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The Southern Pine Beetle

Chapter 6: Sampling and Predicting Population Trends

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Introduction

One of the primary goals of the Expanded Southern Pine Beetle Research and Applications Program has been to develop means for predicting trends in beetle activity. This requires precise and accurate sampling procedures, which are based on an understanding of SPB spatial distributions, as covered in [Chapter 5](#). Accurate prediction of population trends is prerequisite to the development of management strategies to prevent or suppress beetle damage. With adequate forecasts, management can deploy its resources to prevent or mitigate expected outbreaks. Or during severe epidemics, management can direct its suppression efforts against those infestations likely to kill the most trees.

Adequate sampling procedures have other functions as well. They are necessary for evaluating the success of SPB control tactics. One of the basic problems in evaluating control strategies has been the lack of sampling techniques. Without proper sampling, results will be inconclusive because management is unable to measure treatment populations and tree mortality before and after treatment. Standard sampling techniques are also essential in estimating biological and socioeconomic impacts of infestations over large areas of mixed ownership. Survey information is required for making appropriate management decisions and budgeting resources to implement these decisions.

Of course, sampling techniques can also be used in research. Studies on the population dynamics or community ecology of the SPB would probably require more intensive procedures but basically the same techniques. The four uses, then, of SPB sampling plans are prediction of population trends, control treatment evaluations, damage surveys, and population dynamics studies.

The intensity of a sampling effort depends upon how accurate and precise the estimates must be to meet the objectives of management. For example, within-tree sampling to evaluate treatment effects need not be as intensive as sampling to evaluate the impact of a particular parasite on the host population. Important variables to consider in determining the accuracy and precision of a sampling plan are sample unit size, number of samples to be taken, spatial and temporal sampling interval, and distribution of the organism being sampled.

Because the southern pine beetle is a wide-ranging pest that affects several host species (see [Chapter 2](#)), there is considerable value in developing standardized sampling techniques and adhering to them when sampling objectives and target organisms are the same. Similarity in sampling techniques greatly facilitates comparing regional, temporal, and host species differences. Furthermore, analytical techniques developed at one institution can be readily employed at another. Of course, standardized techniques can be employed only after it has been clearly demonstrated that there is no significant change in the beetle's distribution through space and time or with host species, and after the procedures have been shown to produce accurate, precise estimates for the stated sampling objectives.

Certain practical considerations must also be taken into account when developing a sampling plan. Expense is of paramount importance. Financial resources will determine the degree of accuracy of the sampling plan. Compromises on sampling intensity are often required. Sampling procedures should be kept as simple as possible so that field technicians can readily understand and use the system with a minimum of special training. Unnecessarily elaborate and complicated procedures inevitably result in errors. Also, sampling to predict population trends must provide predictions far enough into the future that management can use the data in making action decisions. Finally, the area of applicability for sampling and prediction procedures must be considered. What works in Louisiana may not work in Georgia or Virginia. Thus, extensive testing must be done in several regions of the SPB range to validate the procedures.

This chapter describes the survey, sampling, and prediction procedures developed by several investigators in the Expanded Southern Pine Beetle Research and Applications Program. Relevant knowledge from other studies will also be considered. Specifically, this chapter covers (1) survey methodologies developed for monitoring beetle activities over large areas; (2) quantitative sampling schemes for estimating within-tree and within-spot (= infestation) populations; (3) a practical means of estimating areawide populations; (4) although not yet quantitative, procedures for tagging dispersing beetles to study the insect outside the tree; and (5) various models that have been developed for predicting spot growth and areawide populations. In many cases, several procedures or models have been developed. I will attempt to describe the merits and limitations of each.

Surveys for Monitoring Beetle Activity

Computer-aided systems for acquiring, comparing, locating, and filing tree mortality information obtained from sequential aerial photographs are available as a survey and research tool. Means for more accurately positioning aircraft during aerial photo or sketch-mapping missions have been evaluated using the Loran-C radio navigation system. When cost effective, this system greatly improves the accuracy and reliability of aerial photo and sketch-map surveys. Multistage sampling systems also provide a systematic means for obtaining aerial survey and ground-check information.

Aerial Photography: Computer-Aided Systems

Aerial photography is an effective tool for detecting dead trees with discolored foliage. Although costly and difficult to conduct, photographic surveys are far more precise than sketch-map procedures in locating SPB infestations. Sequential aerial photographs also measure the dynamics of tree mortality. They reveal which infestations are expanding and where new ones are starting, once crown discoloration has begun. Photos may also prove useful in predicting beetle population and tree mortality trends and in evaluating treatment effects.

Although sequential aerial photographs have been used in the past (DeMars et al. 1973, 1980; Heller 1968, 1974; Heller and Wear 1969) for bark beetle surveys and research, the task of evaluating two or more sets of photos has been strictly manual and quite tedious. Without sophisticated navigational guidance systems like Loran-C, no two sets of photos would cover exactly the

same territory. Furthermore, there would be differences in altitude, camera angle, and visibility. These and other variables would make the job of locating and comparing infestation trends in large areas very difficult.

PISYS

Orthophotography and aerotriangulation procedures can solve these problems. However, these methods are expensive, time consuming, and more accurate than necessary for SPB surveys. The linear regression method employed by PISYS — photographic interpretation system — (DeMars, Slaughter, and Green 1977 unpublished; DeMars and Aldrich 1978 unpublished) is less expensive and time consuming but still provides adequate accuracy. The materials needed to operate the system include a digitizer, a light table, a scanning stereoscope, a data logging calculator, a small plotter, small-scale aerial photographs, and topographic maps.

PISYS acquires, compares, locates, and files sets of point locations that represent infested spots detected from aerial photographs (figs. 6-1 and 6-2). The system computes the reference map location and, after establishing control points, computes the average accuracy of the spot location points identified on the photograph. In one study (DeMars et al. 1977 unpublished), the position of the infested spots was mapped with an average accuracy of ± 89 ft. Graphics (fig. 6-3) that permit the production of map overlays can be made. Maps of photo-detected infestations can be prepared at scales other than the photo scale. The system is most accurate for infestations on flat terrain.



Figure 6-1 — In the PISYS system, an operator views aerial photographs using a scanning stereoscope. Points on the photograph are digitized with a Numonics graphics calculator interfaced to a desk-top minicomputer.

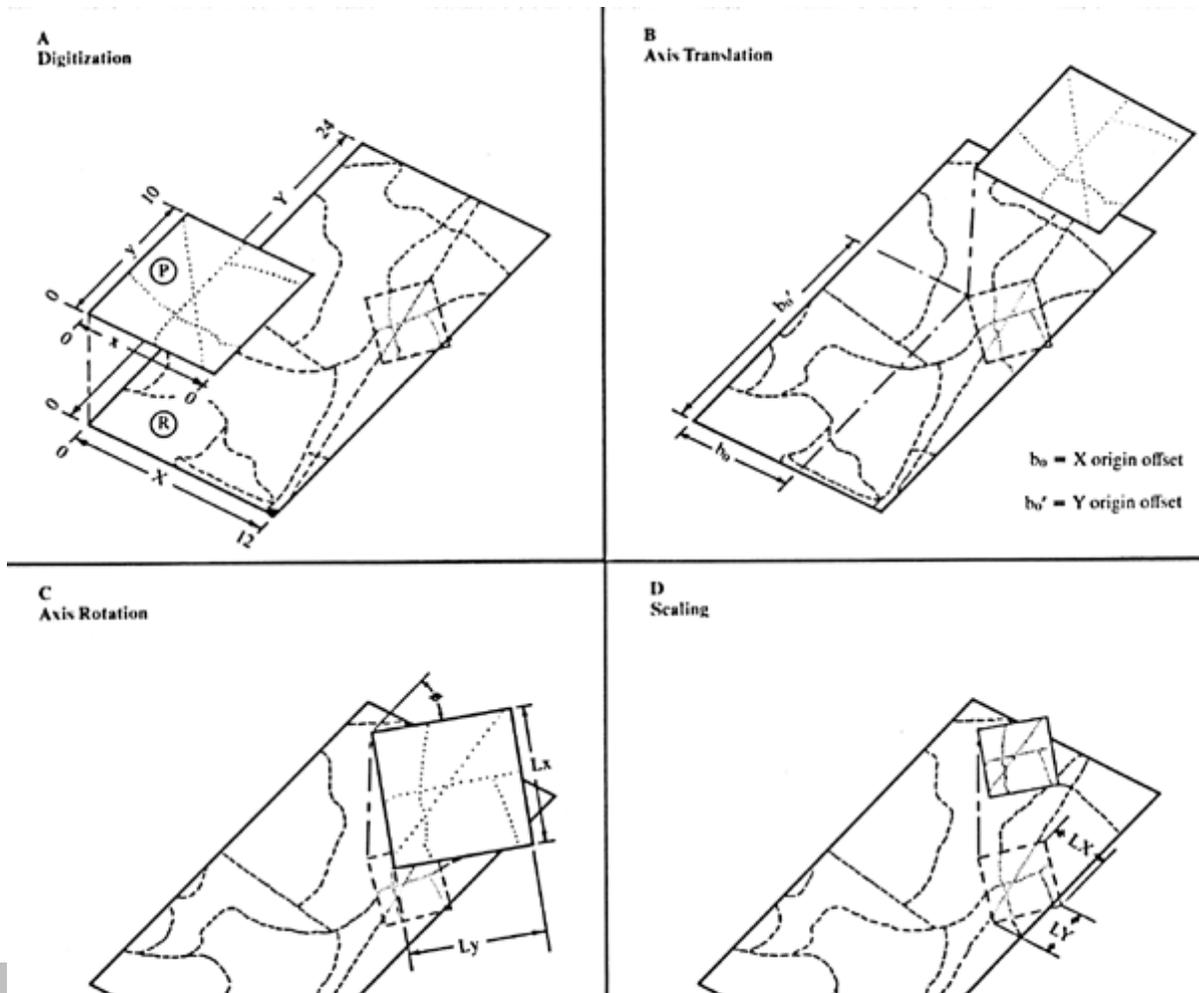




Figure 6-2 – Transforming the digitized locations of points on a large-scale photograph to the corresponding position on a smaller-scale map.

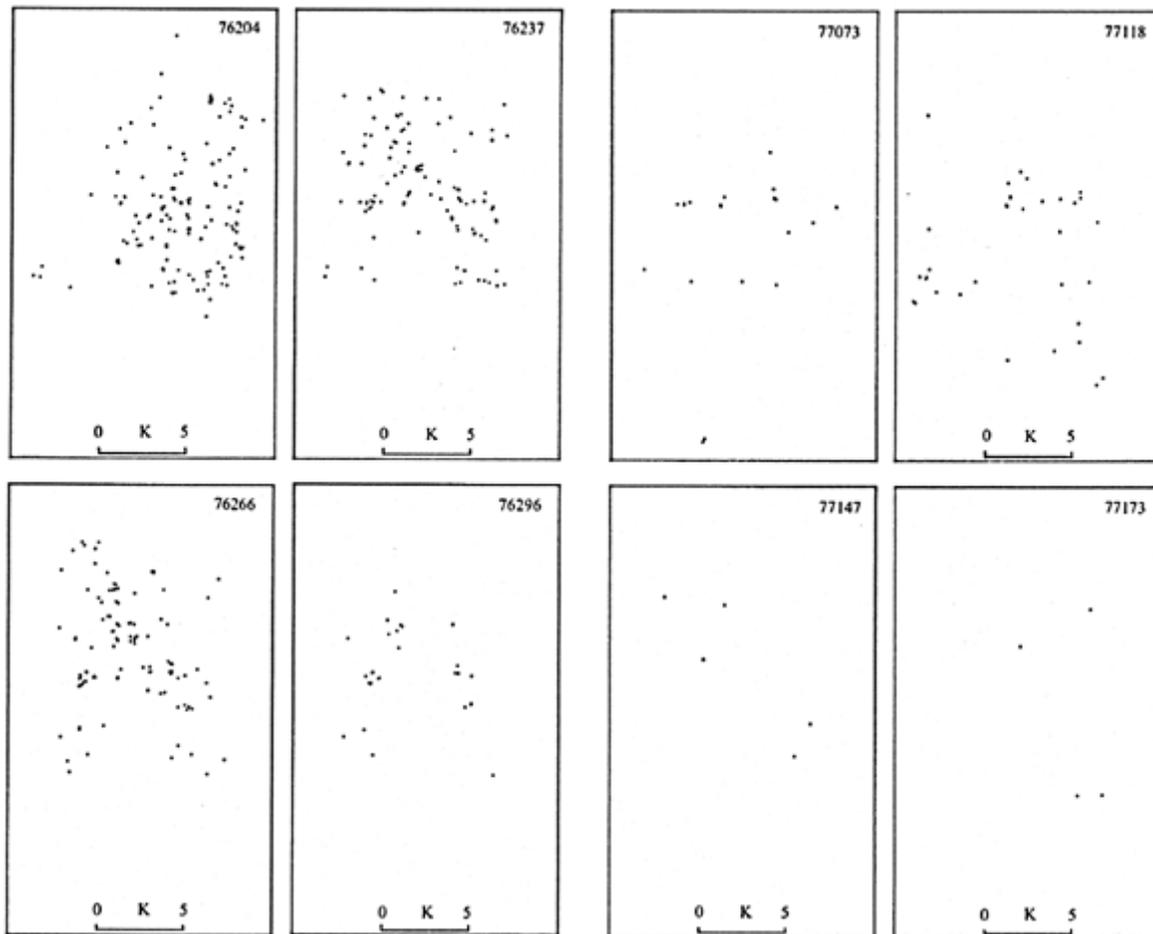


Figure 6-3 – PISYS graphic displays. Each point represents an SPB-infested spot. The identification numbers refer to the year and the Julian date.

With sequential photographs, PISYS can measure tree mortality that has occurred in previously identified plots or larger areas since the last photos were taken. The system can also be used (both for sequential photography and for single-occasion photography) to prepare maps at different scales and to array the findings.

PISYS has utility both as a survey and research tool. It will accurately define the extent of an areawide outbreak and accurately locate infested plots for ground checking. When sequential photos are used, tree mortality trends can be measured as well. PISYS can also provide a data base useful in formulating and testing predictive models and conducting computer simulation studies of pest management strategies. PISYS's utility in evaluating treatment effects was discussed by Hain et al (1979) and DeMars, Hain, and Slaughter (1979). And data collected from an epidemic area in North Carolina were used to evaluate the effect of wind and barometric pressure on the proliferation of infested plots over a wide area (DeMars and Hain 1980).

One of the system's limitations is that it works less accurately on terrain that is not flat. But even in mountainous terrain, the error can be minimized if the sequential photo centers are at nearly the same point. Direct photo-to-photo fitting would then eliminate the need for a reference map. Such photos could be obtained only with an accurate navigational system such as Loran-C.

Clerke and Mahan (1978) have evaluated the utility of the Digital Terrain Information System (DTIS), developed by the U.S. Forest Service for use in mountainous terrain with large-scale aerial photographs. DTIS relies on a digital terrain model as a basis for computation and analysis. Terrain data sources are available. The least expensive source, the Defense Mapping Agency, covers the entire country; but the accuracy of the data is considered sufficient for general planning purposes only. More accurate data sources are more expensive and are generally not available for the entire country. DTIS is considerably more expensive and time-consuming than PISYS, but in mountainous areas DTIS's improved accuracy may be needed.

DTIS performs several functions. It (1) extracts the position of features from aerial photographs, (2) displays the boundaries of the extracted feature on maps or aerial photographs, (3) displays the results of the terrain model analysis, and (4) stores the digitized information and associated data in computer-accessible files. More functions can also be implemented.

DTIS was tested in mountainous terrain on the Chattahoochee National Forest in northeastern Georgia. Preliminary results indicate that the Defense Mapping Agency terrain data may be effectively used for SPB surveys, with acceptable precision.

Thus, two systems (DTIS and PISYS) are now readily available for use in storing and analyzing aerial photographic data. The choice of systems depends upon the objectives of the user, financial resources, availability of terrain data, and the type of terrain to be covered.

Loran-C Navigation System

Aerial navigation equipment can significantly improve the accuracy and reliability of aerial photographic and sketch-map surveys. It will improve the ability of ground crews to locate infested plots, and it will increase the accuracy of aerial photography in photographing the same plots sequentially. The Loran-C² radio navigation system can also be used for navigation and position location by ground personnel.

Most surveys of southern pine beetle damage by pest management personnel have been made by aerial sketch mapping. The accuracy of this procedure is highly variable and depends upon many factors including the experience of the crew and their familiarity with the area, the topography and availability of suitable landmarks, visibility, and the accuracy of maps and photos used in the sketch mapping. It is not surprising that unacceptable errors in flightline navigation and SPB spot detection are frequently encountered (Dull 1980).

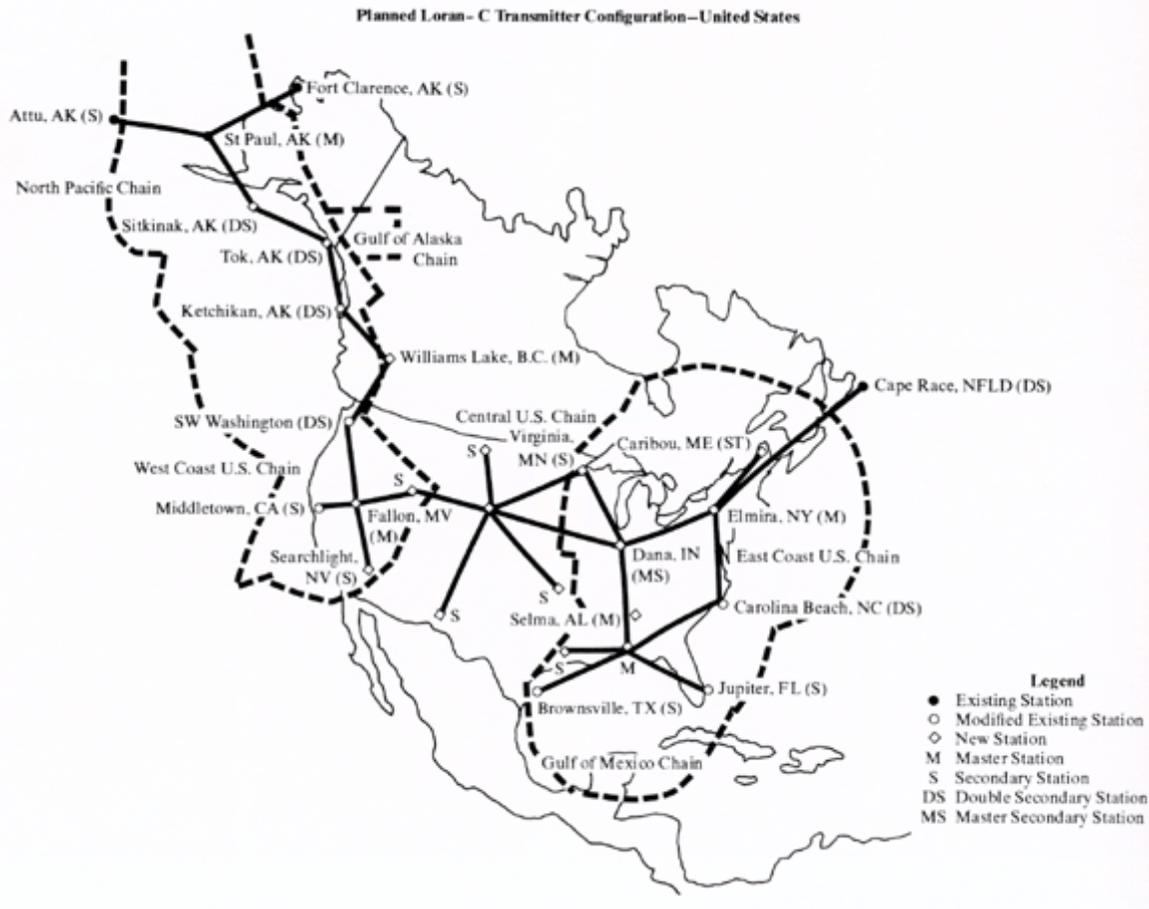


Figure 6-4 – Proposed Loran-C coverage.

Loran-C is an operational, highly accurate radio navigation system (Clerke and Dull 1978 unpublished). The station configuration for the coverage of the Coastal Confluence Zone is shown in figure 6-4. Two-thirds of the United States is now covered, with complete coverage scheduled for 1985. Transmitters for Loran-C are arranged in chains consisting of a master station and a series of secondary stations. The aircraft's position is determined by the differences in arrival time between signals from the master and two secondary stations. The apparatus—Loran-C receiver, navigation computer, output interfaces, and display—weighs only 9 lb (fig. 6-5). Portable receivers are also available to transmit the positions of ground vehicles and aircraft over standard radio channels.

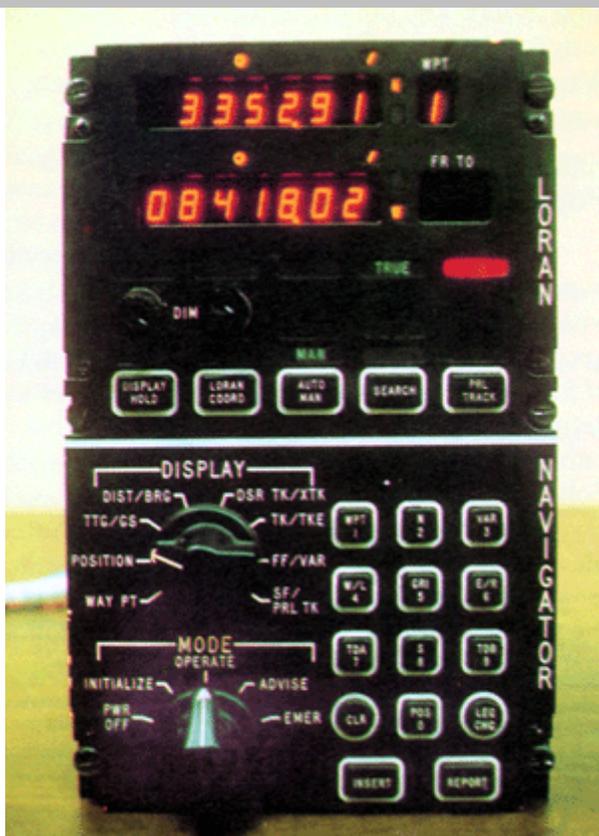


Figure 6-5 – Loran navigation system, by Teledyne Systems, Inc. Less expensive Loran-C systems are available.

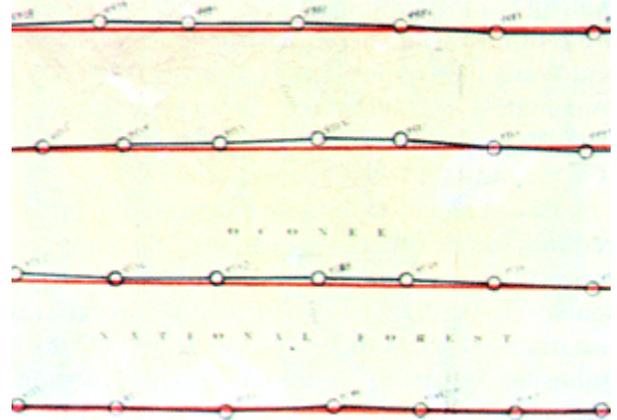


Figure 6-6 – Comparison of actual flight track to desired and Loran-C indicated track.

Dull and Clerke (1979 unpublished) found that the accuracy and reliability of Loran-C for southern pine beetle surveys is more than adequate. Figure 6-6 illustrates the actual track of the aircraft compared to the desired track for a sample survey mission.

When Loran-C aerial photography is used, 93.7 percent of the beetle spots are correctly located. This compares with a desired probability of 95 percent (Dull and Clerke 1979 unpublished). However, the suitability and accuracy of Loran-C should be appreciated even more when a comparison is made to surveys using conventional equipment.

Multistage Sampling Procedures

Two-Stage Design for Tree Mortality Estimation

Researchers have developed two sampling procedures that can utilize the aerial techniques discussed above to estimate southern pine beetle mortality. Schreuder, Clerke, and Barry (1977 unpublished) reviewed some of the multistage sampling procedures that have been used in forestry. Emphasis has been placed on the development of designs that provide efficient and unbiased estimators through the use of sampling with the probability proportional to size (p.p.s. sampling). A ratio estimator is used to estimate the total population. However, stratified sampling may be superior to p.p.s. sampling in some cases. In stratified and p.p.s. sampling the basic idea is that there should be a higher probability of selecting larger units than smaller ones. But in p.p.s. sampling the selection of larger units is left to chance. Stratified sampling, on the other hand, guarantees that a fixed, desired percentage of the sample is allocated to each stratum of the population being surveyed.

In one stratified sample design, the on-the-ground variables of interest are correlated with variables obtained through aerial surveillance (Schreuder et al. 1980). The sampling design consists of two-stage sampling with double sampling estimation at the second stage. The design was tested on three ranger districts of the Chattahoochee National Forest in Georgia. The first sampling stage divided the population (beetle infestations) into subpopulations (timber types) which were more alike in regard to the variables of interest. In the Georgia test, the three ranger districts were divided into six strata based on timber types and on the level of SPB activity (number and size of infestations) observed during a sketch-map survey.

Information from the second stage was used in two ways. First, the strata were divided into substrata that were even more homogeneous. Based upon a second, more intensive aerial survey, the frequency and distribution of spot sizes were estimated.

The second-stage information was also used in a linear regression analysis of the variables of interest. The aerial information at this stage was much easier and cheaper to obtain and correlated well with hard-to-obtain ground data. On-the-ground measurements were done on a random sample of spots in each substratum. Schreuder's team planned their ground checking of

the Chattahoochee to ensure that no less than 5 spots and no more than 90 were sampled in each substratum. Ground checking gave greater emphasis to larger spots. The double sampling estimation refers to the fact that a large sample of second-stage aerial information was used in regression estimation with a smaller sample of ground information (Schreuder et al. 1977 unpublished).

Sampling Design for Periodic Mortality Estimation

A second technique for estimating beetle mortality was developed by Ghent and Ward (1977 unpublished). Their sampling procedures are designed for practical use by State or Federal agencies concerned with extensive areas. The technique provides an annual estimate of timber loss, requires little or no ground checking, and has a satisfactory level of precision (± 20 percent). The system uses sequential aerial photography and local aerial volume tables to meet these requirements.

A modified random sampling plan was employed in a 3-million-acre area in seven central Mississippi counties. Forty-five 500-acre plots of pine type were used. Photo plots were stratified by the proportion of pine in each county to the overall study area. However, stratification by outbreak would have been desirable (Ghent and Ward 1979a unpublished).

Sequential photographs were taken in the spring, summer, and early winter of 1978 and 1979. Loran-C navigational equipment aided in the task of rephotographing the same plots.

The data were analyzed according to a simple procedure developed for plots of different sizes. The ratio of volume loss to acreage is computed and multiplied by the total acreage in the study area (3 million acres) to obtain an estimate of the total volume loss. Volume estimates are computed from aerial volume tables (Ghent and Ward 1980 unpublished). During 1978 approximately 645,000 fbm of timber were lost to the SPB in the central Mississippi study area (Ghent and Ward 1979b unpublished).

Choosing either of these two sampling procedures, or any other, depends upon the requirements of the user and the availability of resources. Regarding the two estimating procedures just discussed, Schreuder's procedures (1977 unpublished and 1979) do provide greater precision and accuracy but at a considerably higher cost. The authors gave a very detailed accounting of their operational expenses. Per-acre costs, using their techniques, ran to almost 4 cents. Estimated costs for the procedures described by Ghent and Ward (1977 unpublished) were half a cent per acre.

Sampling to Estimate Beetle Populations and Tree Mortality

To evaluate the effects of treatment on beetle populations at the spot level or to study the within-tree community ecology, investigators need precise population data. Several attributes of SPB populations can be either beneficial or detrimental to the development of quantitative estimating procedures (Pulley, Coulson, and Foltz 1979). The complicating attributes are (1) asynchronous beetle development with multiple overlapping generations, (2) variations in the length of the life cycle depending upon season of the year and climate, (3) a pattern of colonization that results in clumping of dead trees, (4) variations in life stage distributions within trees, and (5) the number of life stages that may be of sampling interest (attacking adults, reemerging adults, eggs, larvae, pupae, callow adults, and emerging adults). There are at least three *simplifying* attributes. A major portion of the insect's life cycle is spent within the tree. The length of the infested bole and the number of trees infested represent a discrete sampling universe. Finally, precise measurements of the beetle population and its habitat can be obtained.

Sampling Within-Tree Populations

Several authors have discussed bark beetle sampling (Berryman 1968; Carlson and Cole 1965; Coulson et al. 1975, 1976a and e; Foltz et al. 1976a; DeMars 1970; Dudley 1971; Pulley et al. 1977b; and Safranyik and Graham 1971). For sampling SPB populations specifically, Stephen and Taha (1976) and Nebeker et al. (1978a) addressed the problems of optimum sample unit size, number, and placement.

Stephen and Taha (1976) also considered the sampling requirements for the natural enemy complex. Infested bark from southern Arkansas was X-rayed and the resulting radiographs (fig. 6-7) were used as negatives to produce prints. The prints were reassembled to form a complete mosaic of infested bark. SPB attacks, egg gallery length, total brood, parasites, and predators were measured and recorded within each grid cell of the mosaic. This permitted the selection of computer-generated random samples, which could vary in size. Figure 6-8 shows the relationships between sample unit size and the number of samples necessary to estimate the density of a variable.



Figure 6-7 – Radiograph of bark samples infested with southern pine beetle.

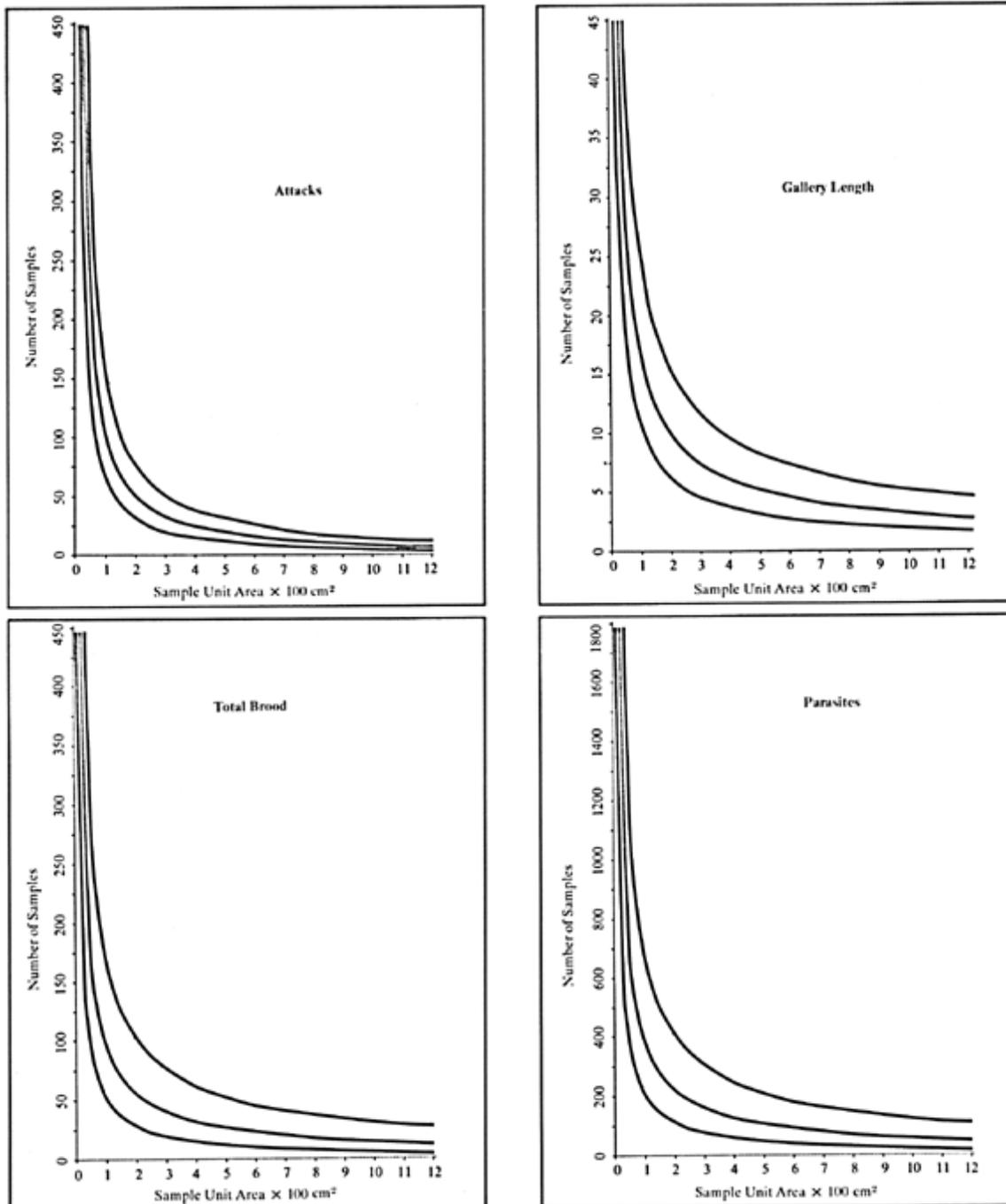


Figure 6-8 – Curvilinear relationship between number of samples needed to estimate total mature brood and the corresponding sample unit area. The 90 percent confidence limits are also included. (Taken from Stephen and Taha 1976).

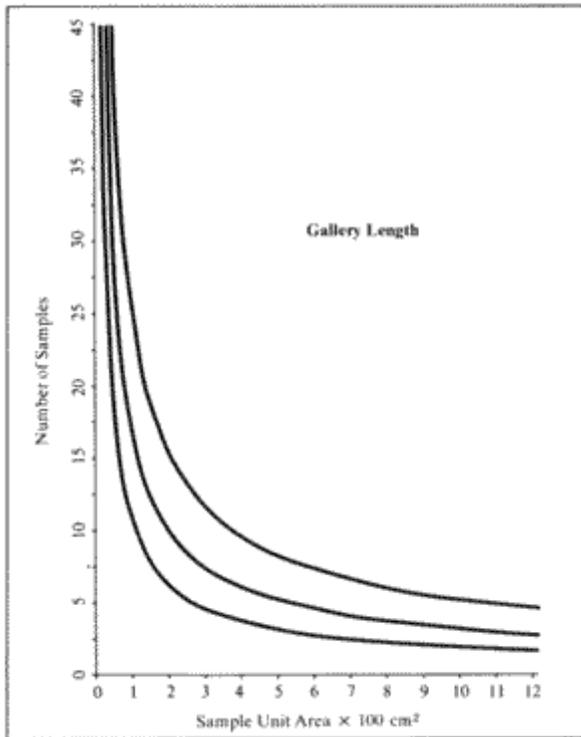


Figure 6-8 – Curvilinear relationship between number of samples needed to estimate total mature brood and the corresponding sample unit area. The 90 percent confidence limits are also included. (Taken from Stephen and Taha 1976)

There were no significant differences among the means computed at the top, middle, and basal sections of the infested trees. This contradicts the distributions shown in [figure 5-1](#) but probably can be attributed to the fact that Stephen and Taha did not sample at the extreme upper or lower portions of the infested bole. Sampling at three levels is recommended, however, for density measurements of individual predator and parasite species.

Nebeker et al. (1978a) did a similar but somewhat more detailed study. His team considered sample unit size, strata size and number, and sample allocation. They also took their analysis one step further by determining the relative efficiency of different sampling schemes and different sample sizes.

The Nebeker team found that the relative efficiency decreases as sample size increases. Thus, the highest relative efficiency would be obtained with a sample unit of 16 cm² – the smallest sample size. However, the loss in efficiency becomes less dramatic as unit size increases and may be inconsequential at unit sizes greater than 64 cm². Thus, if larger units are selected as a matter of

convenience, their selection can be based upon other criteria, such as cost (larger units being easier to collect, handle, and analyze). Relative efficiency increases with the number of strata and with unequal stratification. Unequal stratification allocates the strata toward the center of the infested bole, where more information is obtainable.

Both Stephen and Taha (1976) and Nebeker et al. (1978a) stressed the limited nature of their respective studies – a few trees were sampled very intensively – and cautioned against generalization. However, the procedures they have developed are an important step in the development of sampling methodologies.

A different approach was selected by another team (Coulson et al. 1975a). Rather than intensively sampling a few trees, they devised a convenient sampling scheme, based upon previous work with other bark beetles (DeMars 1970, Safranyik 1968). The scheme allowed for sampling a large number of trees and thus was more representative of the highly variable conditions found in nature.

Bark disks (100 cm²) were removed in four directions at

each sample level. Beginning at 2 m and continuing to the top of the infested bole, crews established sample levels at every 1.5-m interval. The bark disks were removed from the infested trees at three time intervals corresponding with different life stages (egg-attacking adults, late larvae-pupae, emerging adults). The bark disks were collected with a circular hole-cutting saw by climbing rather than felling the tree (fig. 6-9). The disks were X-rayed and insect inclusions and gallery lengths were counted on the radiographs. Host tree parameters also measured included tree height,



Figure 6-9 – Sampling on SPB-infested tree.

height of the infestation, diameter, and bark thickness at each sample level. A total of 134 trees were sampled during the study (Pulley et al. 1979).

Attacking Adults

Other investigators have used modified versions of Coulson's procedures to sample different southern pine beetle life stages. Linit and Stephen (1978) investigated several techniques that can be used for estimating attacking adult populations: (1) X-ray determination of attacking adults, (2) dissection for attacking adults, and (3) attack site determination.

Linit and Stephen concluded that each of the three methods can provide reliable estimates of numbers of attacking adult southern pine beetles. But the attack-site method eliminates the need for precise timing of the sampling and the need for taking sapwood with the disk sample. The sapwood can decrease the quality of the radiograph image or require tedious laboratory procedures for removal.

Attack sites were recognized by the following criteria. First, pitch tubes were present at the suspected attack site. Second, the attack hole was slanted in relation to the bark surface and filled with an oleoresin/frass mixture. Finally,

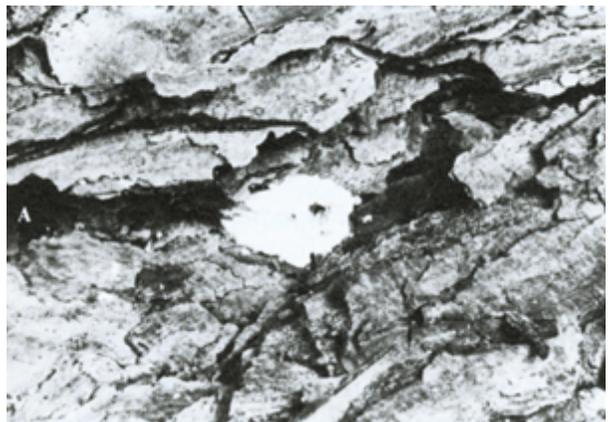


Figure 6-10A – Criteria used for the identification of SPB attack sites: (A) the outer bark surface showing a pitch tube that marks the point of attack. (Taken

the position of the suspected attack site to the egg gallery was logical, e.g., at the "beginning" of a gallery (fig. 6-10).

from Linit and Stephen 1978).



Figure 6-10B – Criteria used for the identification of SPB attack sites: (B) a cross section of bark showing the pitch tube on the outer bark surface. (Taken from Linit and Stephen 1978).



Figure 6-10C – Criteria used for the identification of SPB attack sites: (C) the inner bark surface showing the entry point of an attack and the construction of egg galleries. (Taken from Linit and Stephen 1978).

But the attack-site method is not without its limitations. Sample timing cannot be totally ignored. If samples are taken too late, the substantial foraging of cerambycids and buprestids will partially or totally obliterate SPB egg galleries.

Eggs

Various methods for sampling southern pine beetle eggs have been reported. In a Texas study, bark disk samples of 100 cm² were removed just after mass attack was complete (Foltz et al. 1976a). Eggs and egg niches were counted following bark dissection in the laboratory. It was assumed that empty egg niches contained an egg that was destroyed during the dissection. A statistical analysis showed an average of 1.59 eggs per centimeter of gallery.

Lashomb and Nebeker (1979), working in Mississippi, felt that counting egg niches might result in an overestimate of egg deposition. So they took precautions to include the remains of eggs that were destroyed during dissection. They concluded that counting egg niches caused a 36 percent overestimate in egg deposition.

However, in a North Carolina study, Hain (unpublished data) sampled for egg production when the brood were in late larval stages. Live egg counts were made if egg niches were associated with a larval gallery. Dead egg counts were made if the egg was still present or if an empty egg niche without a larval gallery was observed. By this method, less than 5 percent of the egg niches were empty or had unhatched eggs. Using the same method in Arkansas, F.M. Stephen (personal communication) also found less than 5 percent empty niches or dead eggs.

In all three studies numbers of eggs had a linear relationship with gallery length. Thus, measurements of gallery length can be used to estimate egg deposition. The differences in egg density reported by the three studies could result from regional differences in the insect's biology or population characteristics, or reflect errors associated with the sampling techniques used.

Emergence

Various modifications for sampling bark beetle emergence have also been devised. McClelland et al. (1978) reviewed several of these approaches and proposed the use of a new emergence trap to solve many of the problems associated with the other techniques. They stated that emergence estimates have been derived by two means: those that do not interrupt or modify ongoing physical or biological processes within the tree (nondisruptive), and those that do (disruptive).

The nondisruptive techniques correlate emergence with counts of exit holes. Thus the tree remains unaltered until emergence

is complete. Unfortunately a one-to-one relationship between exit holes and emergence does not always exist. Multiple use of a single hole and utilization of bark cracks and fissures commonly occurs.

The disruptive techniques include (1) removing samples before emergence to count callow adults within the bark (potential emergence), (2) placing bark slabs or bolts in field cages to monitor emergence under "natural" conditions, (3) placing bark slabs or bolts in environmental chambers to simulate natural conditions, and (4) attaching emergence traps to the tree. All methods involve some interference with biological processes operating during late brood development and emergence. The degree of disruption varies with the technique but is usually quite substantial.

The authors concluded that the most practical and unbiased estimates of emergence can be obtained by using on-tree traps constructed and installed to minimize the disruption of biological processes. They describe a basic trap design, with modifications, that utilizes a nylon screen and collecting bottle. The trap is designed to fit over a circular bark surface of 100 cm². McClelland's team acknowledged that the screening inhibited parasitism of late brood stages. But this inhibition could be minimized by placing the traps on the tree as late as possible, but before emergence begins. The traps are rugged, pliable, simple to construct, and easily attached and removed.

The emergence traps have also been used to sample reemergence of parent adults (see Chapter 5 and Coulson et al. 1978). Emergence traps were placed on infested trees when attacking adult density was judged to be at a maximum. Field crews placed traps at several heights on the infested bole and monitored them daily for the duration of reemergence (16 to 20 days) (fig. 6-11).

It is not always practical to monitor the traps daily or to revisit the trees more than once. Cooper and Stephen (1978) used laboratory rearing techniques to determine reemergence. With daily observations, lab workers determined a lag time between reemergence and brood adult emergence. All beetles collected up to this lag time were considered reemerging parent adults. Attack density, as determined by the attack-site method, and reemergence holes were linearly



Figure 6-11 – Infested loblolly pine tree equipped with pole steps to permit access to reemergence traps. (Courtesy of the Entomological Society of Canada).

related to reemergence and had significant predictive values. Holes that penetrated the bark perpendicular to the inner surface and directly connected to an egg gallery were considered reemergence holes. Workers must take care not to confuse these with holes caused by other SPB associates. Both of the above studies found high reemergence rates.

Estimating Total Within-Tree Populations

With an understanding of the various procedures and modifications for sampling southern pine beetle populations, let us proceed with a discussion of analytical methods for estimating total within-tree populations. Basically this involves the techniques that

were developed from the data base of 134 infested trees sampled by Coulson et al. (1975a).

As mentioned earlier, an essential step in the development of precise estimating procedures is a clear understanding of the spatial and temporal distribution of the population being sampled. We must first consider the within-tree distribution of SPB. Beetle distribution within an "average" sample disk is uniform (Foltz et al. 1976a). In comparing the samples taken at four aspects (NE, SE, SW, NW) at each sample height, Foltz's team found no consistent directional bias. The population density along the infested bole varied with life stage but was generally greatest near the center of the infested bole and lower at the extremes (Mayyasi et al. 1976a and b, Coulson et al. 1976a and e, Foltz et al. 1976a). The generalized spatial and temporal within-tree distributions were depicted in figures 5-2, 5-4, 5-7, and 5-10. The functional distributions of the attacking adults, eggs, larvae, and pupae-callow adults, and emerging adults in relation to the normalized infested bole (sample height/infested bole height) were described. Probability density functions for the various within-tree life stages have been determined (Mayyasi et al. 1976b). The probability density function (PDF) is the ratio between the insect density at a given height and the average insect density along the entire infested bole.

With regard to nonlinear models for describing the within-tree distributions, Nebeker et al. (1978b) analyzed these models with gallery length data collected from shortleaf pine in Mississippi. Figure 6-12 shows the curves of the various models they analyzed. Model I-A is the two-parameter model described by Coulson et al (1976a) and Mayyasi et al. (1976a and b). They forced the density to be zero at the bottom and the top of the infested bole. The model explains about 25 percent of the total variability in the data. Model I-B forces the density to be zero only at the bottom of the infestation and explains about 32 percent of the variability. Model I-C places no restrictions on the density and raises the explanation percentage to 34. In contrast Model II, which was proposed by Foltz et al., (1976a) to describe the within-tree distribution of gallery length, explains only 25 percent of the variability when no conditions are placed on the parameters. Model III is model I-D with the following tree parameters added: (1) average inner-bark thickness at the middle of the infested bole, (2) infested bole length/tree height, and (3) diameter at breast height multiplied by the infested bole height. Model III explains 68 percent of the variability.

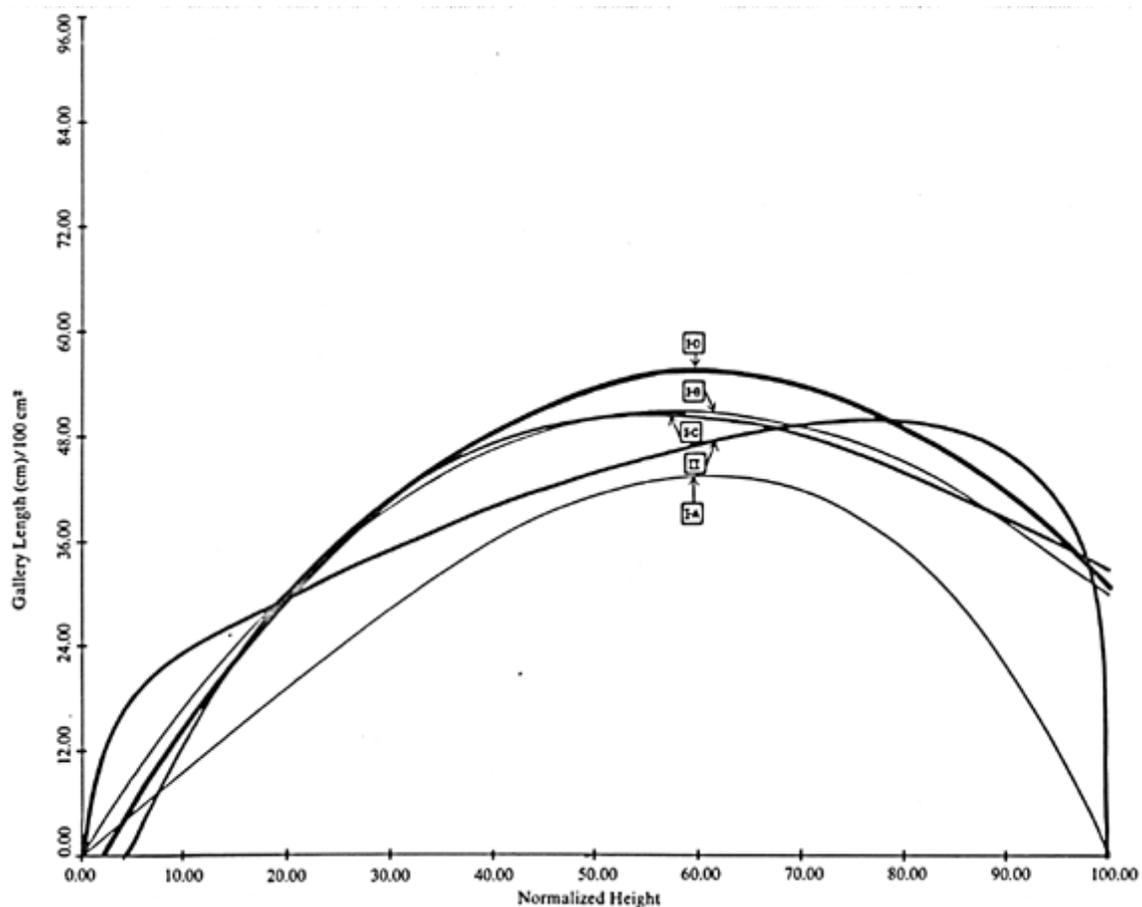


Figure 6-12 – Plot of raw data and resulting curves for various models discussed in Nebeker et al. (1978b). Models I-D and III are the same when all trees are combined. (Taken from Nebeker et al. 1978b).

Pulley et al (1976) developed the topological mapping routine for computing the total number of beetles on a tree using data provided by Coulson et al. (1975a). This procedure used all the data available to derive a best estimate for the total population.

The topological estimates were used as a basis of comparison with all other estimating procedures. To understand this procedure, visualize a film of uneven thickness surrounding a tree. The thickness of the film is proportional to the insect density. If the volume of the film can be determined, the number of insects on the tree can also be determined. The topological technique assumes a gradual change in insect density between observation points.

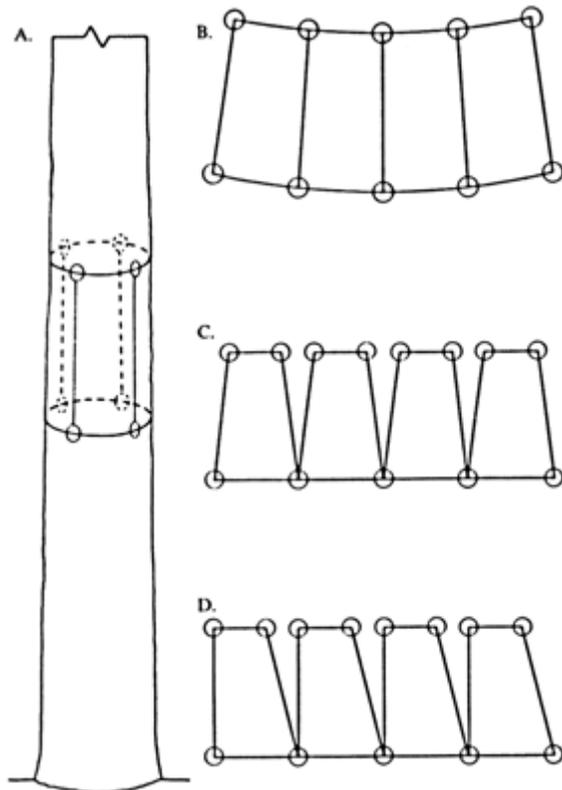


Figure 6-13 – Successive transformations of the tree surface. A. Truncated cone and sample locations on the standing tree. B. Flattened surface of truncated cone. C. and D. Sections of the conical surface transformed to trapezoids of equivalent area. (Taken from Pulley et al. 1976).

The topological mapping procedure starts by considering the interval between sample heights as a truncated cone and transforms the surface of the cone to a plane. The individual segments between sampling points are transformed to trapezoids (fig. 6-13). A model to describe this surface was selected. To determine the volume and hence the insect count, it is necessary to derive the specific contour associated with a given section, as depicted in figure 6-14 (Pulley et al. 1976). Summing for all the sections then yields the estimate of beetle numbers for the infested tree.

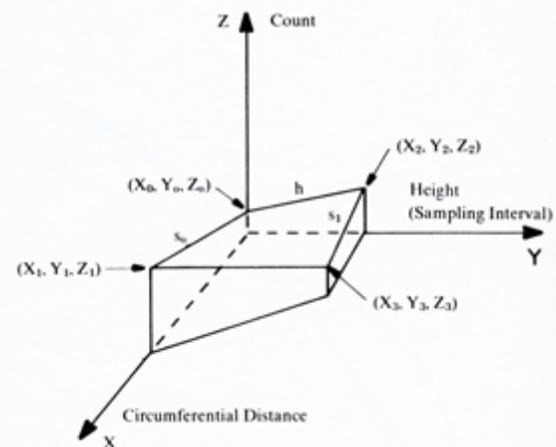


Figure 6-14 – Solid of volume equivalent to the insect count on a particular section of the tree. (Taken from Pulley et al. 1976).

Pulley et al. (1977a) selected a series of sampling plans and tested their suitability for estimating within-tree populations of attacking SPB adults. Later other life stages were estimated and the procedures evaluated (Coulson et al. 1976e). The accuracy and precision of the various estimating techniques was determined by comparing the estimates to the topological estimates.

Two types of estimates are necessary to obtain an estimate of total within-tree population: an estimate of the surface area or bark volume of the tree, and an estimate of the beetle density within the tree. Pulley et al. (1977a) selected five procedures each for calculating surface area and beetle density. The long cylinder and the tree geometry model techniques for estimating surface area, and the extrapolated disk and PDF techniques for estimating beetle density can be considered small sampling plans since little data is required for the execution of these procedures. The remaining techniques can be considered large procedures since a substantial amount of data is required.

The small sampling schemes are inherently more interesting because they are likely to have practical applications. The primary function of the large schemes would be as research tools. There are several possible combinations of the small surface-area estimation techniques and the small beetle-density techniques.

The tree geometry model PDF combination (TG-PDF) illustrates a small sampling plan (Coulson 1976e). The tree geometry model utilizes the nonlinear model developed by Foltz et al. (1976b) to estimate surface area. Tables of surface area based on the tree geometry model are provided for three bark thickness classes of loblolly pine in Coulson et al. (1976e). To estimate the number of beetles in a tree using the PDF technique, the observed density is divided by a PDF value tabulated in Coulson et al. (1976e) and multiplied by the surface area of the infested bole. The TG-PDF procedure is illustrated in figure 6-15. The procedure requires only one sample or set of samples at a given level, but multiple-level sampling can also be done. Procedures for multiple-level sampling are also discussed in Coulson et al. (1976e). Of course, if three or more levels are sampled, the topological estimating procedures can be employed with equal or greater precision (McClelland, Hain, and Mawby 1979).

The above procedures were developed from a data base collected in southeast Texas during an SPB epidemic. Hain et al. (1978) evaluated the same sampling and analytical procedures using data collected in North Carolina during a period when SPB populations had declined to a

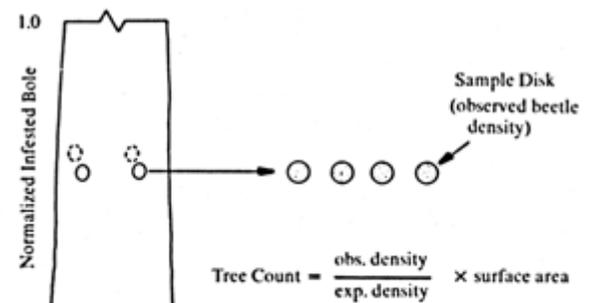
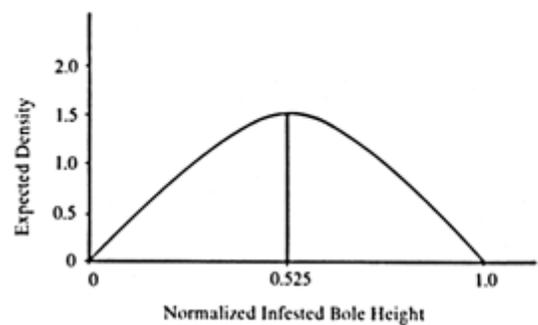


Figure 6-15 – Schematic illustrating the use of the probability density function (PDF) method of estimating within-tree attacking adult populations of southern pine beetle. (Taken from Pulley et al. 1977b).

"sparse" population phase. If the procedures proved applicable under the population conditions experienced in North Carolina, then the procedures should be applicable on a regional basis (subject to validation).

Estimates of the infested surface area were obtained from the tables provided in Foltz et al. (1976b) and Coulson et al. (1976b). These tables were derived from the tree geometry model. The estimates were compared to the topological surface area estimates. The average relative error of the tree geometry estimate for the North Carolina trees was + 4.19 percent and compared favorably with the + 3.50 percent bias found in Texas.

The within-tree distribution of life stages in North Carolina was evaluated using the model of Mayyasi et al. (1976a and b). There were no significant differences between North Carolina and Texas, and the authors concluded that the PDF values given in Coulson et al. (1976b) are suitable for use in North Carolina.

Thus the TG-PDF procedures for estimating within-tree populations should be applicable in North Carolina as well as Texas and other regions of the South. As a final analysis, the North Carolina estimates were obtained using North Carolina parameters (PDF values and correction weights) and compared to estimates for the same trees using Texas parameters. A comparison of mean relative errors showed only minor differences (Hain et al. 1978).

In comparing the within-tree distribution of infested shortleaf and loblolly pines, researchers found no significant differences between the two host species (McClelland et al. 1979). Hence a standardized approach to a regional research effort may be taken to determine regional differences in population parameters.

Pulley et al. (1977c) described the advantages of a sampling plan derived from a knowledge of the within-tree distribution of southern pine beetles. These authors contrasted the TG-PDF procedure to random and stratified random sampling plans. The random techniques required large quantities of data and were therefore less suitable. They also showed that the sample location on the tree greatly influenced the precision of the estimate. Various sample level locations were analyzed using the TG-PDF procedure with sampling intensities ranging from one to seven levels. The gain in information content became marginal after three levels were sampled. Dispersing the sample levels over the infested bole, while avoiding the extremes, produced the best results.

Pulley, Coulson, and Kelly (1979) investigated the accuracy and precision of the topological mapping procedure for a variety of different sampling intensities. Results showed that the penalties in bias and lack of precision due to sampling at wider spacings and taking fewer samples at each level were not large. For example, taking just one sample from the northeast aspect at a sampling interval of 250 cm would result in an underestimate of 10.29 percent, which is the largest proportional error. The sampling plan described by Coulson et al. (1975a) would result in an underestimate of 1.38 percent.

Nebeker (1979) presented a view of the hierarchy of within-tree estimating procedures based upon their level of precision. A complete census is, of course, the most precise, followed by estimates from large sampling plans, small sampling plans, and indirect procedures. The indirect procedures utilize host characteristics to determine the estimate rather than taking samples of infested bark. Model III, described earlier in this chapter and depicted in [figure 6-12](#), can estimate the within-tree population by utilizing host characteristics as the only parameters.

Estimating Within-Spot Populations

The next step in the development of quantitative sampling procedures is estimating beetle populations within an entire infested spot. Intensively sampling each tree is not practical. But since procedures do exist for nonintensive within-tree sampling, it should be possible to extend these methods to an entire infestation.

At least four factors need to be considered in sampling an infestation (Pulley et al. 1977a): (1) precision of the within-tree estimates, (2) total number of infested trees, (3) number of trees to sample, and (4) methods of selecting sample trees and scaling the observed counts.

Using the 134-tree data base, infestations of various sizes were simulated (Pulley et al. 1977a, Foltz et al. 1977). The infestations were considered a population of infested trees stratified by the SPB life stage. Sample trees were selected and estimates made of the within-tree populations. The information was then extrapolated to all the trees within each stratum.

Ten procedures were evaluated by Pulley et al. (1977a). The single-level (5.0 m) TG-PDF procedure and the two-level (3.5, 6.5 m) TG-PDF procedure were compared for precision. Researchers chose these sample heights because they were among the most precise of the single- and two-level estimating procedures. Methods of selecting the trees were evaluated by comparing random selection with the intentional selection of the largest trees. Methods of extrapolating sample tree estimates to calculate within-spot estimates included scaling according to the proportion of the tree numbers, tree diameters, or infested phloem areas included in the sample.

The best precision was obtained by selecting trees with the greatest infested phloem area or the largest diameter. The least costly procedure for obtaining a desired level of precision consisted of selecting the trees of the largest diameter and sampling at the 5-m level. A guide to using these estimation procedures has been published (Foltz et al. 1977).

Estimating Areawide Populations

Stephen and Taha (1976) outlined the following procedure for sampling SPB in an area of Arkansas consisting of several to many infestations: (1) Determine the number of samples for the sample unit area to be used. (2) Survey the area to estimate the number of spots. (3) Allocate a proportionate number of the samples to each infestation, depending on the number of infested

trees with pupae or callow adults. (4) Subdivide the infested bole into at least three sections and sample each section.

Stephen and Taha expanded these techniques to permit estimations of the total numbers of SPB of their natural enemies within a defined area. The methods were specifically designed to provide the forest manager or pest control specialist with a tool to determine if treatment was necessary. Two methods have been described — one fairly simple but less precise, the other requiring intensive data collection and resulting in more precision. The simple method, which I will call the "prediction" method (Stephen and Taha 1979b), is practical, does not require intensive within-tree sampling, is relatively inexpensive, does not require highly trained specialists nor specialized sampling and X-raying equipment, and reduces the time between data collection and estimation. The other method is more complicated and does require within-tree sampling and the analysis of those samples. I will refer to this method as the "sampling and tree measurement" method (Stephen and Taha 1979a).

Both methods incorporate aerial survey information with ground survey information, and estimations of age structure, beetle density, and infested bark area. The aerial survey determines the location and relative number and size of infestations within a give area. The ground surveys for the prediction method locate each infestation to assess the predominant life stage at breast height, to measure the d.b.h. of each infested tree, and to obtain an estimate of the average height of infestation within each infested spot. In the prediction method, the authors have assumed a constant life stage along the length of the bole. Of course, this is rarely the case, but a large error should not be incurred if a relatively large, heterogeneous population is measured.

Estimates of beetle density were obtained for the prediction method from a 3-year data base of 181 trees in Arkansas. During all seasons, samples were collected from the full spectrum of infestation sizes available there. Stephen and Taha felt that such data should provide a reliable range in mean densities for each SPB life stage that would be encountered if intensive sampling were conducted over a large area.

An alternative to this simple, less precise approach is to determine the mean densities for infested trees in the study area using the "sampling and tree measurement" method. The procedures described above (Stephen and Taha 1976) represent a part of the sampling and tree measurement method.

To estimate the absolute population density in a given area, two variables are required: an estimate of the average beetle density, which can be obtained by either of the two methods described above, and an estimate of the total infested bark area. Using the 181-tree data base, the investigators calculated infested bark areas. A model was developed to predict infested bark area based upon d.b.h. measurements. But the authors felt a measure of the height at the top of the infestation (HTI) was also necessary because a control treatment could have an influence on the physical limits of the infestation. The trees were classed by HTI and d.b.h. A table of infested bark areas was prepared using the d.b.h. classes and height classes represented in the data bank. This table is used in predicting areawide population densities.

Stephen and Taha developed an alternative model for estimating infested bark area. They found the tables presented by Foltz et al. (1976b) to be inadequate since a substantial number of infested trees in Arkansas were in a size class not included in the tables. However, the techniques are quite similar and the differences are insignificant. This model is used in the "sampling and tree measurement" method. The amount of infested bark over the entire area is obtained by multiplying the average infested bark area per tree by the number of infested trees in the area.

Given the estimates of average beetle density for each life stage, plus an estimate of the total infested bark area, investigators can readily obtain an estimate of the total beetle population in an area. Stephen and Taha (1979a and b) compared the two methods for estimating total SPB populations. The sampling and tree measurement method produced an estimate of SPB attacks (on 16 trees) of $188,235 \pm 18,929$. Using the prediction method, the researchers obtained an estimate of $164,310 \pm 14,922$. Although the population totals differ by 13 percent, a substantial area of overlap occurs between the confidence limits of the two estimates.

Monitoring Emerging SPB Populations

Thus far this chapter has dealt with monitoring infested trees and sampling populations within infested trees. Since a high percentage of the SPB's life cycle is spent within an infested tree, this is not unreasonable. But a significant, though small portion of the life cycle is spent in flight to new host trees. Monitoring or sampling dispersing populations is extremely difficult. And the technology for doing this is not as well developed as the technology for sampling within-tree populations or for monitoring bark-beetle-caused tree mortality from the air.

The use of pheromone traps for monitoring beetle dispersal has been discussed in Chapter 5. Procedures for quantitatively estimating between-tree mortality based upon observations of spot growth and within-tree population were also covered. Here we will discuss a technique that has been developed to monitor beetles as they emerge from an infested tree. The implications of this technique are far-reaching since it would allow researchers to identify the source population of a newly infested tree. Therefore, it has applications for beetle dispersal studies.

The procedure involves the use of radioisotope tagging as reported by Moore and Taylor (1976), Taylor and Moore (1978), and Moore, Taylor, and Smith (1979). In selecting a potential tagging isotope, the authors were looking for the following properties: (1) The material should be able to soak into the bark of treated trees or stick to the outside and adhere to emerging beetles. (2) The isotope must have a half-life that will allow for the detection of SPB that have emerged and attacked another tree. (3) The material must not adversely affect the beetles' behavior.

Moore and Taylor found that emerging beetles carried the tag (^{32}P) from infested bolts to fresh bolts and were still tagged after entering the fresh bolt. The investigators concluded that part of the radioactivity rubbed off during excavation because frass and pitch collected from the entry holes were also radioactive. When the experiment was repeated on living trees, the pitch tubes were found to be radioactive and could be detected with a portable ratemeter. The beetles from treated bolts could be identified for at least 19 days, well beyond the 14-day half-life of the isotope.

The ^{32}P tagging technique was successfully applied in the field to evaluate the dispersal and attack potential of beetles emerging from felled brood trees. (This was done because cut-and-leave is a recommended control tactic in some States). An infestation as far as 365 m from the felled trees was found, and 75 percent of the 12 infested trees contained radio-tagged pitch tubes. Radioactivity could still be detected 41 days after the study began. Other studies (Coster and Johnson 1977 unpublished) have had mixed results with the ^{32}P tagging technique.

Predicting Population Potential

Models for predicting the potential growth and expansion of a southern pine beetle population have been developed at the spot level and the area level. Models at the spot level have been referred to as "spot growth" models. For a more detailed discussion of population modeling, see Stephen, Searcy, and Hertel (1980).

Spot Growth Models

Regression Models

Hedden and Billings (1979) monitored the growth of 62 east Texas infestations during the summers of 1975 and 1977. Field crews visited the infested spots upon first detection and again at 2-week intervals during the summer or until the individual spots became inactive. Two thresholds of summer spot growth activity were identified. First, infested spots having 10 trees or fewer seldom experienced further tree killing. The proportion of infested spots that became inactive was inversely related to initial number of brood trees. Second, when rates of attack exceeded ca. 2.5 trees per day (> 80 active trees), spot expansion became largely independent of stand density. Between these thresholds, spot expansion was correlated with the number of infested trees per spot, total BA, and average d.b.h.

Two increase ratios were calculated to compare infested spot growth trends among spots and among years. These were:

Spot Growth Index (SGI) = (BA of new trees killed/day) / (BA of active trees at first visit)

and

Active Tree Index (ATI) = (BA of active trees at day 30) / (BA of active trees at first visit)

Sample plots were then categorized into four groups based upon spot growth trends: (1) no infestation growth (ATI or SGI = 0); (2) declining growth (ATI < 0.8); (3) static growth (0.8 < ATI < 1.2); and (4) increasing infested spot growth (ATI > 1.2).

The mean rates of spot growth in summer-infested spots varied among years, directly reflecting the annual changes in areawide beetle population levels. As a result, the spot growth models of Hedden and Billings (1979) are appropriate only for increasing or peak populations in the Gulf Coast region during summer months.

Hedden and Billings's models were tested in 24 infestations located in Texas, Louisiana, and Mississippi, but principally in Louisiana (Twardus, Hertel, and Ryan 1978). The test was run during a general collapse in populations: 18 of the infestations were inactive by the second visit. The remaining six plots were inactive by the third visit. The results do not compare well with those of Hedden and Billings (1979). For example, of the six infestations in which additional tree mortality occurred, four had 30 or more active trees at the initial visit. Of the 18 spots that went inactive, seven had 30 or more infested trees at the initial visit. Hedden and Billings found that all infestations with 30 or more infested trees continued to grow. Basal area and average d.b.h. did not significantly differ between active and inactive infestations. They also observed that spots which later became inactive had no freshly attacked trees. In the Twardus team's study, however, the number of freshly attacked trees was not found to be correlated with additional tree mortality.

The results discussed in Twardus et al. (1978) do not invalidate the spot growth models of Hedden and Billings (1979) — they simply emphasize our lack of understanding about what causes a general collapse in SPB populations, as occurred during the three-State study. Hedden and Billings point out that their models are appropriate only for increasing or peak beetle populations. And, of course, it is during such times that the forest manager is most concerned about timber losses.

A nonlinear spot growth model (Reed et al. 1980) was developed using the data collected by Hedden and Billings. The model simulates the spread of SPB infestations using stand-level variables. The model consists of two principal functions: (1) a function to predict the rate of spread, in terms of trees killed per day, and (2) a function to predict the probability of a spot becoming inactive. The model was tested on 11 infestations from northern Georgia and underpredicted the total number of trees killed by 6 percent. It was not very precise in estimating damage from individual infestations, however.

Moore (1978) and Moore, Hertel, and Bhattacharyya (1979 unpublished) developed a trend predicting procedure that relies almost exclusively on evaluating beetle population parameters — specifically, attack: emergence ratios determined from bark samples taken during the first visit to an active spot. When the attack: emergence ratio (A: E) exceeded 1: 10, the active spot was considered to be increasing. That is, the spot would have 1.5 times as many dead and infested trees at the second visit as it had at the first visit. If the A: E ratio fell between 1: 5 and 1:9.9, the infested spot was considered static. That is, the number of dead and infested trees at the second visit would be between 0.5 and 1.5 times as great as at the first visit. The infested spot was considered to be decreasing if the A: E ratio fell below 1: 4.9. In that case, the number of dead and infested trees at the second visit would be less than 0.5 as great as at the first visit.

The time between first and second visits of 4 months was considered adequate for summer predictions, when infestations were growing rapidly. Timing of sampling was critical. Bark samples had to be taken at 2 and 5 m from recently abandoned trees. If sampling was too late, large portions of the egg and brood galleries were obliterated by wood borers feeding in the inner bark. All beetle counts, from attacking adults to emerging adults, were determined from this one sample. In this respect, this procedure differs from all other sampling procedures discussed here.

Two subcategories (static-declining and static-increasing) were added, to account for infestations where the beetle activity was static (A: E 1:5 — 1:9.9). To make this prediction, the investigators examined secondary factors. These included percent brood emergence, relative amount of disease, length and condition of egg and larval galleries, number of clerid larvae, number of SPB emerged per unit area, number of infested trees, and pine BA.

In 11 infested plots located in the Georgia Piedmont, Moore's team concluded that if those infestations classified as increasing had been removed, 80 percent of the subsequent damage would have been prevented. If those infestations classified as increasing or static-increasing had been removed, 96 percent of the damage would have been prevented.

Moore et al. (1979 unpublished) developed a continuous model to predict the number of trees killed over a given period. The only variable in the equation was the attack: emergence ratio. Continued evaluation of the models and procedures described by Moore is in progress.

All models that have been discussed to this point are statistical regression models. In other words, these models are used to summarize data collected under changing environmental conditions. Such models highlight the important variables contributing to the system's dynamics. However, they can be used only under conditions similar to those that prevailed when the original data were collected.

Mechanistic Models

In contrast, biophysical mechanistic models require an understanding of the mechanisms responsible for the observed behavior. As explained by Coulson et al. (1979c), this modeling approach describes processes in mathematical terms and then integrates them into a model of the entire system. If the individual hypotheses are correct, such a model would allow for predictions outside the range of the original data.

Often a combination of the statistical approach and the biophysical approach can be used in developing the system model. But usually the model will be predominantly one or the other. The following is a description of a predominantly biophysical spot growth model.

TAMBEETLE

The TAMBEETLE model (Coulson et al. 1979c) is a biophysical mechanistic spot-growth model that accounts for the reproduction and mortality of beetles within an infested spot. The model is organized around trees which are active (currently infested), inactive (dead and vacated trees), or potentially active (trees that are in close proximity to active trees). The basis of the model is a series of submodels that are mathematically interconnected, to account for beetle reproduction and mortality. At present, the component submodels simulate the following processes: (1) brood emergence, (2) oviposition, (3) reemergence, (4) beetle allocation, (5) pheromone emission and distribution, and (6) tree drying.

The model follows the progress of the developing beetle cohorts as well as the infested tree cohorts. At present, the development, reproductive, and mortality components of the model are driven by temperature only. But there are plans to include a moisture variable.

The model is set up on a daily increment basis, and all the temperature-driven processes are calculated at the start of each day. Beetle cohorts initiate flight, attack trees, construct galleries, lay eggs, develop, pupate, and emerge. Emergence follows an extended probability distribution whose shape is determined by the previous temperatures experienced by the brood. The between-tree population, which consists of all emerged and reemerged beetles, forms the nucleus for beetle attack on active and potentially active trees. Figure 6-16 illustrates the organization of the model.

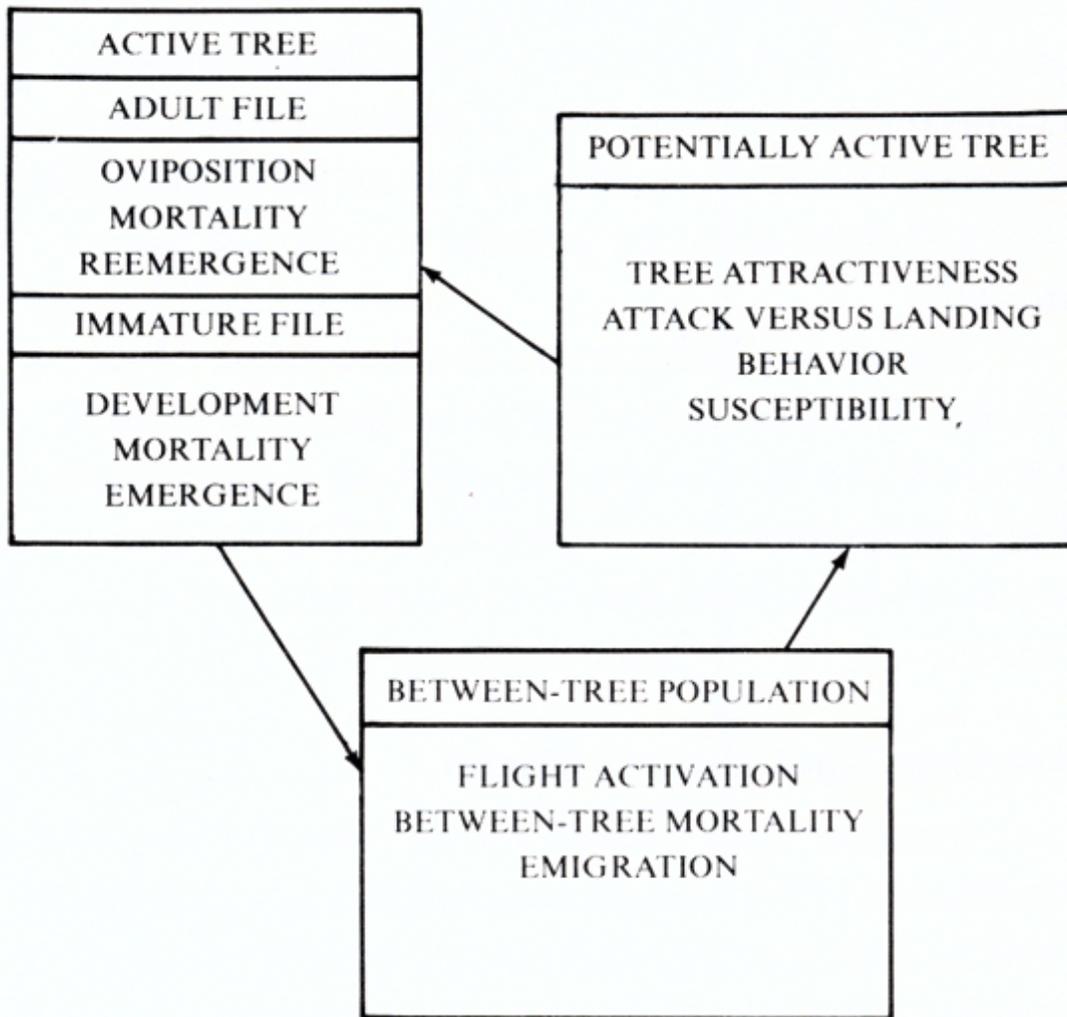


Figure 6-16 – Population growth sequence followed in the TAMBEETLE infestation dynamics model.

The TAMBEETLE model allocates the between-tree population to active and potentially active trees. Potentially active trees are defined by their proximity to active trees. The effective distance is a function of the size and shape of the pheromone plume emanating from the active tree. This plume, in turn, is affected by climatological conditions. Once the beetles have been allocated (equivalent to landing on a tree), the probability of a successful attack is a function of the amount of gallery construction already completed within the tree (equivalent to an inhibitor of further attack). If the beetles do not attack, they are available to attack other potentially active trees.

A potentially active tree becomes an active tree, in the model, if it has become "susceptible" to beetle attack. Susceptibility is a tree vigor parameter measured by the number of beetles initially required to overcome the natural resistance of the tree. Once this resistance is overcome, the tree is subject to mass attack (aggregation).

At the end of each day, the between-tree populations are combined for allocation the next day. If the between-tree population is not successful in colonizing a tree, the beetles will disperse, retarding spot growth. Factors that limit the growth of a spot are high tree resistance, wide tree spacing, and weather factors which interrupt pheromone communication and/or flight activity.

Little or no knowledge of computer technology is required to use the model. An interactive question-and-answer routine is available for the user to input information about an infested spot. The routine is set up to follow the sampling procedure described by Coulson et al. (1976e) and Foltz et al. (1977), and reviewed earlier in this chapter. The input values that the user must supply to activate the model are (1) the number of active trees, (2) an estimate of the beetle population (the number of beetles per bark sample), (3) the infested phloem area for each tree, (4) the mean and standard deviation of all d.b.h. and infested bole height measurements, (5) mean bark thickness, (6) tree susceptibility (assumed to be between 100 and 500 beetles per tree), (7) immigration (usually set at 0), (8) pine BA, and (9) daily minimum and maximum temperatures. Other input parameters that will be added to the model include wind, cloud cover, and precipitation. An effort is being made to reduce the number of input parameters so as to make the model more practical for pest control specialists. The user can then output a vast array of predicted information for any given day. The output could include the numbers of trees killed, trees under attack, trees with brood, attacks per day, reemerging beetles per day, and emerging beetles per day. The model cannot provide the specific geometry for the location of infested trees. Nor is it a spot initiation model. A cohort of beetles and infested trees must be present to activate the model.

Figure 6-17 illustrates the flow logic of the model. The first three blocks initiate the model. The next

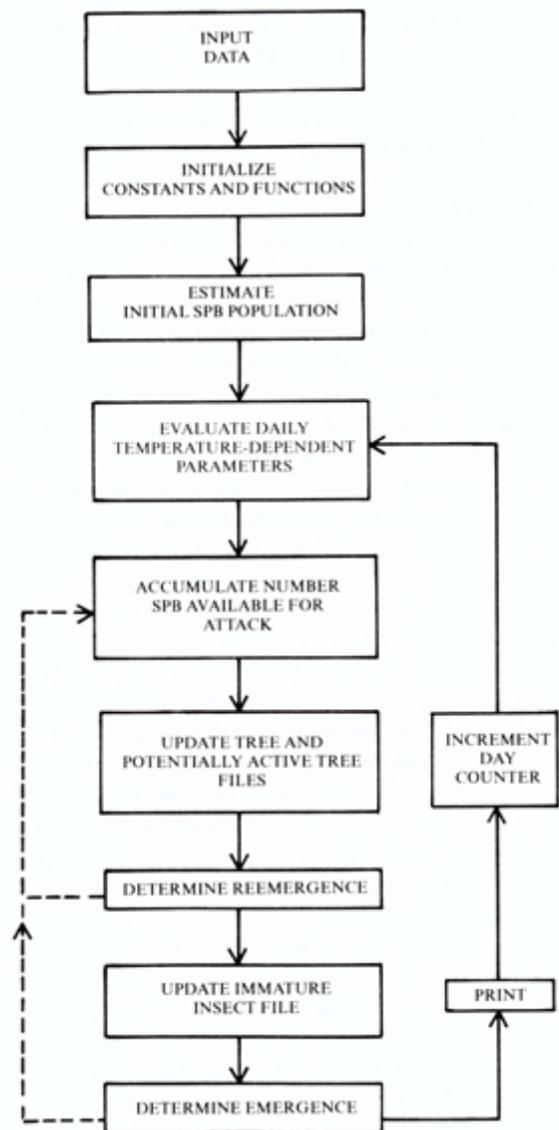


Figure 6-17 – Information flow chart for the TAMBEETLE infestation dynamics model.

six blocks are recycled on a daily basis. Field validation is complete for some components of the model and is in progress on the others.

Arkansas Spot Growth Model

Another spot growth model was developed by Hines (1979) and Hines, Stephen, and Taha (1980). This model predicts not only spot expansion but also the monetary loss on beetle-killed pulpwood and sawtimber, based on current stumpage prices.

Figure 6-18 illustrates the information flow within the model. It shows the basic SPB life cycle with assigned rates and variables. Rates (bottlenecks) regulate the rate of flow of materials through the system and thus control the magnitude of change. Variables alter the rates through time.

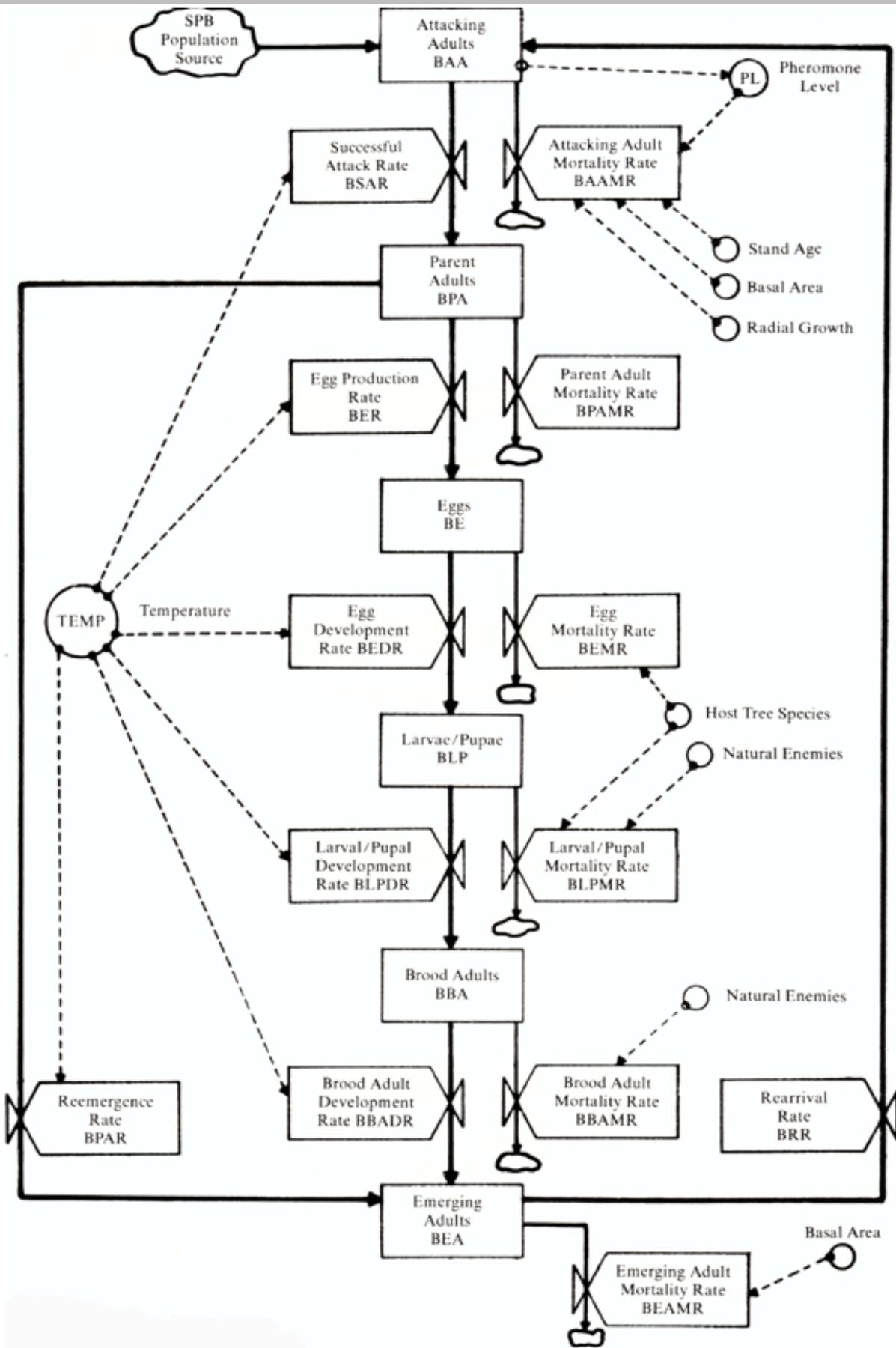


Figure 6-18 – Graphic representation of levels, rates, and paths of information flow within the Arkansas spot growth model.

The input parameters necessary to initiate the model can be obtained by a forest technician. A computer interactive question-

and-answer program is available. The forester or pest management officer needs only a description of site and stand conditions. The input values are (1) date of observation, (2) length of time the user wishes to simulate, (3) geographic location, (4) BA, (5) tree growth rate, (6) tree age, (7) species composition of the stand, (8) d.b.h. class, (9) a tree count by SPB life stage (parent adult, larvae, pupae, or brood adult), (10) the average height at the top and the base of the infested portion of the trees, (11) average circumference at the top of the infestation and at breast height (optional), and (12) current stumpage prices.

Detailed information on beetle density is not needed because the model assumes an average density for each life stage based on previous intensive within-tree sampling. An estimate of the infested bark area is converted to numbers of beetles in each life stage.

The mortality rates of the various life stages are affected by the stand's basal area, growth rate, age, and species composition. The model employs geographic area and date to access the appropriate temperature files. And, of course, the current stumpage price is needed to assign a dollar value to the predicted timber loss.

The model outputs a weekly prediction of the number of dead and infested trees classified by life stage, a volume estimate of the timber loss, and a monetary value of that loss. The infested tree prediction is obtained by converting the number of beetles to an equivalent amount of infested bark and dividing that by the average amount of infested bark per tree.

The Arkansas model has certain assumptions and limitations. Many of these can be refined as more data becomes available. For example, the system is closed, allowing neither emigration nor immigration of flying adult beetles. The food supply is unlimited, and there are no physical barriers within and no disturbances of the habitat. Average beetle density and average infested bark area are constants. Finally, the model is appropriate only for the months of April through September and for a period of not more than 90 days.

Areawide Modeling Efforts

Several efforts have been made to model southern pine beetle activity on an areawide basis. Since forest management plans are developed for large areas and the cost for management's decisions and actions is frequently budgeted well in advance of actual implementation, some means of predicting SPB incidence and severity is desirable. The following is a discussion of those modeling efforts that are attempting to address this question.

FRONSIM

Leuschner, Mattney, and Burkhart (1977) developed a simulation model to estimate timber mortality in future years over large geographic areas. The Frontalis Simulator (FRONSIM) estimates damages by simulating the number of infested spots for a given year. This model, although rudimentary, is available for use now with only basic data required. After estimating the number of infested spots in a year, the model applies a frequency distribution of the number of trees per spot to estimate the total number of trees. It then applies a frequency distribution of infested tree d.b.h. measurements to estimate the number of trees in each d.b. h. class. Timber mortality and monetary value are estimated using a local volume table and current stumpage prices. The procedure can be done for any number of years in the future and summed over all years. The number of spots can be simulated by a completely random model or a regression model.

This model has some built-in assumptions and limitations. First, because the model averages the results for any one year, severe outbreaks or collapses cannot be predicted. In fact, extreme beetle activity cannot be predicted. Second, FRONSIM estimates the value of timber lost in future years but does not include other, less tangible losses such as the impact on the subsequent stand, recreation, wildlife, or water. Third, the areawide data required for the model are relatively unavailable at this time, although some data are being collected. Lack of data naturally hinders validation and implementation. Finally, the model provides predictions on a regional basis by averaging the experience on all infested lands in the region and projecting it into the future. Thus it is not useful to the small landowner.

Estimating Incidence of Outbreaks in a Stand

Daniels et al. (1979) discussed a methodology for estimating the probability of an outbreak (= incidence) in a stand. The method does not predict the severity of the infestation. It is based upon a logistic probability function with total basal area and the proportion of the BA in pine as the independent variables. Other variables (e.g., average height, age, average current radial growth, and soil variables) were also evaluated but gave similar results.

Table 6-1 documents the results of fitting the model to data collected from disturbed and undisturbed, natural stands. Disturbances included lightning strikes and harvesting activity during the past year. **Table 6-1** shows that the probability of an infestation increased as total BA and proportion of pine BA increased. And the probability in disturbed stands were considerably higher than in undisturbed stands.

Daniels et al. concluded that the model has two major advantages. It provides a continuous measure of probability, even in low-susceptibility stands – a probability that can be partitioned into categories within the context of the users' objectives. Also, the probabilities can be used in more sophisticated decision guideline models or outbreak severity models.

Hicks, Howard, and Watterston (1980) also developed a methodology for estimating the probability of an outbreak in a stand. The model was developed by a stepwise discriminant analysis and requires pine BA, average tree height, and a categorical evaluation of landform (e.g., flood plain, lower slope, ridge) as input parameters. The predicted probabilities of attack were valid for data collected in east Texas when assumptions were made about the beetle population level. Thus the actual frequency of attack depends on both stand characteristics and SPB population levels.

Table 6-1. – Test probabilities for *Dendroctonus frontalis* incidence in nonplantation stands. (From Daniels et al. 1979)

Undisturbed Stands							
Total basal area		Proportion pine basal area					
(ft ² /ac)	(m ² /ha)	0.5	0.6	0.7	0.8	0.9	1.0
50	11.48	0.0016	0.0022	0.0031	0.0043	0.0060	0.0083
100	22.96	0.0027	0.0037	0.0051	0.0071	0.0099	0.0137
150	34.44	0.0044	0.0061	0.0085	0.0118	0.0164	0.0226
200	45.93	0.0073	0.0101	0.0141	0.0195	0.0269	0.0371
Disturbed Stands							
50	11.48	0.0014	0.0022	0.0036	0.0056	0.0093	0.0150
100	22.96	0.0045	0.0073	0.0117	0.0188	0.0301	0.0478
150	34.44	0.0135	0.0217	0.0345	0.0547	0.0855	0.1312
200	45.93	0.0396	0.0625	0.0972	0.1482	0.2195	0.3126

DAMBUGS

By combining a spot growth model with a spot incidence model, it should be possible to derive an estimate of southern pine beetle damage for a region. DAMBUGS (Reed 1979 unpublished) represents such a combined model. It utilizes the spot incidence model of Daniels et al. (1979) with a spot growth model that relies solely on stand conditions as input parameters (e.g., forest type, stand age, site class, total BA, mean d.b.h.). In this system, the incidence model estimates the size of each infestation. The damage from all simulated infestations is summed to arrive at an estimate for the region. SPB population parameters are not included in the model.

Modeling the Endemic-Epidemic Cycle

Modeling the severity of southern pine beetle activity over large areas is still at the conceptual level. Models that can predict with a reasonable degree of accuracy when and where outbreaks are likely to occur would undoubtedly be a useful management tool. Gold, Mawby, and Hain (1980) have set up a framework for modeling the transition of SPB activity from the endemic (low level) to the epidemic state. By necessity, the model includes the insect-host interaction in a hierarchy of four levels: the individual tree, local neighborhood (group of trees that influence the dynamics of a given tree, or all trees that are influenced by a given tree), quasi-uniform patch (the partitioning of a larger region), and large region. Individual trees can be described in terms of attack threshold, potential brood productivity, stress state, relative attractiveness to beetle attack, pheromone emission, and beetle production.

Certain stress factors substantially reduce the susceptibility and the brood productivity of the tree. This effect is made the basis of a distinction between endemic and epidemic modes of infestation within an individual tree. An endemic mode tree may have been predisposed to SPB attack by lightning strikes, *Ips* bark beetles, water stress, or disease (Hain 1980 unpublished). Thus its susceptibility and capacity for beetle production have been substantially lowered. In this mode SPB is secondary invader. The span of time over which beetles attack and subsequently emerge is commonly longer than in epidemics. Since brood emerge over a longer period, their ability to attack en masse is lessened. An epidemic mode tree is mass-attacked by SPB as the primary invader, resulting in the tree's death. In the modeling framework, the degree to which epidemic mode trees dominate the dynamics of the neighborhood, patch, and region is made the basis of the endemic-epidemic transition at these levels.

The dynamics of a local neighborhood are determined by the states and interactions between the individual trees of which it is composed. The dynamics of a patch are determined by the states and interactions of the local neighborhoods, thus allowing for the introduction of environmental fluctuations as disturbances within the patch. The dynamics of the region is determined by the states and interactions between the patches of which it is composed, allowing for consideration of regional differences.

The regionwide description can be in terms of a mosaic of probability distributions of endemic mode and epidemic mode trees. Hopefully these descriptions can be drawn from a common distributional family and quantified for each patch. The probability distributions of each patch must be adjusted for the microheterogeneities, such as edge effects and proximity to infested trees. Therefore, it is clear from this framework that an understanding of the overall system requires a consideration of all four levels in the hierarchy (tree, neighborhood, patch, and region).

Model Validation

Little has been stated about model validation. Hines (1979) points out that a model is valid when it can predict changes with reasonable accuracy. The first stage of model validation is to determine if the model duplicates previously obtained field data. This is done implicitly in estimating unknown parameters. The second stage of validation is carried out concurrently with implementation of the model. The results of the model's prediction are compared with what is observed in the field.

As observed and predicted changes occur during implementation, model improvements can be initiated. This procedure is repeated indefinitely until the model predicts changes with a reasonable degree of accuracy. Thus the model is in a constant state of evolution from a primitive to a sophisticated structure.

Of course, changes in the model structure must be based upon a sound understanding of the beetle's biology and its interaction with the host.

Summary

A great deal of subject matter and information has been covered in this chapter. At first glance, the topics may appear unrelated. However, the underlying theme has been the development of procedures for monitoring and/or predicting population trends. Depending upon the objectives of the user, a procedure can be used singularly or in conjunction with other procedures. As an example of a user objective that would require several of the procedures discussed in this chapter, let

us consider a case study of a control treatment evaluation. This case study was discussed during a recent symposium (Smith and Twardus 1979). The objective is to evaluate cut-and-leave as a tactic for controlling SPB over a large area. The change in timber volume loss and the effect on beetle populations needed to be determined.

Coulson et al. (1979c) outlined a stepwise protocol for evaluating treatment tactics. The first step is to consider the probable effects of the proposed treatment in light of current knowledge on beetle dynamics and host tree interactions. For the purpose of illustration, we will assume that cut-and-leave can affect within-tree survival and dispersal mortality. The second step is to simulate the infested spot conditions in both the presence and absence of the treatment using the TAMBEETLE population dynamics model. Variables can be manipulated to test the treatment under a variety of conditions and thus indicate the conditions under which the treatment would be effective. This step eliminates expensive field testing of tactics with low utility potential. The third step is to compare the cost of applying the treatment with the value of the expected timber protected.

If the procedure still appears promising, the next and most expensive step is field testing. For discussion purposes, two areas with about equal distribution of susceptible host type and active spots could be used as treated and check blocks, respectively. Sequential aerial photography with navigation guidance by Loran-C can monitor tree mortality and infested spot proliferation before and after treatment. PISYS can store and analyze the aerial data. With ground checking, volume loss can be estimated. To determine within-tree survival in selected treated and untreated areas, the within-tree sampling and estimating procedures (Coulson et al. 1975a, 1976e) should be employed. The areawide populations can be estimated in both areas using the approach of Stephen and Taha (1979a and b). Also the probability of beetles emerging from treated areas and contributing to infested spot proliferation can be examined using radioisotope tagging techniques (Moore and Taylor 1976, Moore et al. 1979, and Taylor and Moore 1978).

The final step would be to reevaluate costs and benefits in light of the experimental results. If the procedure becomes operational, continued monitoring and evaluation can be done using multistage sampling techniques (Ghent and Ward 1977 unpublished, and Schreuder et al. 1977 unpublished and 1979).

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