of individual loblolly and shortleaf trees based on physical characteristics of the oleoresin system. These predictions are presented in table 6. Of these physical characteristics (total flow, rate of flow, time to crystallization, and viscosity), Hodges (personal communication) considers total flow the most important in determining susceptibility. It is the characteristic to measure in relation to the evaluation of control tactics.

Table 4.--Comparison of various estimation procedures for tree 1301

Procedure	Estimate ($\hat{T}_{GL}$)	90% C.I.
TAMU Methods[1]		
(Long cylinder)		
Single level (n=4)		
2.0 m	12,383	±4,688
3.5 m	11,840	±2,229
5.0 m	14,319	±4,230
Two levels (n=8)		
2.0 m, 5.0 m	13,351	±3,445
MSU Methods		
$y = a_1+a_2A^1+a_3R+a_4C$	9,906	±6,796
Stratified sampling[2]		
1[3]	15,056	±2,091
2	15,360	±3,342
3	10,667	±2,248
Absolute Gallery Length (100 cm² sample units)	15,119	±2,248

[1] Methods described by Coulson et al. (1976).
[2] Three equal strata, n = 10, distributed according to optimal allocation after Nebeker et al. (1978a), with two samples from lower strata, six from middle, and two from upper strata.
[3] This procedure repeated three times with new samples being selected at random each time.

CONSIDERATION OF SITE AND STAND CONDITIONS IN EVALUATING CONTROL TACTICS

In order to evaluate any treatment, an understanding of the experimental conditions is required. In some cases, based on prior knowledge, the result can be predicted at a fairly high probability. It is useless to try to evaluate a control tactic without considering these conditions. Within the site/ stand subject area of the Expanded Southern Pine Beetle Research and Applications Program, the general objective has been to estimate stand susceptibility. The ability to rank stands as to susceptibility to SPB attack should aid in developing an experimental design to evaluate control tactics.

It was generally concluded (Porterfield and Rowell 1978) that using baseline (uninfested) natural, undisturbed, Coastal Plain data, and assuming that infested data are representative of all SPB spots, general conclusions can be drawn as to differences in stand susceptibility.

Table 5.--Comparison of various estimation procedures for tree 1101

Procedure	Estimate ($\hat{T}_{GL}$)	90% C.I.
TAMU Methods[1]		
(Long cylinder)		
Single level (n=4)		
2.0 m	45,896	±17,374
3.5 m	44,796	±8,438
5.0 m	38,619	±11,409
6.5 m	39,935	±8,515
Two levels (n=8)		
2.0 m, 5.0 m	42,258	±10,899
3.5 m, 6.5 m	41,708	±6,567
MSU Methods		
$y = a_1+a_2A^1+a_3R+a_4C$	29,914	±21,069
Stratified sampling[2]		
1[3]	35,229	±10,035
2	40,871	±7,478
3	34,849	±11,132
Absolute Gallery Length (100 cm² sample units)	44,390	

[1] Methods described by Coulson et al. (1976).
[2] Three equal strata, n = 10, distributed according to optimal allocation after Nebeker et al. (1978a), with two samples from lower strata, six from middle, and two from upper strata.
[3] This procedure repeated three times with new samples being selected at random each time.

Methods for obtaining the data and analytical procedures are outlined by Rowell (1978). In general, it was found that five variables, selected through discriminant analysis, best aided in differentiating between infested and uninfested plots. Total pine cubic-foot volume was the most important discriminating variable chosen and was followed in order by percent pine basal area, slope, 10-year radial growth, and average bark thickness. The general results for the Coastal Plain can be divided further by landform. Each landform model usually includes at least one of these five variables, as well as other variables that aid in characterizing the uniqueness of each individual landform. Table 7 shows the discriminant equations for various landforms. I believe this information may be useful and should be considered in developing the experimental design for evaluating control tactics.

A final idea in this regard that might shed some light on the effect of the treatment--or lack of effect--is one presented by Rowell (1978). This has to do with the prediction of the final spot size (number of trees) based on the previous information. It seems reasonable that these ideas might be tested with little additional effort when evaluating a given tactic and might provide insight as to how to evaluate control tactics in light of the site and stand conditions.

Table 6.--Oleoresin characteristics and results of induced attacks on loblolly and shortleaf pines classified as resistant or susceptible to attack by southern pine beetle (Hodges et al. 1979)

Species/ tree #	Total flow (ml)	Rate of flow (ml/hr)	Time to crystal-lization (hrs)	Viscosity (stokes)	Score[1]	Classification	No. of attacks	Attacks/ m² (number)	Brood # m²	Comments
SHORT 42	14.7	1.84	0.5	22.1	+.614(-.167)	RES.	488	100.1	--	ALIVE
SHORT 62	12.7	0.81	1.5	27.4	+.136(-.793)	RES.	489	78.5	--	ALIVE
LOB 9	17.5	2.19	0.5	6.8	+.098(-.453)	RES.	1116	156.0	--	ALIVE
LOB 14	16.9	2.84	1.0	8.5	-.080(-.132)	RES.	776	95.8	--	ALIVE
LOB 22	15.9	1.19	0.5	22.9	+.790(-.502)	RES.	273	58.1	--	ALIVE
LOB 53	23.8	2.28	0.3	17.4	+.870(-.112)	RES.	800	138.8	--	ALIVE
SHORT 6	2.8	0.23	3.5	31.4	-.978(-1.116)	SUS.	604	97.9	122.7	KILLED
SHORT 15	4.8	1.06	4.0	31.9	-1.361(-.371)	SUS.	1891	92.5	145.3	KILLED
SHORT 33	1.3	0.11	8.0	13.8	-1.320(-2.236)	SUS.	344	67.8	64.6	KILLED
SHORT 70	9.4	0.97	1.3	9.4	-.996(-1.739)	SUS.	765	80.7	[2]	KILLED
LOB 27	7.6	1.15	1.0	11.3	-1.320(-1.496)	SUS.	886	100.1	[2]	KILLED
LOB 52	6.0	0.54	0.5	14.9	-.472(-1.986)	SUS.	175	52.7	[2]	KILLED

[1] Discriminant Function Scores when loblolly/shortleaf trees were compared to longleaf trees. Numbers not in parentheses are based on values for total flow, rate of flow, and time to crystallization. Numbers in parentheses are based on same values plus viscosity. Mean scores for loblolly were -.226 and -.946 (with viscosity); for shortleaf they were -.540 and -.996; for longleaf +.744 and +1.853.
[2] Brood not determined.

Table 7.--Discriminant equations developed to rank stand susceptibility to SPB over the entire Gulf Coastal Plain and its landforms (Porterfield and Rowell 1978)

(More positive scores = more resistant stands)

Landform Model	Discriminant Score	Critical "Break" Point
Gulf Coastal Plain	(slope × 0.3877) + (total pine ft³ volume × -0.00048) + (percent pine BA × -0.01576) + (radial growth [last 10 years] × 0.00462) + (avg. bark thickness × -1.27966) + 2.63682	0.050675
Flood Plains	(total ft³ pine volume × -0.00019) + (percent pine BA × -0.01897) + (radial growth [last 10 years] × 0.02267) + (slope × 0.11563) + 0.86301	0.36074
Stream Terrace	(slope × 0.04772) + (percent pine BA × -0.01404) + (live crown × 0.03155) + (total ft³ pine volume × -0.00028) + 0.25799	0.25964
Bay	(surface pH × 0.39946) + ("in" hardwood [10 FAC] × 0.09327) + (total ft³ pine volume × -0.00052) - 1.07507	0.05639
Upland Flat	(surface soil depth × 0.005) + (site index × -0.01555) + (avg. d.b.h. × 0.16864) + (percent pine BA × -0.02084) + (radial growth [last 10 years] × 0.00877) + (avg. bark thickness × -0.00054) + 2.63957	0.03769
Lower Slope	("in" hardwoods × 0.0889) + (radial growth [last 10 years] × 0.02131) + (live crown × 0.02766) + (avg. bark thickness × -3.55167) + (total pine ft³ volume × -0.00023) + 0.82083	0.20145
Side Slope	(total pine ft³ volume × -0.00083) + (avg. bark thickness × -2.39826) + 2.83116	0.24885
Steep Side Slope	(slope × 0.01618) + (total "no" trees × 0.19508) + (total pine ft³ volume × 0.00010) - 1.41592	-0.1199
Ridge	(slope × 0.09066) + (subsurface percent sand × 0.01282) + (avg. bark thickness × -3.40071) + (total pine ft³ volume × -0.00034) + 1.81909	-0.41086

For definitions and units of measure, see Rowell (1978).

ECOLOGICAL CONSIDERATIONS

The impact of the control tactic on populations other than the pest population has to be considered, in particular the parasite and predator community associated with the SPB. Science has embraced the general philosophy of developing control tactics that preserve, complement, and augment the biotic and physical mortality factors associated with the system of interest. It is also necessary to evaluate the control tactic from the point of view of other potential pest species. For example, will the treatment provide additional resources for pest population buildups? What impact will the control tactic have on other nontarget populations? And finally, what is the socioeconomic impact? If these concerns are not taken into account in the evaluation process, the advantages and disadvantages of the control tactic cannot be evaluated completely.

In conclusion, there are numerous considerations in the development of a program aimed at evaluating control tactics. I have addressed myself to a few; many others could have been included. The major point that needs to be addressed is the objective of the control tactic. Is it biological, economic, ecological, or a combination of all three? This has to be clearly stated along with the management objectives. In many cases clarifying the objective of the control tactic is the most difficult thing to do. Once this has been done, considerations of experimental design, data analysis, and other topics presented in this symposium should be emphasized in evaluating control tactics.

ACKNOWLEDGMENT

I wish to sincerely thank my associates and friends R. R. Hocking, O. P. Hackney, D. L. Shankland, R. L. Porterfield, J. D. Hodges, C. E. Rowell, and R. F. Mizell for the time they spent sharing their thoughts freely and discussing the various points presented in this paper.

LITERATURE CITED

Berryman, A. A. 1968. Development of sampling techniques and life tables for the fir engraver *Scolytus ventralis* (Coleoptera:Scolytidae). Can. Entomol. 100(11):1138-1147.

Carlson, R. W., and W. E. Cole. 1965. A technique for sampling populations of the mountain pine beetle. 13 p. USDA For. Serv. Res. Pap. INT-20. Ogden, Utah.

Cochran, W. G., and G. M. Cox. 1957. Experimental design. 611 p. John Wiley and Sons, Inc., Philadelphia, Penn.

Coulson, R. N., F. P. Hain, J. L. Foltz, and A. M. Mayyasi. 1975. Techniques for sampling the dynamics of southern pine beetle populations. 18 p. Tex. Agric. Exp. Stn. Misc. Pub. 1186.

Coulson, R. N., P. E. Pulley, J. L. Foltz, and W. C. Martin. 1976. Procedural guide for quantitatively sampling within-tree populations of *Dendroctonus frontalis*. 29 p. Tex.Agric. Exp. Stn. Misc. Pub. 1267.

DeMars, C. J., Jr. 1970. Frequency distributions, data transformations, and analysis of variation used in determination of optimum sample size and effort for broods of the western pine beetle. pp. 41-65, *In* Studies on the population dynamics of the western pine beetle, *Dendroctonus brevicomis* LeConte (Coleoptera: Scolytidae). R. W. Stark and D. L. Dahlsten, eds. Univ. Calif. Publ. Div. Agric. Sci.

Dudley, C. O. 1971. A sampling design for the egg and first instar larval populations of the western pine beetle, *Dendroctonus brevicomis* (Coleoptera:Scolytidae). Can. Entomol. 103: 1291-1313.

Hodges, J. D., W. W. Elam, W. F. Watson, and T. E. Nebeker. 1979. Oleoresin characteristics and susceptibility of four southern pines to southern pine beetle attack. Can. Entomol. [In review.]

McClelland, W. T., F. P. Hain, C. J. DeMars, W. S. Fargo, R. N. Coulson, and T. E. Nebeker. 1978. Sampling bark beetle emergence: A review of methodologies, a proposal for standardization, and a new trap design. Bull. Entomol. Soc. Am. 24(2):137-140.

Nebeker, T. E., O. P. Hackney, R. R. Hocking, M. Paz, and J. H. Lashomb. 1978a. Methods for and comparison of sampling schemes for estimating within-tree southern pine beetle populations. Can. Entomol. 110: 1015-1022.

Nebeker, T. E., R. R. Hocking, O. P. Hackney, and J. H. Lashomb. 1978b. A comparison of non-linear and linear models for describing gallery length distribution of *Dendroctonus frontalis* attacking shortleaf pine. Environ. Entomol. 7:636-640.

Parvin, D. W., Jr. 1978. Cotton research validation, Mississippi, 1978. *In* Proceeding of seminar sponsored by Cotton Incorporated, Integrated Management System in Cotton, December 1977, New Orleans, La.

Porterfield, R. L., and C. E. Rowell. 1978. Analysis of site-stand factors affecting southern pine beetle infestation incidence. 29 p. Progress report to Expanded Southern Pine Beetle Research and Applications Program. Feb. through Sept. 1978.

Pulley, P. E., R. N. Coulson, J. L. Foltz, W. C. Martin, and C. L. Kelly. 1977a. Sampling intensity, informational content of samples, precision in estimating within-tree populations of *Dendroctonus frontalis*. Environ. Entomol. 6(5):607-615.

Pulley, P. E., J. L. Foltz, A. M. Mayyasi, R. N. Coulson, and W. C. Martin. 1977b. Sampling procedures for within-tree adult populations of southern pine beetle, *Dendroctonus frontalis* (Coleoptera:Scolytidae). Can. Entomol. 109:39-48.

Rowell, C. E. 1978. Describing and predicting the susceptibility of Gulf Coastal Plain stands associated with southern pine beetle. M. S. thesis. Miss. State Univ, Mississippi State, Miss. 114 p.

Safranyik, L., and K. Graham. 1971. Edge-effect bias in the sampling of subcortical insects. Can. Entomol. 103(2):240-255.

Stephen, F. M., and H. A. Taha. 1976. Optimization of sampling effort for within-tree populations of southern pine beetle and its natural enemies. Environ. Entomol. 5:1001-1007.

EVALUATION OF A SOUTHERN PINE BEETLE CONTROL TACTIC:

A CASE STUDY FOR SYMPOSIUM PARTICIPANTS

James D. Smith and Daniel B. Twardus[1]

Abstract.--The current southern pine beetle (SPB) outbreak on the Bienville National Forest in Mississippi provides a basis for determining the effectiveness of a SPB control tactic over a large geographic area. The effects of treatment on numbers of beetles, and spot growth, proliferation, and size might be focal points for study group analysis. Patterns of land ownership, acres of host type, and information on both host and pest are provided for the determination of an experimental approach.

INTRODUCTION

One objective of the Expanded Southern Pine Beetle Research and Applications Program is to evaluate the effectiveness of recommended control tactics. This paper provides subject matter for study groups to use in developing an approach to the evaluation of treatment effectiveness. Cut-and-leave will be the control tactic studied.

Measuring the effectiveness of control tactics for southern pine beetle, *Dendroctonus frontalis* Zimmerman, is difficult due to the nature of the host/pest interaction, and the physical constraints and management of the area. It is relevant to seek answers to these questions: (1) Does the tactic kill beetles? (2) Does the tactic prevent additional tree mortality within spots? (3) Does the tactic prevent spot proliferation? (4) Does the tactic reduce the number and size of spots over time?

[1] Entomologists, USDA Forest Service, Southeastern Area, State and Private Forestry, Pineville, La. (Mr. Twardus is now affiliated with Forest Insect and Disease Management in Portland, Ore.)

The management situation and techniques presented herein do not fully represent National Forest resource management practices, but are developed to provide adequate problem analysis.

Information from one geographic area with a recent history of SPB will be used in this paper as the basis for developing an approach to evaluate a control tactic. Information provided will contain data on the study area, history of outbreak, forest conditions, and constraints involved with evaluating the treatment. The study area, the Bienville National Forest, is made up of two Ranger Districts.

To date, no SPB investigations have included an analysis of treatment effectiveness over a large area with intermingled land ownership. Study groups are asked to address this problem through information presented here. More specifically, the following points should be considered in designing a treatment effectiveness evaluation:

(1) A treatment evaluation is desired which analyzes the effects of the treatment on a spot basis and on an area basis.

(2) The effects of treatment are analyzed when only some portion of the SPB spots are treated. For example, treatment effect on an outbreak may be the same if only selected SPB spots are treated as opposed to all SPB spots.

(3) The treatment is compared to no treatment.

(4) The effects of intermingled ownership and the consequent immigration of uncontrolled SPB populations are considered.

(5) The effects of treatment are analyzed over time.

AREA OF EVALUATION

U.S. Forest Service personnel are currently engaged in a southern pine beetle suppression project on the Bienville National Forest in south-central Mississippi. The objective of the suppression project is to minimize resource losses from the SPB. The Forest is located

Table 1.--History of southern pine beetle outbreak on Bienville National Forest, Mississippi

Period of treatment	Bienville R.D.	Strong River R.D.
Oct 1976--Sept 1977		
Chemically treated	1,153 stems	4,010 stems
Salvage MBF	1,466 MBF	1,165 MBF
Percent of infestation treated	80 %	80 %
Oct 1977-Sept 1978		
Chemically treated	2,214 stems	3,765 stems
Salvage MBF	2,389 MBF	943 MBF
Percent of infestation treated	80 %	80 %

in all or parts of Smith, Newton, Jasper, and Scott Counties. Rectangular survey puts this area between Range 6 E. and Range 11 E., and between Township 2 N. and Township 9 N. as measured from the Choctaw Meridian.

The Forest contains 177,070 acres of forested land. However, 206,130 acres of private land are intermingled within Forest Service administrative boundaries. There are two ranger districts on the Forest (Bienville R.D. and Strong River R.D.).

HISTORY AND STATUS OF SPB OUTBREAK

The history of major SPB outbreaks on the Bienville National Forest began in 1976 (Twardus and Smith 1977). In October of that year, a control effort was begun. It was implemented based on the time of the evaluation and an estimate as to whether or not the outbreak would continue. Control Project accomplishments for 1977 are presented in table 1 (Smith 1977). The control project was continued in the fall of 1977 (Twardus 1977).

The Strong River District started a computerized reporting program during February 1978. This program reports infestation size, amount of timber in each control class (buffer and infested), dates of work, and type of control effort made (chemical or salvage). Spot locations were recorded on a map (fig. 1). Figure 2 shows the locations of infestations found on the last flight (October 1978).

The Bienville National Forest was examined again during September-October 1978 to determine the need for additional control work (table 2). Using

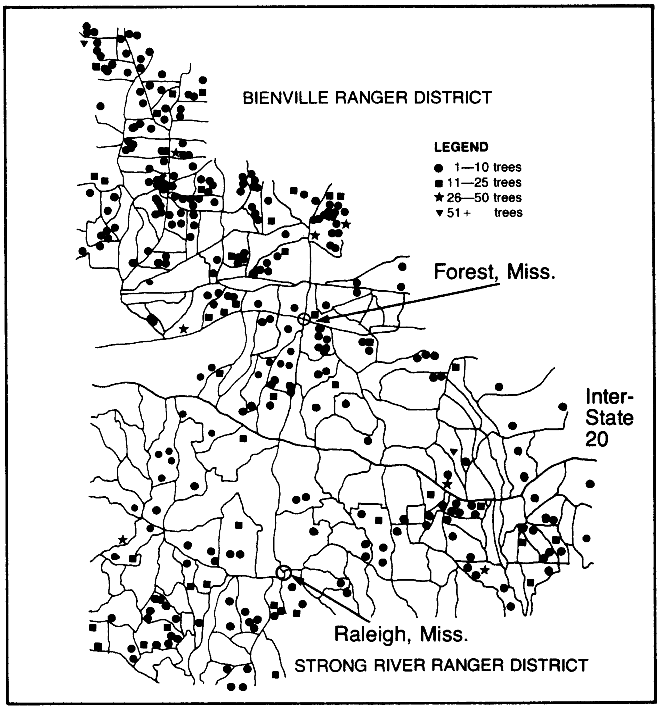


Figure 1.--Location and size of SPB infestations, January--September 1978, Bienville National Forest, Mississippi.

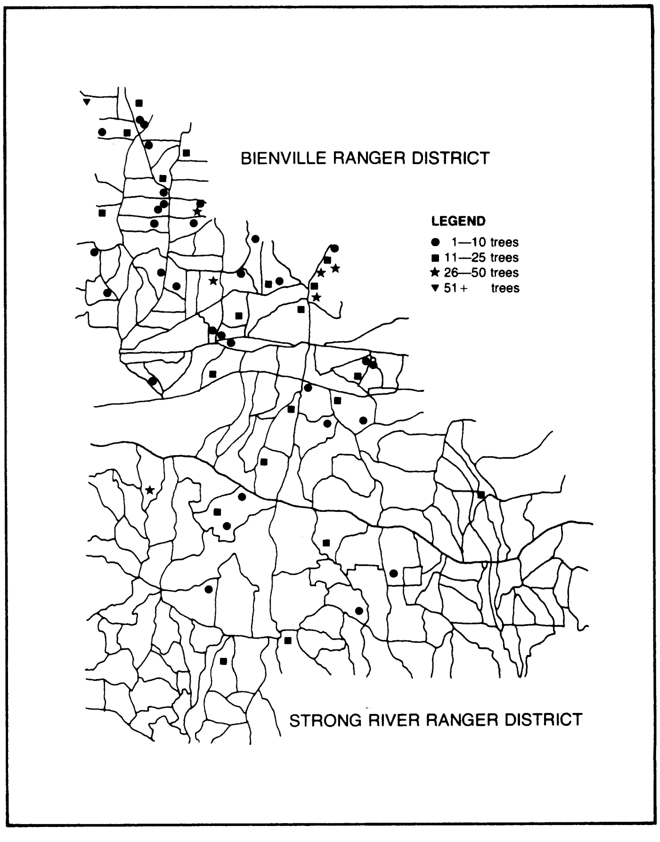


Figure 2.--Infestations on the Bienville National Forest, Mississippi, flight of October 1978.

Table 2.--Data from 1978 biological evaluation

	Bienville Ranger District	Strong River Ranger District
No. spots/district (Oct 1978)	50	10
Average spot size	13	13
Total spots FY 1978 (Oct 1977-Sept 1978)	300	120
Location of spots (Oct 1978)	Fig. 3	Fig. 3
Location of spots (Jan-Sept 1978)	Fig. 2	Fig. 2
Spot growth hazard[1] rated $\left(\frac{\text{\# new attacked trees}}{\text{\# newly vacated trees}}\right)$	1.34	1.34

[1] These data were taken on National Forest and private lands encompassing the Bienville National Forest and Wayne, Clarke, Jones, Jasper, Covington, Smith, Jefferson Davis, Simpson, and Rankin Counties (Twardus, Hertel, and Ryan 1978).

Moore's (1977) attack:emergence procedure, SPB populations were determined to be static (Smith 1978). This means that trees are becoming infested at the same rate older infested trees are being vacated. This procedure is being evaluated as a predictive tool for an area basis. The static condition indicates that the same amount of damage will occur in FY 1979 as that which occurred the previous year. Theoretically, the SPB population should be causing levels of damage in May 1979 similar to those of May 1978. The control project was continued based on results of this evaluation.

The Study Area

The Bienville District is composed of 98 compartments (fig. 1), with each compartment subdivided into stands (fig. 3). There are 74,750 acres of shortleaf-loblolly timber type in all age groups; 45,308 acres are greater than 40 years old. Figure 4 blocks out compartments to be entered for silvicultural examination in FY 1979 and FY 1980. Table 3 shows the distribution of host type by site index and acres.

The Strong River District is composed of 80 compartments. There are 63,055 acres of loblolly and shortleaf timber in all age groups, with 42,315 acres of pine timber greater than 40 years old. Host type is listed by site index and acres in table 4.

Seventy-eight percent of the total forest is in the pine host-type (137,805 acres). Of this host type, 64 percent is over 40 years old (87,622 acres). Acres of host type greater than 40 years old are presented by compartments in figure 5. The host type is distributed in stands 10 to 1100 acres in size. Some stands within compartments contain all pine over 40 years of age; others may contain little or no susceptible host type.

Table 3.--Distribution of pine host type, site index, and acres on the Bienville District, Mississippi

Loblolly (≥ 70% pine)		Shortleaf (≥ 70% pine)	
Site index[1]	Acres	Site index	Acres
52	38	71	764
71	752	73	79
72	68	81	2,174
73	439	83	144
80	5	91	641
81	29,687	93	60
82	265		
83	2,454		
91	26,465		
93	1,685		
101	5,563		
111	1,332		

[1] Site Index = Amount of height based on 50 years' growth.

Table 4.--Distribution of pine host type, site index, and acres on the Strong River District, Mississippi

Loblolly (≥ 70% pine)		Shortleaf (≥ 70% pine)	
Site index[1]	Acres	Site index	Acres
53	21	71	1,402
71	314	72	153
73	42	81	7,762
81	12,730	82	114
82	482	83	67
83	235	91	2,421
53	21		
71	42		
82	482		
83	239		
91	25,006	93	112
92	144	101	184
93	774		
101	5,008		
102	135		
103	61		
111	130		
112	21		
113	41		

[1] Site Index = Amount of height based on 50 years' growth.

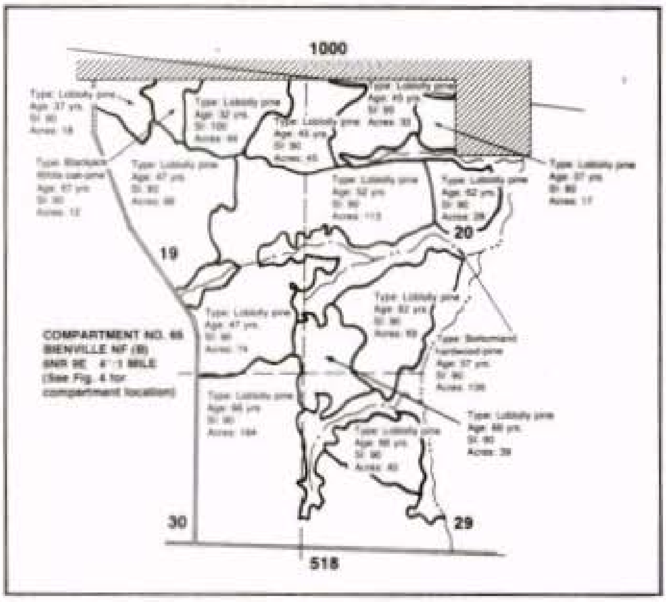


Figure 3.--Example of stand makeup within a compartment.

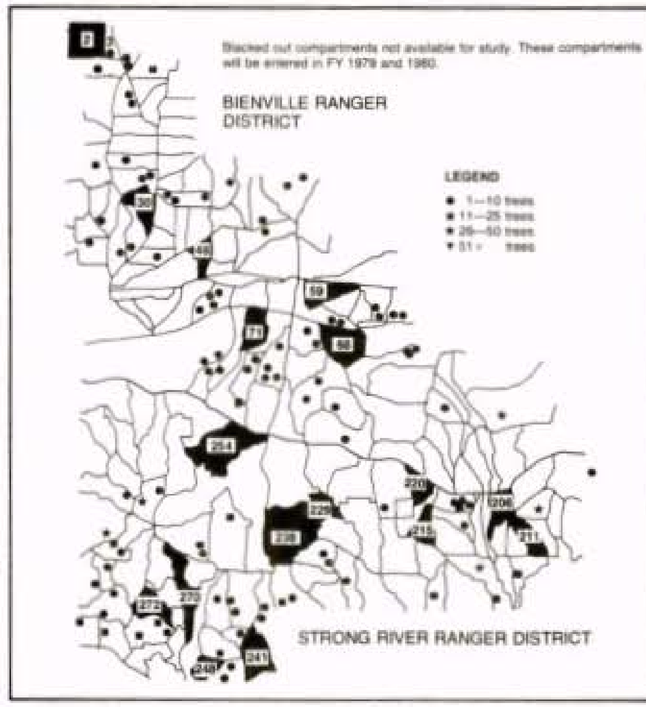


Figure 4.--Compartments in the Bienville National Forest, Mississippi, showing predicted location of SPB spots--May 1979.

Management Policies

National Forest land is managed according to the principle of multiple use (Forest Management Act 1976). This means that values such as recreation, hiking, camping, mining, and hunting are managed for, in addition to timber resources. Each compartment under the forest management is examined once every 10 years for silvicultural treatment. Even-aged management is usual for timber production. Stands are both natural and planted. Compartments vary in acreage and in number of stands. Each stand is categorized based on timber type, site index, merchantability of the timber, stand condition class, and the presence of key wildlife species.

Treatments prescribed are done in the intervening period between examinations. For example, if a thinning is prescribed in 1981, it could be done as early as 1982 or as late as 1990. Each year the District sets priorities. The total amount of timber cut is determined by the sustained yield principle. Budget determines the source of this timber (which compartment and stand). Each year the forest has a budget for thinnings and a budget for harvest cuts. Salvage timber is added to the total allowable cut; therefore, many Districts are unwilling to do work other than salvage for SPB control. This is especially true of the larger spots since the District spends time doing suppression work that would have otherwise been spent marking green timber for regular sales.

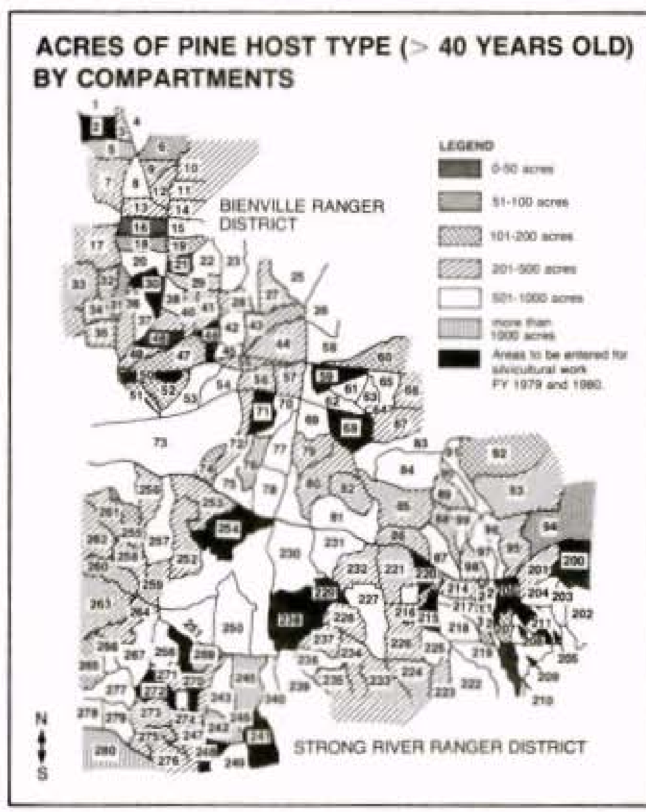


Figure 5.--Compartment configuration on Bienville (top) and Strong River Districts.

Current Recommendations

Control methods recommended for use on the National Forest are salvage, cut-and-leave, and chemical treatment. Salvage has been the most widely used suppression tool, with other methods being used on a supplemental basis. Cut-and-leave is used only as a summer treatment. Cut-and-leave is recommended for FY 1979 as an optional treatment for inaccessible spots (< 50 infested trees) or for small spots predicted to grow in size (Smith 1978). Usually, chemical treatment is recommended for small, non-merchantable spots and for areas with little spot growth. Killing beetles in spots that are not growing is a low-priority treatment.

Constraints

National Forest management has imposed some constraints to the study. Compartments that will be entered during 1979 and 1980 are not eligible to be used in study analysis (fig. 3). All spots will be salvaged by logging crews working in these compartments.

Adjoining landowners may or may not treat SPB infestations on their land. The most recent forest survey (October 1978) shows these stands to contain SPB. Salvage is the most likely type of suppression effort to be used on private land.

The study will be allowed on National Forest lands for a period of 2 years. For purposes of developing the analysis procedure, use the hypothetical situation found in figure 4 with <u>May 1979</u> as the starting point for the study.

It may be desirable to use one block of land within a District for evaluation purposes. When this is done, the rest of the District will be free to use any recommended suppression tactic.

All spots with more than 50 active trees, or 1 acre of dead timber, *will be salvaged* by the District. This is the usual constraint imposed by the District to prevent excessive volume losses.

Cut-and-Leave

Cut-and-leave is the tactic to be evaluated by symposium participants. This suppression tactic is most effective during spring and summer (Texas Forest Service 1975). To accomplish application of this tactic,

(1) Identify the active trees within the spot.

(2) Fall all active trees toward the center of the spot.

(3) Fall a horseshoe-shaped buffer of green, uninfested trees around the active head of the spot and leave them lying on the ground with crowns pointed toward the center of the spot. The buffer should be as wide as the average height of the trees in the spot (40 to 60 ft wide).

(4) Old dead trees with no bark beetles remaining should be left standing to allow development of parasites and predators that help control beetle populations.

(5) If possible, check the treated spot after 2 weeks for reinfestations (breakouts) around the periphery. Retreat all breakouts.

Theoretically, cut-and-leave affects the SPB by reducing beetle populations in the trees through affecting the physical environment (temperature and phloem moisture) and disrupting the growth of the treated spot by causing any emerging beetles to disperse. Hodges and Thatcher (1976) discovered that cut-and-leave did not affect beetle population. Texas Forest Service data show that cut-and-leave stops spot growth and reduces proliferation (Billings et al. 1975).

Case Study Objective

Study groups should use information supplied in this paper and knowledge developed earlier in the symposium to evaluate cut-and-leave on an area basis. Both Districts on the Bienville National Forest or either District can be used. Any area inside National Forest land may be set aside as a study area. Treatments will be applied according to Texas Forest Service Circular 223. Starting in May 1979, there are 2 years to complete the study. All study recommendations must agree with the *Constraints* section of this paper.

LITERATURE CITED

Billings, R. F., R. L. Hedden, and H. A. Pase III. Developing improved techniques for evaluating the operational effectiveness of southern pine beetle control tactics. 13 p. Unpublished progress report submitted to ESPBRAP for July 1-December 31, 1975.

Hodges, J. D., and R. C. Thatcher. 1976. Southern pine beetle survival in trees felled by the cut and top--cut and leave method. USDA For. Serv. Res. Note SO-219. South. For. Esp. Stn., New Orleans, La.

Moore, G. E. 1977. Factors for determining trends in southern pine beetle spots. J. Environ. Entomol. 7(3):335-341.

Smith, J. D. 1978. Biological evaluation of the southern pine beetle on the Bienville National Forest. 11 p. USDA For. Serv. Rept. 79-2-2. USDA For. Serv., Southeastern Area, State and Private Forestry, Atlanta, Ga.

Texas Forest Service. 1975. Cut-and-leave, a method to reduce losses from the southern pine beetle. 5 p. Tex. For. Serv. Circ. 223. Texas Forest Service, College Station, Tex.

Twardus, D. B. 1977. Evaluation of southern pine beetle infestations on the National Forests in Mississippi. 4 p. USDA For. Serv. Rept. 78-2-7. USDA For. Serv., Southeastern Area, State and Private Forestry, Atlanta, Ga.

Twardus, D. B., G. D. Hertel, and G. W. Ryan. 1978. Southern pine beetle infestation growth and decline--1977. 13 p. USDA For. Serv. Rept. 78-2-8. USDA For. Serv., Southeastern Area, State and Private Forestry, Atlanta, Ga.

EVALUATION OF CONTROL TACTICS FOR SOUTHERN PINE BEETLE:

HAVE USER NEEDS BEEN MET?

William M. Ciesla[1]

INTRODUCTION

Coming back to the South after an absence of nearly 9 years and becoming reacquainted with the southern pine beetle has rekindled a lot of memories.

My first experience with the SPB came in 1960, when I was assigned as a project entomologist on a cooperative suppression project in eastern North Carolina. The infestation occurred on industrial forest lands in Dare County. There was no commercial market for infested material at the time and access was limited; however, the company decided to treat in order to protect stands for future harvests. The only treatment tactic available was to fell infested trees and spray them with BHC. Some spots were so inaccessible that no treatment could be applied.

One of my duties as project entomologist was to conduct a postcontrol evaluation. I caged treated and untreated sections of logs and compared emergence in the classic manner. As one would expect, many beetles emerged from the untreated logs and very few from the treated sections. This didn't really mean too much to me; however, I knew it would mean even less to the foresters I was assisting. They were interested in knowing how much less tree mortality there was, because they were spending $2 to $3 per tree to treat the outbreak.

To try to satisfy this need, at least partially, I conducted an aerial survey the following spring. The spots that we were able to treat seemed to have been contained. There was no new spot proliferation in areas we treated, nor had the old spots expanded. We had done quite well, I thought. I then flew over the areas we had been unable to treat. These spots, too, were inactive, with no new faders. It rapidly became apparent that any benefits derived from the treatment were not going to be measurable, and thus I was introduced to the frustration of evaluating southern pine beetle control tactics, the subject of this symposium.

A RAPIDLY EXPANDING PINE FOREST

Another memory that has been rekindled during the past few days is how rapidly trees grow in the South. This was very striking to me as I drove from Alexandria to Leesville through Vernon Parish, a trip I made frequently during 1967-70, when I had many occasions to work with the Texas Forest Service in Lufkin.

In years past, artillery ranges from Fort Polk and cattle interests kept a large portion of Vernon Parish burned off, so much so that foresters called this country the "burnin' Vernon." Following implementation of a more or less effective fire prevention and suppression program, extensive young stands of pine became established. These stands were largely in the seedling and sapling stage during the late 1960's, when I worked here. Today, just 9 years later, they are of pulpwood size and the appearance of the area has changed drastically.

The phenomenon is not, by any means, restricted to Vernon Parish, Louisiana. Recent forest statistics for east Texas indicate that increases in pure growing stock and sawtimber volume have occurred during the past 10 years (Earles 1976).

If you subscribe to the hypothesis that bark beetle populations are regulated by available food supply in the form of susceptible host material, the implications are somewhat frightening. Future outbreaks of SPB may be more widespread than ever, thus making the research products of this program even more important.

The recent, devastating outbreak that collapsed last year may be an indicator of what the future holds. During this outbreak, infestations occurred in areas where the insect was rarely collected in the past. Outbreaks occurred

---

[1] Group Leader, Forest Insect & Disease Management/Methods Application Group, USDA Forest Service, Davis, Cal.

in northeast Texas, Arkansas, central Mississippi, Florida, and Kentucky, in addition to the areas where the insect has historically been a pest. Perhaps pine stands in these areas are reaching age classes and stocking levels that are just beginning to be suitable for invasion by SPB.

IMPORTANCE OF EVALUATING CONTROL TACTICS

My specific charge here was to review and critique this symposium so that future symposia sponsored by the Expanded Southern Pine Beetle Research and Applications Program (ESPBRAP) could be planned and structured more effectively.

First, I would like to say that the idea of a symposium covering a specific subject area is excellent. It provides an opportunity for workers and users to interact and evaluate progress on a single facet of the total problem, conduct an in-depth review of the state of the art, and identify opportunities for implementation of new technology.

The topic "Evaluating Control Tactics for Southern Pine Beetle" is a very appropriate one to begin with, because it forms the basis for quantifying efficacy of alternative pest management strategies that might emerge as products of this expanded research effort. Implementation of an integrated pest management system for the SPB is dependent upon the availability of a number of effective (prevention and suppression) tactics whose efficacy can be quantified relative to land management objectives and resource outputs.

The ESPBRAP Technology Transfer Plan (USDA Forest Service 1978) targets implementation of 12 major areas of new or improved technology for management of southern pine beetle (table 1). Successful completion of at least seven of these is dependent upon the ability to quantify the efficacy of control tactics. Therefore, the very success or failure of ESPBRAP depends on the effectiveness and credibility of procedures discussed during the past 2 days.

WHO ARE THE CUSTOMERS FOR THIS TECHNOLOGY?

ESPBRAP Management stated that the objectives of this symposium were "to synthesize and collate new and existing technology that may be used to evaluate treatments in SPB management." Furthermore the purpose of this symposium was *not* to develop procedural protocols for evaluating control tactics. It was also stated that this symposium was not necessarily to be user-oriented.

Table 1.--Areas of new or improved technology anticipated from the Expanded Southern Pine Beetle Research and Applications Program

Rating stand susceptibility to SPB attack.

- * Silvicultural practices for preventing or reducing southern pine beetle damage.
- * New insecticides for remedial and preventive control of southern pine beetle.
- * Improved spray equipment for application of insecticides.
- * Behavioral chemicals for suppression of southern pine beetle.

Utilization guidelines for SPB-killed timber.

Aerial navigation system for SPB surveys.

- * Improved aerial survey system to estimate timber mortality over large areas.

Sampling methods for within-tree and spot populations of SPB.

- * Socioeconomic guidelines for making decisions on pest management actions.

Predictive models for SPB population trends.

- * Integrated control strategies.

* Outputs dependent upon an effective control tactic evaluation capability.

My reaction to the latter statement was, "If this symposium is not user-oriented, what the hell am I doing here?" What are any of us doing here?

Since we have established a need for this technology, let's identify who the users might be. I think that there are three broad user groups who have a need for control evaluation capability: the research scientist, the pest management specialist, and the resource manager. Two levels of resource manager probably should be identified, the on-the-ground forester who must decide for or against treatment of a specific area of land, and the regional or national program administrator who must acquire and allocate funds and set program priorities (table 2).

Needs vary significantly depending upon the user group. The research scientist's charter is to develop and test new tactics. He requires detailed field procedures, designs, and sampling methods to assess effects of treatments on the target pest. Often his orientation is the insect, a single tree, or a spot. His data requirements include preand posttreatment population levels of the target pest in a tree or spot, spot growth, spot proliferation, insect dispersal, and tree or stand susceptibility.

Table 2.--Uses and output requirements of a southern pine beetle control tactic evaluation capability as seen by different user groups.

User Group	How user group would utilize capability	Output required
Research scientist	Evaluation of laboratory and field experiments of alternative control (prevention and suppression) tactics with emphasis on a tree or spot basis	Methodology for data, capture, analysis, and display
Pest management specialist	Evaluation of pilot projects of new and promising control tactics	Methodology for data capture, analysis, and display
	Projection of losses with and without control, with emphasis on an area basis (district, forest portion of state)	
Resource manager		
Forest or unit planning level	Decision for or against control in specific stands Reporting of accomplishments to Regional or National program managers	Data on stand susceptibility, projected losses, value of resources threatened
Regional or national planning Level	Acquisition of funds Setting of priorities Report of accomplishment, to state legislatures Congress, OMB, and the general public	Summaries of actual and projected losses, losses avoided by control in formats that can be aggregated or disaggregated by unit, forest, state, etc.

Like the research scientist, the pest management specialist requires methodology as a program output. He is often interested in the same parameters as the research scientist but must be able to make statements for a larger area--a district, a forest, portion of a state, etc. His objectives include projection of losses over time for a given outbreak in the absence of treatment, and an estimate of loss to be avoided or recovered by application of alternative treatments. He requires methodology to validate these projections if treatment is applied. In addition, he requires methodology to evaluate efficacy of new treatment tactics on a pilot basis.

The resource manager couldn't care less about the methodology other than to be comfortable in knowing that the entomologists from whom he seeks advice have a sound data capture capability. His need is for the data itself! He requires data for decision-making, for benefit/cost analysis of alternative tactics. Should he salvage, cut-and-leave, or do nothing? He requires these data in units that are meaningful to him: cords of pulpwood, board feet of sawtimber, recreation visitor days, dollar value of projected losses, all in levels of precision that he has confidence in.

He is not concerned with numbers of insects per tree or insects per acre. As was stated earlier in this symposium, "dead bugs do not make 2 × 4's." Unfortunately, resource managers as a user group have been conspicuously underrepresented at this symposium.

HAVE CUSTOMER NEEDS BEEN MET?

Methodology for evaluating the effects of certain treatment strategies on the insect and individual spots has been presented. These approaches, concepts, and systems could ultimately serve as protocol for evaluating such tactics as chemical control of infested trees, cut-and-leave, and application of behavioral chemicals (e.g., pheromones) in a confusion strategy. The approaches are oriented toward measurement of the target insect, dispersal, spot growth, and proliferation.

Methodology for evaluating effectiveness of preventative strategies is still lacking. We did not review appropriate sampling designs or procedures for evaluating efficacy of preventative sprays in high-value areas such as campgrounds, scenic vistas, or urban areas. Nor did we discuss approaches that might be taken to evaluate effect of cultural treatments such as thinning to reduce hazard of SPB infestations. Both tactics are cited as part of the 12 areas of new or improved technology to be made available by ESPBRAP. Therefore, we can conclude that the needs of even the research scientist have been met only partly.

Some methods for quantifying treatment effects on an area-wide basis were described. A sampling procedure for estimating numbers of insects before and after treatment was presented. Sampling concepts, stratification to reduce sampling error, and the relative merits of aerial sketch mapping versus aerial photography were reviewed. The merit of describing population in terms of pattern and abundance was discussed and an example of accessing an existing data base to evaluate relative effectiveness of alternative treatment strategies in an operational mode was presented.

We still do not have available an efficient, reliable method for measuring and projecting losses in units that resource managers understand: cords, board feet, or cubic feet. Until such time as we can express losses in these terms it will be impossible for pest management specialists to (1) effectively convince small landowners that they should institute treatment, or (2) display to a forest resource manager the consequences or merits of alternative tactics in a quantitative manner. Consequently, acquisition of funds for large-scale projects will continue to be more of a political process rather than one based on sound ecological and economic decision criteria.

IDENTIFICATION OF USER NEEDS-- A SHARED RESPONSIBILITY

Failure to meet anticipated program accomplishments is not always the fault of the research scientist. Frequently potential users of new technology fail to state their needs in quantifiable terms. Thus it becomes difficult, if not impossible, to assess whether or not an R&D program is on target.

Recently I had the opportunity to review several U.S. Air Force R&D programs. In each case, the R&D was in response to a clearly and concisely stated objective. The objective was quantitatively stated in terms of time requirements, output expectations, efficiency, or resolution, to provide for a meaningful measure of accomplishment. Similarly, several years ago NASA assembled an R&D proposal in the field of agriculture aviation (NASA 1976). Their planning document identified clear, concise objectives and targets by which program accomplishments could be measured.

Most of us in the Forest Service are familiar with the concept of management by objectives. In this planning process, objectives and targets are identified in terms of measurable outputs and time frames. Users in today's audience must learn to formulate their research needs in ways that will enable scientists to give quantifiable results. For example, users need to specify what units of measure an output should be recorded in, how many tactics of what sort are desired, and what time frame is appropriate for a postcontrol evaluation.

Joint development of objective statements in clear, concise, measurable terms is of great value to a research administrator, who could then measure the progress of an R&D program and be more accountable to his user groups.

CONCLUSION

In conclusion, my evaluation of this symposium is somewhat mixed. I am disappointed that it was not more user-oriented. On the other hand, a great deal of promising methodology was presented. I am particularly glad to see more interaction between universities, Forest Service Research, and forest pest management specialists than when I was in the South. The involvement of universities in improvement of survey methods, population estimation, and evaluation of control tactics is particularly encouraging and should go a long way toward achieving ESPBRAP objectives.

I hope that in the final years of ESPBRAP an effort will be made to quantify efficacy of control tactics in units that resource managers can relate to, and that users will give more thought to the definition of specific data requirements.

I hope that my comments will be of help and thank you for inviting me to participate.

LITERATURE CITED

Earles, J. M. 1976. Forest Statistics for east Texas piney woods counties. USDA For. Serv., South. For. Exp. Sta. Res. Bull. SO-60. New Orleans, La.

NASA. 1976. Agriculture aviation study and program plan. Volume I. Project summary 47 p. NASA, Office of Aeronautics and Space Technology. Washington, D. C.

USDA Forest Service. 1978. Southern pine beetle program--Communicating research results to practitioners--A technology transfer plan. 12 p. USDA For. Serv., South. Pine Beetle Res. and Appl. Prog. Pineville, La.

A SECOND REVIEWER'S IMPRESSIONS

Ron W. Stark[1]

As I understand it my charge is not to summarize but to comment on this symposium--its format and the degree to which it met its planned objectives. I could discharge my responsibilities in 30 seconds by stating flatly that its format was excellent and participation outstanding, and to my less-than-expert eye expectations were fully met. But that would not be appropriate for an ex-Dean or an academician.

You have scheduled an hour so I feel obligated to use at least a significant portion of that time. I will give you some personal impressions. There are several things which impressed me considerably.

First, the fact that you have in hand all but one of the manuscripts of the presentations, making possible the rapid publication of the Proceedings. Having been involved in two fairly large efforts of a similar nature (the Mountain Pine Beetle Symposium held last spring and the Douglas-fir Tussock Moth Compendium now awaiting the awarding of the printers' contract), I am not unfamiliar with the problems of publishing symposium proceedings. I can only assume that the ESPBRAP either has a very big stick or the participants are dedicated, conscientious contributors. I lean to the latter conclusion. I congratulate you all on both the content and timely presentation of these papers for publication.

My next impression concerns the amazing degree of commonality emerging from this program and the others I am familiar with (The Douglas-fir tussock moth program, the mountain pine beetle program, and the gypsy moth program). I suppose I should not be amazed because if one examines their original original structure and the cross-fertilization processes, one would expect a certain conformity or similarity. But I know a large number of the participants in all programs, and as a student of human nature I assumed that many would seek to assert their individuality and radical departures would occur. That this did not happen (either here or in the other programs) indicates to me that the fundamental principles and methodology of integrated pest management are sound. The differences that appear are those of intensity and quality, and I must conclude after these past 4 days that this program scores very high with contributions. I believe that when the smoke settles, and all R&D monies are spent, someone will be able to develop a set of principles and protocol that will facilitate future IPM programs for all pests. This program will be a major contribution.

Another impression: since my early association with aerial photography on the western pine beetle I have become a skeptic. The reports given here were encouraging and I shall be pleased to report to Bob Heller that aerial photography has once again assumed respectability.

Although there were periodic lapses to our former philosophy that the bug is the center of the scientific universe, it is quite clear that we are all now recognizing that we are a part of forest management and that our responsibility is to provide (1) information to enable managers to make better decisions, and (2) technology to implement and evaluate the consequences of those decisions. On this tack, a decade ago few State and Private people would have the courage to make the heretical statements I have heard here. Prior to that time bugs were put on this earth to be controlled; controls were always justified and almost always effective, even if not measured. There appears now, particularly in this group, a commonality of purpose and understanding that is essential if research and management are to be successful in improving insect and disease management practices.

Although I am greatly impressed by what I have heard and look forward to studying the papers in more depth, I have a few impressions which are not criticisms but which, if correct, indicate need for continued emphasis.

[1] Coordinator of Research, College of Forestry, Wildlife, and Range Sciences, University of Idaho, Moscow, Id.

Frequently we heard hypotheses advanced; only a few times was this cast as a null hypothesis. In the area of pest management evaluation, we have a tendency to forget the scientific method. There were excellent papers reminding us of what scientific methodology is, but there were also statements which suggested that we do not always practice it. We have to be certain in this difficult area of biostatistics that we are not using "cosmetic statistics" to prove our position. Many recent advances in statistical evaluation have been made possible by computer power. That some of you are aware of--even contributing to--this science is obvious. It is less obvious that all subscribe to the need for com puterized statistics and solicit help in implementing them. Perhaps it is ignorance on my part, but I also felt that utilization of historical records was less than it could be. While these are often in a form that will not stand up to rigorous testing, we can learn much from them.

Another area I was a trifle disappointed in might be called an imbalance. To my view, there was not sufficient coverage of what Campbell calls "crisis prevention strategies." These are largely cultural and long-term and their evaluation probably will be difficult and tricky. But prevention must be addressed because we will hopefully be using more such strategies in the era of pest management.

Lastly--although it was treated in some depth in one paper and referred to in one or two others--the evaluation processes discussed by and large did not address the complexities introduced by the National Forest Management Act. As we know the Act mandates that National Forests will be truly managed for *all* resources. Further, although we may designate a prime use, we must measure the effect of that use on the other uses. Some kind of cost-benefit ratio must be determined for each resource. There are increased requirements in the evaluation of effects on soil and water and other somewhat prescriptive requirements. The Act and its regulations will have significant implications for pest management. For example we might be managing for other "pests" than herbivores. In a planned high-intensity-use recreation area, mosquitoes, deer flies, hornets, etc., may require treatment. The same size populations of SPB may be a problem in one management unit but not in another. Or because of different management objectives and outputs the net benefits in eliminating SPB may make treatment impractical.

The final exercise, a case history, was an imaginative and excellent way to end such a symposium. I congratulate you all on the high quality of the research being done as demonstrated by your papers, on your obvious commitment to the objectives of the program, and on an outstanding symposium that will make a substantial contribution to the literature.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1979 O - 302-623