United States
Department of
Agriculture

Forest Service

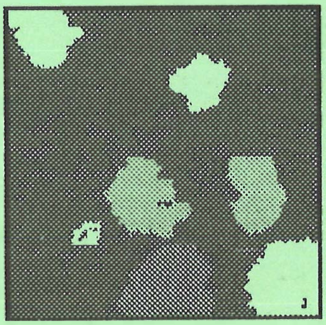
**Northeastern Forest
Experiment Station**

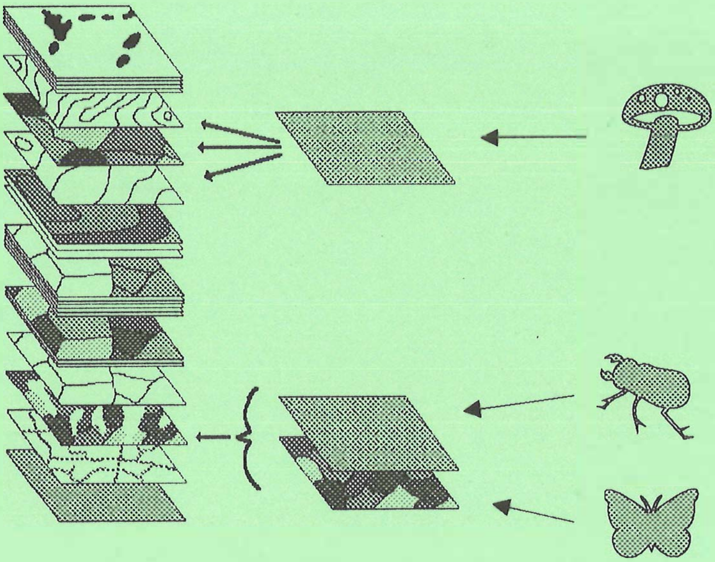
General Technical
Report NE-175

Proceedings

Spatial Analysis and Forest Pest Management

$$N_{x,t} = \frac{N_{0,0} \; e^{rt-x^2/4Dt}}{4\pi Dt}$$





All of the papers published in these proceedings were submitted electronicly and were edited to achieve a uniform format and type face. Each contributor is responsible for the accuracy and content of his or her own paper. Statements of the contributors from outside the U. S. Department of Agriculture may not necessarily reflect the policy of the Department. Some participants in the workshop did not submit papers, so they have not been included.

Remarks about pesticides appear in some technical papers contained in these proceedings. Publication of these statements does not constitute endorsement or recommendation of them by the conference sponsors, nor does it imply that uses discussed have been registered. Use of most pesticides is regulated by State and Federal Law. Applicable regulations must be obtained from the appropriate regulatory agencies.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish and other wildlife--if they are not handled and applied properly. Use all pesticides selectively and carefully. Follow recommended practices given on the label for use and disposal of pesticides and pesticide containers.

Northeastern Forest Experiment Station
5 Radnor Corporate Center
100 Matsonford Road, Suite 200
Radnor, Pennsylvania 19087-8775

June 1993

PROCEEDINGS

SPATIAL ANALYSIS AND FOREST PEST MANAGEMENT

April 27-30, 1992
Mountain Lakes, Virginia

Edited by

ANDREW M. LIEBHOLD AND HOPE R. BARRETT
USDA Forest Service
Northeastern Forest Experiment Station
180 Canfield St.
Morgantown, WV 26505

Sponsored by:

USDA Forest Service
  Northeastern Forest Experiment Station
  Computer Sciences and Telecommunications
  Forest Insect and Disease Research
  Forest Pest Management

Virginia Polytechnic and State University

FOREWORD

Over the last 20 years technologies have been developed that provide new tools for analyzing and modeling spatial processes. These tools have allowed scientists to overcome the conceptual problems and data management complexities that in the past prohibited exploration of spatial problems. These new technologies include geographic information systems (GIS), which are software for managing and manipulating spatial data, more powerful computer systems that are able to handle the computationally intensive needs of spatial data analysis, and new numerical procedures that allow analysis and modeling of spatial data. These technologies have been embraced in a variety of disciplines ranging from mining engineering to biomedical research but one field where these tools are being rapidly applied is forestry. Typically, forest management entails making decisions on land use over large, heterogeneous landscapes. This decision making typically involves the integration of multiple data themes (such as vegetation, topography, hydrology) over large geographical areas and is therefore a prime candidate for application of GIS.

The U.S. Forest Service is currently implementing a national GIS plan that will integrate GIS and other spatial analysis technologies into many aspects of forest management. This technology is similarly being applied by state and private forest management organizations around the world. In 1990 the Computer Sciences and Telecommunication staff of the US Forest Service headquarters realized that during the implemention of this plan, there was a need to bring together university and Forest Service scientists from a variety of disciplines to discuss accomplishments and future needs in spatial analysis.

In early 1991 a team of scientists working in the field of forest insect and disease management and research began to organize a workshop that would address accomplishments and future needs in the spatial analysis of forest pest problems. This group included Andrew Liebhold, Northeastern Forest Experiment Station, Donald Jameson, Computer Sciences and Telecommunications, Ross Pywell, Forest Pest Management, Patrice Janiga, Forest Pest Management, J. Robert Bridges, Forest Insect and Disease Research, Brian Geils, Rocky Mountain Forest and Range Experiment Station, Jesse Logan, Virginia Polytechnic and State University, and Lukas Schaub, Virginia Polytechnic and State University. The objectives of the workshop that they organized were:

1. Exchange information on current and near-future needs and opportunities for application of spatial analysis to describe and predict the dynamics of insects and pathogens as well as their affects on forest ecosystems.

2. Identify critical gaps in our understanding of ecosystem properties or processes that require spatial analysis to describe, maintain, and improve forest health.

3. Develop a strategic plan whereby emerging concepts and technologies using spatial relationships could be better incorporated into forest planning, monitoring, and research.

The workshop was held April 27-30, 1992 at Mountain Lakes, Virginia. The first two days of the meeting were used by the participants to make presentations on current accomplishments in spatial analysis. The last day was spent in break-out groups, discussing gaps in our current knowledge and setting priorities for future research and development.

These proceedings contain papers authored by workshop participants and a final report at the end of this volume summarizes the conclusions made by the participants in the break-out groups. The purpose of publishing these proceedings was to allow individuals who were not at the workshop to learn about what research and development is underway in the area of spatial analysis of forest pests and to communicate the participants' conclusions about future research and development needs.

SPATIAL ANALYSIS AND FOREST PEST MANAGEMENT
April 27-30, 1992
Mountain Lakes, Virginia

CONTENTS

HISTORIC, CURRENT AND POSSIBLE FUTURE ANALYTICAL CAPABILITIES OF GEOGRAPHIC INFORMATION SYSTEMS (GIS)

DONALD A. JAMESON
USDA Forest Service, Computer Science and Telecommunications Staff,
201 14th St., SW, Washington, DC 20250

Abstract. In Forest Service use of GIS, we continue to emphasize that we are concerned about spatial analyses, rather than just mapping. Pursuit of object-oriented software technology should lead to better understanding of an "objects-in- space" approach to resource analysis and enhanced applications to questions like watershed (hydrologic), wildlife, pest and recreation management that are treated with difficulty with current procedures. We can expect that GIS software will move toward object-orientation, and it would be well to have our analyses concepts moving in a direction that would allow us to capitalize on the software. Additional developments in spatial statistics, Kriging, dynamics and fractal analysis coupled directly to GIS can also be anticipated.

HISTORIC AND CURRENT ANALYTICAL CAPABILITIES IN GIS

Recent developments in computer processing speed and color graphic displays have brought GIS to the forefront, but the cartographic and analytical concepts behind GIS are much older. Historic precedents of GIS include mapping and cartography, processing of remote sensing imagery, and spatially-oriented site and corridor analysis. Although image processing has maintained a more-or-less separate identity, the other historical precedents have had a definite impact on the subject matter of current GIS.

Among geographers, cartography and mapping are commonly seen as the dominant influence of GIS, but for natural resource managers independent developments in site and corridor analysis may assume more importance. Development of techniques by McHarg (1969) in the use of transparent overlays to study location of environmentally sensitive activities has had a major impact. At that time there was sufficient computer capability to move from hand drawn transparencies to computer manipulations with a few primitives, namely arithmetic, Boolean and set operators. An example "GIS" of the era was Harvard IMGRID, which could produce only gray maps with the line printers of the time. It is interesting that some current GIS's do little more than McHarg overlays (plus a computerized planimeter), but of course modern computers can make the process much faster and color graphics make the outputs more attractive.

Tomlinson et al. (1976) described the analytical subsystem of a GIS as including the following parts:

(1) Retrieval of data from storage.
(2) Measurement of areas or calculation of distance.
(3) Comparison of multiple data sets, i. e., a procedure to overlay one data set upon another and to determine the intersection or union of the variables.
(4) Statistical analyses appropriate for spatial data.
(5) Specific analytical procedures determined by the user.

Pages 1-7 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis of Forest Pest Management. USDA Forest Service General Technical Report NE-175.

Part (1) is represented by attribute files (either flat files or relational databases) that are used or created by the analysis and display portions of the GIS. Parts (2) and (3) have evolved to current vector GIS (see USDA Forest Service 1991, Appendix C, for capabilities). Part (4) is expressed in continuing work in spatial statistics (e.g., Haining 1990, Cressie 1991).

Vector GIS has been very useful in mapping and inventories. In addition, most analyses of linear features, such as roads, trails and streams, can be well treated with vector GIS. However, many specific analyses of areas (Part 5 above) require a raster GIS.

Raster analysis was advanced with the Tomlin-Berry operators, which were first described by Dana Tomlin and Joe Berry (Tomlin and Berry 1979, Tomlin 1983), largely promoted by Berry (1987a, 1987b), and more fully described in Tomlin (1990). The MAP analysis package, implemented by 1980, included these operators as first described, and most commercial raster GIS's do the same. Authors of more recently coded commercial raster packages like to point out that they have implemented the operators described by Tomlin (1990), which has become the defacto commercial standard.

In addition to the primitives used by GIS circa 1970, the analytical GIS of the 1980's included local area descriptors (e.g., slope, aspect, diversity, variance); smoothers (e.g., majority membership, averages, polynomial smoothing); pattern analysis (e.g., clumps, connectivity, convexity, narrowness, and holeness or Euler numbers). Classification procedures (e.g., maximum likelihood, discriminant function multipliers, fuzzy classifiers) were generally reserved for separate packages known as image analysis software, but are included in some GIS's. Kriging, a more advanced smoothing procedure, and fractal dimensions, a more recently developed technique for pattern descriptions, are rarely included in standard GIS's and must be added as extensions if they are to be used.

Included in the Tomlin-Berry operators were habitat relationships RADIATE (for viewsheds), DRAIN (for watersheds), and SPREAD (over a friction or impedance surface). SPREAD operators are used for variable-width buffers and other analyses that are essential in habitat and landscape analyses. They have been included in better commercial raster packages, but are absent in others. Note that in vector GIS, only fixed-width buffers based on distance relationships are possible; variable width buffers of raster GIS depend on other relationships.

The Tomlin-Berry operators can lead to hypothesis statements. For example:

- Light travels in a straight line, but is interrupted by any opaque object (RADIATE). For the purposes of landscape/habitat analysis, this is appropriate (i.e., light bending is ignored), but the hypothesis hardly needs additional testing.

- Water follows the steepest descent pattern (DRAIN operators). This is somewhat shakier that the light hypothesis (i.e., the hypothesis ignores infiltration, evaporation, and movement along aquifers), but is still useful.

Marble (1990), in assessing the potential changes in views of the world that might result from applications of GIS, wrote:

> "I would submit that social scientists concerned with human spatial behavior ... have adopted a limited and myopic view of the subject, and that this myopia has been in large part the result of our inability to visualize, let alone model, the full scope of human spatial behavior ... we have lacked the tools which would permit us to organize and comprehend the data defining the real and extremely complex spatial environment in which human behavior actually takes place."

From an anthropocentric view, this statement seems appropriate. However, if we substitute "entomologists" or "pathologists" for "social scientists", and substitute "pest" for "human", the statement is patently inadequate because it ignores any consideration of explicit statements of pest behavior. For example, the SPREAD operator in raster GIS is one of the most powerful analytical tools available for studies of spatial behavior. However, it is incomplete because the only thing known for sure about the object to be spread is its location. Behavioral attributes of the moving object that control its spread are therefore imbedded in the description of the habitat (the friction or impedance layer), and relevant behavioral hypotheses are clouded. Development of the impedance layer often becomes contorted, and will require some kind of lineage tracking for documentation. This approach also commonly leads to the need for a reinventory when properties of the moving object are changed.

There has been some commentary about the need for dynamic GIS, but the application of a clear methodology to dynamics is practically unknown in GIS software. At a minimum, a dynamic GIS should have a simulation modeling aspect. It should also have the capability of including new observations as they become available, using a conditional probability procedure similar to or an improvement on the Kalman filter approaches adapted by Jameson (1985, 1986) to natural resource monitoring.

THE FUTURE - OBJECT-ORIENTED APPROACHES?

With the development of improved graphics and object-oriented computer languages, such as Smalltalk, C++, Object Pascal, and CLOS (an extension of Common LISP), software capability now seems to be catching up with many of the problems identified by proponents of adaptive resource management during the past two decades. Developments in these languages have led to specialities in software design, knowledge-based user interfaces, and database management (Khoshafian and Abnous 1990, Zdonik and Maier 1990). For information on object-oriented concepts in software design and programming, see Wirfs-Brock et al. (1990), Booch (1991), Smith (1991a), Taylor (1991), and others. Many current computer science topics in object-oriented approaches are published in the Journal of Object-Oriented Programming.

Use of object-oriented approaches to user interfaces is now so common that it can assumed to be the standard method for new developments (e.g., Dorfman 1990, Tello 1990, Smith 1991b, and many others). Much attention is also being given to object-oriented databases. A principal advantage of object-oriented database management is that the database can include functions (i.e., behavior) as well as state descriptions (Atwood 1991, Heintz 1991). In the general area of object-oriented database management, books and tutorial articles include Brown 1991, Gupta and Horowitz 1991, Hughes 1991, Joseph et al. 1991, Kim 1990, Kim and Lochovsky 1989, and Nahouraii and Petry 1991.

The application of object-oriented concepts to spatial data is currently in a rapid state of flux. Grosky and Mehrotra (1989) stated that relational databases are proving inadequate for spatial data, and have predicted that the relational approach will be supplanted by object-oriented databases in these cases. Kasturi, et al. (1989) have predicted that object/raster approaches will have more application than object-oriented vector systems, but this could change with further developments. There are several articles in the open literature on object-oriented spatial databases (e.g., Jagadish and O'Gorman 1989, Mohan and Kashyap 1988, Orenstein and Manola 1988, Oxborrow et al. 1991, Pizano et al. 1989, Robert et al. 1991, Worboys 1990).

Although at least two companies have long experience with object-oriented GIS, or at least a GIS that is written in an object-oriented language, commercial interest in object-oriented GIS is not as yet widespread. It appears likely that object-oriented CAD will appear as commonplace before object-oriented GIS. However, delays in industry-wide standards can be expected because there is not yet an ANSI C++, and there is no general agreement on standards for object-oriented spatial databases. In addition, most of the work on object-oriented databases has been done in academia or by small firms, so the forces for standardization have not yet focussed.

Much of the advanced development of an objects-in-space approach to spatial analysis has been spawned by a research group at Texas A&M University, with extension to cooperators at other institutions (e.g., Coulson et al. 1987, Saarenmaa et al. 1988, Folse et al. 1989, Folse et al. 1990, Mueller 1991, Roese et al. 1991). Their procedures feature individual or population models coded in a LISP-derived language (e.g., Keene 1989); these populations move through, modify, and learn from habitat features (points, lines and polygons) that are also coded with an object-oriented language. Work of this group has primarily been applied to wildlife and pest populations. Saunders et al. (1992) have summarized these approaches with a description of the union of knowledge based rules of animal behavior with object-oriented programming techniques to produce an intelligent GIS. Applications to hydrology have been presented by McKay et al. (1991) and Whittaker et al. (1990).

Fire behavior appears to be another promising area for an objects-in-space technique, but thus far there have been no published examples. However, the Advanced Resource Technology Lab (ART) at the University of Arizona is working on modeling of fuzzy moving objects in fuzzy space, using a GIS of their own design (George Ball, UA, personal communication), that could be helpful in fire applications. Because object-oriented approaches are an active research area, other applications will undoubtedly surface.

Extensions to the basic operators described earlier in this paper frequently are implemented through access to the source code of public domain computer programs such as GRASS. Developmental efforts involving open source codes are important and will continue to play a role not filled by commercial software. However, too often the results are obscure and contorted procedures that may be understood only by the programmers and difficult for less experienced users to explain.

Further development toward an elegant (in the mathematical sense) object- oriented GIS may be furthered as fundamental work in topology is advanced. For example, Egenhofer and Herring (1990) and Egenhofer and Franzosa (1991) have defined a set of topological spatial primitives that are independent of distance. The inheritance property of object-oriented languages should facilitate adaptation of these primitives to new situations. Inclusion of such primitives, much as the arithemetic, Boolean, and set operators are now part of GIS, should be helpful for the next generation of GIS to evolve on a broad scale.

DISCLAIMER

This paper is intended only to explore some historical developments of GIS. It is not an official policy statement of the USDA Forest Service, nor does it reflect in any way on any pending or future computer system procurement by the Forest Service.

LITERATURE CITED

Atwood, T. M. 1991. The case for object-oriented databases. IEEE Spectrum **28**(2):44-47.

Berry, J. K. 1987a. A mathematical structure for analyzing maps. Environmental Management **11**:317-325.

Berry, J. K. 1987b. Fundamental operations in computer-assisted map analysis. International Journal of Geographical Information Systems **1**:119-136.

Booch, G. 1991. Object-oriented design with applications. Benjamin/ Cummings, Redwood City CA. 580p

Brown, A. W. 1991. Object-oriented databases and their application to software engineering. McGraw-Hill, New York. 224 p.

Coulson, R. N., L. J. Folse, and D. K. Loh. 1987. Artificial intelligence and natural resource management. Science **237**:262-267.

Cressie, N. 1991. Statistics for spatial data. Wiley, New York. 900 p.

Dorfman, L. 1990. Building C libraries; windows, menus and user interfaces. Windcrest Books, Blue Ridge Summit, PA. 415 p.

Egenhofer, M. J., and R. D. Franzosa. 1991. Point-set topological spatial relations. International Journal of Geographical Information Systems **5**(2):161-174.

Egenhofer, M. J., and J. R. Herring. 1990. A mathematical framework for the definition of topological relationships. In: Proceedings, 4th International Symposium on Spatial Data Handling; Zurich, Switzerland; **2**:803-813.

Folse, L. J., H. E. Mueller, and A. D. Whittaker. 1990. Object- oriented simulation and geographic information systems. AI Applications **4**(2):41-47.

Folse, L. J., J. M. Packard, and W. E. Grant. 1989. AI modelling of animal movements in a heterogeneous habitat. Ecological Modelling **46**:57-72.

Grosky, W. I., and R. Mehrotra. 1989. Image database management. Computer **22**(12):7-8.

Gupta, R., and E. Horowitz. 1991. Object-oriented databases and applications to CASE, networks and VLSI CAD. Prentice Hall, Englewood Cliffs, NJ. 447 p.

Haining, R. 1990. Spatial data analysis in the social and environmental sciences. Cambridge Univ. Press. 409 p.

Heintz, T. 1991. Object-oriented databases and their impact on future business database application. Information & Management **20**(2):95-103.

Hughes, J. G. 1991. Object-oriented databases. Prentice Hall, New York. 280 p.

Jagadish, H. V., and L. O'Gorman. 1989. An object model for image recognition. Computer **22**(12):33-41.

Jameson, D. A. 1985. A priori analysis of allowable interval between measurements as a test of model validity. Applied Mathematics and Computation **17**:93-105.

Jameson, D. A. 1986. Sampling intensity for monitoring of environmental systems. Applied Mathematics and Computation **18**:71-75.

Joseph, J. V.; S. M. Thatte, C. Thompson, and D. L. Wells. 1991. Object-oriented databases: design and implementation. Proceedings of the IEEE **79**(1):41-64.

Kasturi, R., R. Fernandez, M. L. Amlan, W. Feng. 1989. Map data processing in geographic information systems. Computer **22**(12):10-21.

Keene, S. E. 1989. Object-oriented programming in common Lisp: A programmer's guide to CLOS. Addison-Wesley, Reading MA. 266 p.

Khoshafian, S., and R. Abnous. 1990. Object orientation: concepts, languages, databases, user interfaces. Wiley, New York. 434 p.

Kim, W. 1990. Introduction to object-oriented databases. MIT Press, Cambridge, MA. 234 p.

Kim, W., and F. W. Lochovsky. 1989. Object-oriented concepts, databases and application. ACM Press, Addison-Wesley, Reading MA. 602 p.

MacKay, D. S., L. E. Band, and V. B. Robinson. 1991. An object-oriented system for the organization and representation of terrain knowledge for forested ecosystems. GIS/LIS Proceedings; Atlanta GA **2**:617-626.

Marble, D. F. 1990. The potential methodological impact of geographic information systems on the social sciences. *In* Allen, K. M. S., S. W. Green, and E. B. W. Zubrow, editors. Interpreting space: GIS and archaeology. Taylor and Francis, London.

McHarg, I. L. 1969. Design with nature. Natural History Press, Garden City NY. 197 p.

Mohan, L., and Kashyap. R. L. 1988. An object-oriented knowledge representation for spatial information. IEEE Transactions on Software Engineering **14**:675-681.

Mueller, H. E. 1991. Object-oriented simulation : a new ecological tool emerges. GIS World **4**(5):42-44.

Nahouraii, Ez; Petry, Fred, eds. 1991. Object-oriented databases. IEEE Computer Society Press, Los Alamitos CA. 245 p.

Orenstein, J. A.; Manola, F. A. 1988. PROBE spatial data modeling and query processing in an image database application. IEEE Transactions on Software Engineering **14**:611-629.

Oxborrow, E., M. Davy, Z. Kemp, and R. Thearle. 1991. Object-oriented database management in specialized environments. Information and Software Technology **33**(1)22-30.

Pizano, A., A. Klinger, and A. Cardenas. 1989. Specification of spatial integrity constraints in pictoral databases. Computer **22**(12):59-71.

Robert, S. A., M. N. Gahegan, and B. Hoyle. 1991. Application of object-oriented databases to geographic information systems. Information and Software Technology **33**(1):38-46.

Roese, J. H., K. L. Risenhoover, and L. J. Folse. 1991. Habitat heterogeneity and foraging efficiency: an individual-based model. Ecological Modelling **57**:133-143.

Saarenmaa, H., N. D. Stone, L. J. Folse, and others. 1988. An artificial intelligence modelling approach to simulating animal/habitat interactions. Ecological Modelling **44**:125-141.

Saunders, M. C., R. N. Coulson, L. J. Folse. 1992. Application of artificial intelligence to agriculture and natural resource management. *In*: Kent, A., and J. G. Williams, editors. Encyclopedia of Computer Science and Technology, Marcel Dekker. Volume **25**, Supplement 10:1-14.

Smith, D. N. 1991a. Concepts of object-oriented programming. McGraw-Hill, New York. 87 p.

Smith, J. D. 1991b. Object-oriented programming with the X window system toolkits. Wiley, New York. 576 p.

Taylor, D. A. 1991. Object-oriented technology: a manager's guide. Addison - Wesley, Reading MA. 147p.

Tello, E. R. 1991. Object-oriented programming for windows. Wiley, New York. 351 p.

Tomlin, C. D. 1983. Digital cartographic modeling techniques in environmental planning. New Haven CT; Yale University. PhD dissertation. 300 p.

Tomlin, C. D. 1990. Geographic information systems and cartographic modeling. Prentice-Hall, Englewood Cliffs, NJ. 249 p.

Tomlin, C. D., and J. K. Berry. 1979. A mathematical structure for cartographic modeling in environmental analysis. Pages 269-283 **in** Proceedings of the American Congress on Surveying and Mapping 39th annual meeting held at Washington, DC, 18-24 March 1979.

Tomlinson, R. F., H. W. Calkins, and D. F. Marble. 1976. Computer handling of geographical data. Natural Resource Research Series 13. UNESCO Press, Paris. 214 p.

U. S. Department of Agriculture, Forest Service. 1991. Appendix C of GIS evaluation report, October. Washington, DC.

Wirfs-Brock, R., B. Wilkerson, and L. Weiner. 1990. Designing object-oriented software. Prentice-Hall, Englewood Cliffs, NJ. 341 p.

Whittaker, A. D., L. J. Folse, H.E. Mueller, and M. L. Wolfe. 1990. Object-oriented extension to GRASS (GIS) for modeling and simulation. Pages 121-126 *in* Zazueta, F. S., editor. Proceeding of the 3rd International Conference on Computers in Agricultural Extension Programs held at Gainesville, Florida, 31 January - 1 February 1990. Florida Cooperative Extension Service, University of Florida.

Worboys, M. F. 1990. Object-oriented data modelling for spatial databases. International Journal of Geographical Information Systems **4**(4):369-393.

Zdonik, S. B., and D. Maier, editors. 1990. Readings in object-oriented database systems. Morgan Kaufman, San Mateo CA. 629 p.

FOREST INSECT AND DISEASE RISK AND OCCURRENCE MAPS IN GIS: APPLICATION TO INTEGRATED RESOURCE ANALYSIS.

HELEN M. MAFFEI
Forest Pest Management, Pacific Northwest Region, U.S. Department of Agriculture, Forest Service, Bend, OR 97701

JOHN V. ARENA
Bureau of Indian Affairs, Warm Springs Indian Reservation, Warm Springs OR 97761

Abstract: Insect and disease (I&D) considerations impose important limitations on management options on the Warm Springs Indian Reservation. Difficulties have arisen, when evaluating the management implications of I&D from a big picture or landscape susceptibility perspective. Adding I&D occurrence and risk maps to the GIS data base will help to address landscape issues as well as incorporate forest I&D considerations into the overall integrated resource analysis process. Our approach to developing these layers in the face of time and budget constraints included: light surveys to answer specific I&D questions; use of aready existing information; and dividing up the reservation into several forest type strata. We found that needed I&D layers were either occurrence and risk maps. An example of each category is given using a 7,690 acre analysis area. Development of risk rating maps for western spruce budworm was also presented.

INTRODUCTION

Insect and disease (I&D) considerations impose important limitations on silvicultural management options on the Warm Springs Indian Reservation as they do on most of Central Oregon's forested lands. Difficulties have arisen, when evaluating the management implications of I&D in a context larger than the stand or cutting unit. Yet, these big picture or landscape susceptibility questions are commonly asked and the penalty of inadequate answers can be severe. For example, if the Tribal Council is not aware of the overall magnitude of I&D damage or threat to resource values (be they timber-, visual quality-, wildlife- or recreation values) they may not support silvicultural treatments required to deal with the problem. As a result, irretrievable losses multiply and future management options are lost.

In addition, previously collected I&D information is often lost, scattered, or in a form difficult to cross-reference with other resource information. Although analysis is still possible, it is time consuming to locate the information as well as interface it with other pieces of crucial information; if that is, the land manager is even aware of its existence. With limited time and personnel gathering together all the necessary I&D- and other types of information from these widely scattered sources is cumbersome and often doesn't take place. Instead the project is implemented without the information or the area is re-surveyed again wasting time and money.

Several years ago the Confederated Tribes of Warm Springs purchased a complete GIS system and hired two full time system's analysts. These employees have since been building a variety of resource information layers (36 in all) some of which include: registered ortho-quad maps; continuous forest inventory (CFI) plot summary information; plant associations; elk and deer habitat data; roads; rivers; sale area boundaries; harvest activity maps; and, rainfall maps.

Pages 8-14 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

We believe that adding an insect and disease occurrence and risk layer to the existing GIS data base will better enable us to address insect and disease issues from a big picture or landscape perspective. In addition, when used together with the other layers, it will help us to look at how these agents may limit or affect other resources outputs. Thus, we believe it will be easier to evaluate the role of I&D in a true integrated resource management framework.

STRATEGY AND METHODS

While we can make a convincing argument in the long term for the usefulness of I&D information in the data base, we are still faced with the problem of limited personnel and the up front cost of getting the information into the data base. Our approach to these limitations may be summarized as:

1. **Streamline and work smart**. We wanted to collect additional I&D information using efficient, economical procedures. We also wanted this information to be sufficient not only to project landscape effects, but also to select a preferred alternative (this includes the ability to run the I&D model extensions), and develop a general treatment diagnosis for each stand. Thus, we chose surveys which were light and tailored to answer management questions associated with specific pest problems (see mistletoe example) commonly encountered on Warm Springs.

   At the time of project implementation, additional data for specific unit prescriptions can be gathered on an "as needed basis". We suspect that this additional information will not be needed most of the time.

2. **Use what you have.** If good information already exists (at the required level) we don't want to recollect it. Therefore, we plan to make use of any credible pre-existing pest surveys or risk maps. These can simply be added to the data base. Useful I&D information can also be derived from a wide variety of other sources including aerial surveys, biological evaluations and, forest inventory efforts.

3. **Compartmentalize the work**. The reservation contains a wide, and some may say, "bewildering" array of forest types and associated pest problems. We find switching back and forth from one forest type to another in course of a survey, usually results in confusion and inaccurate data, even from the best field crews. We are therefore compartmentalizing surveys by three general forest types (Figure 1); the pine, the mixed conifer, and, the true fir/hemlock. Not only do these forest type groupings improve the accuracy of the survey by making it easier on field crews, they also help us form a perspective on the size, cost, and scheduling of surveys needed to complete the I&D layers.

RESULTS

We found that needed I&D information was either: 1. **Occurrence and severity maps**, where the location of specific existing insect and disease populations are mapped along with the severity of damage or infection; 2. **Risk rating maps**, where the level of risk to a damaging outbreak of a specific insect or disease is mapped across the landscape. Although both types of maps are useful, some pests lend themselves more to one of these systems than the other. For example, many insect pests lend themselves better to risk rating than mapping because of their mobility. In the following paragraphs, we will illustrate examples of how these two types of I&D maps can be used in the pine forest type. We will then illustrate how risk ratings can be developed to predict western spruce budworm outbreaks in the mixed conifer and fir/hemlock forest types.

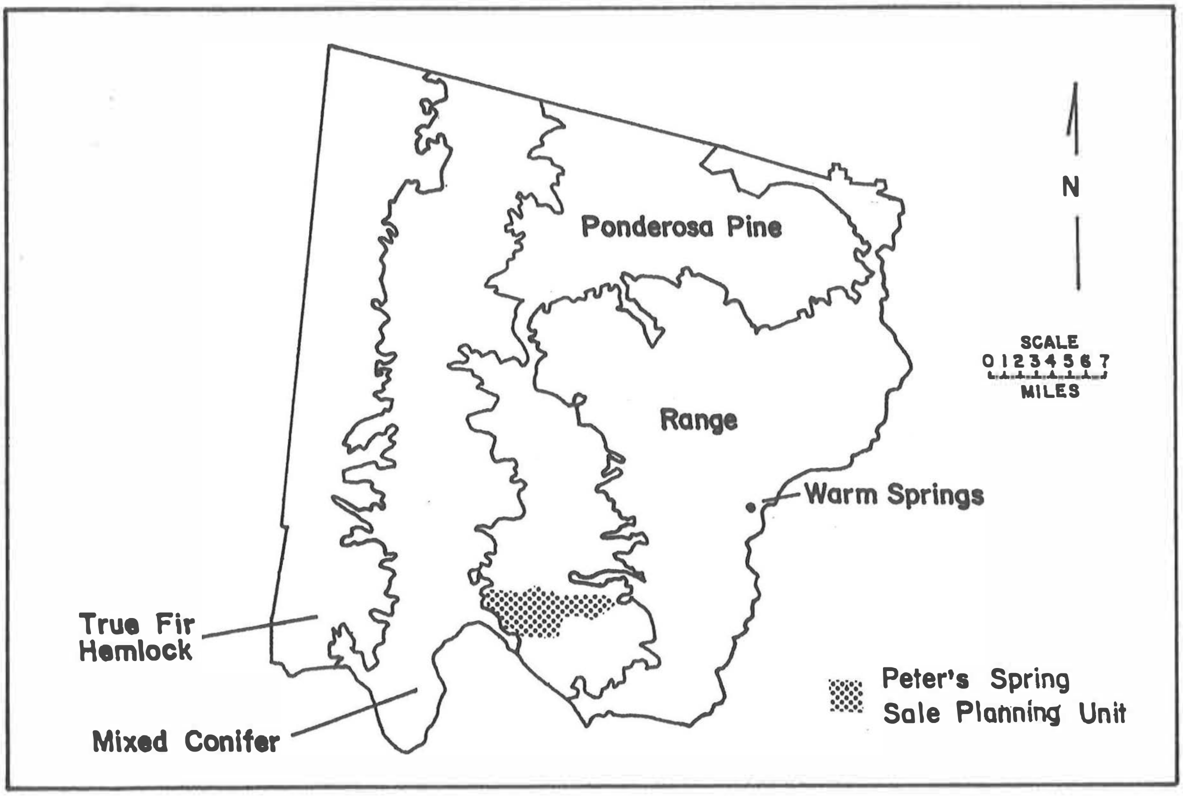


FIG. 1. Forested land on the Warm Springs Indian Reservation divided into 3 general forest types: 1. The pine type (177,000 acres); 2. The mixed conifer type (152,000 acres); 3. the true fir/hemlock type (119,000 acres). Location of Peter's Spring analysis area (7,690 acres) in the pine type forest.

Mapping dwarf mistletoe occurrence and severity

In order to develop an area based program to treat western pine dwarf mistletoe (*Arceuthobium campylopodum*) silviculturally, it is important to know it's distribution and severity with a reasonable degree of accuracy. Hence, we have developed a method of detection call the "mistletoe reconnaissance survey". This is a light survey which provides 100% forest area coverage while collecting general information with respect to species composition, size, stand structure, dwarf mistletoe infection incidence and severity (the dwarf mistletoe rating system (DMR) (Hawksworth 1977) was used). It is a visual reconnaissance, comparable to the roadside surveys done in the Southwest and Colorado in the 1980's (Maffei et al 1987a,b and c; Merrill et al 1985) except survey point centers were set up on a 5 by 5 chain grid system over the entire ponderosa pine type rather than surveying only along roads. The survey method assumes a 2.5 chain (165 ft.) line of sight in all directions from survey point center (approximately 2.5 acres).

To give you a general idea of how this survey can be used to evaluate the spatial attributes of dwarf mistletoe treatments we will use a project analysis area called Peter's Spring. A significant amount of this 7,690 acre ponderosa pine forest is infected with dwarf mistletoe(Figure 2).

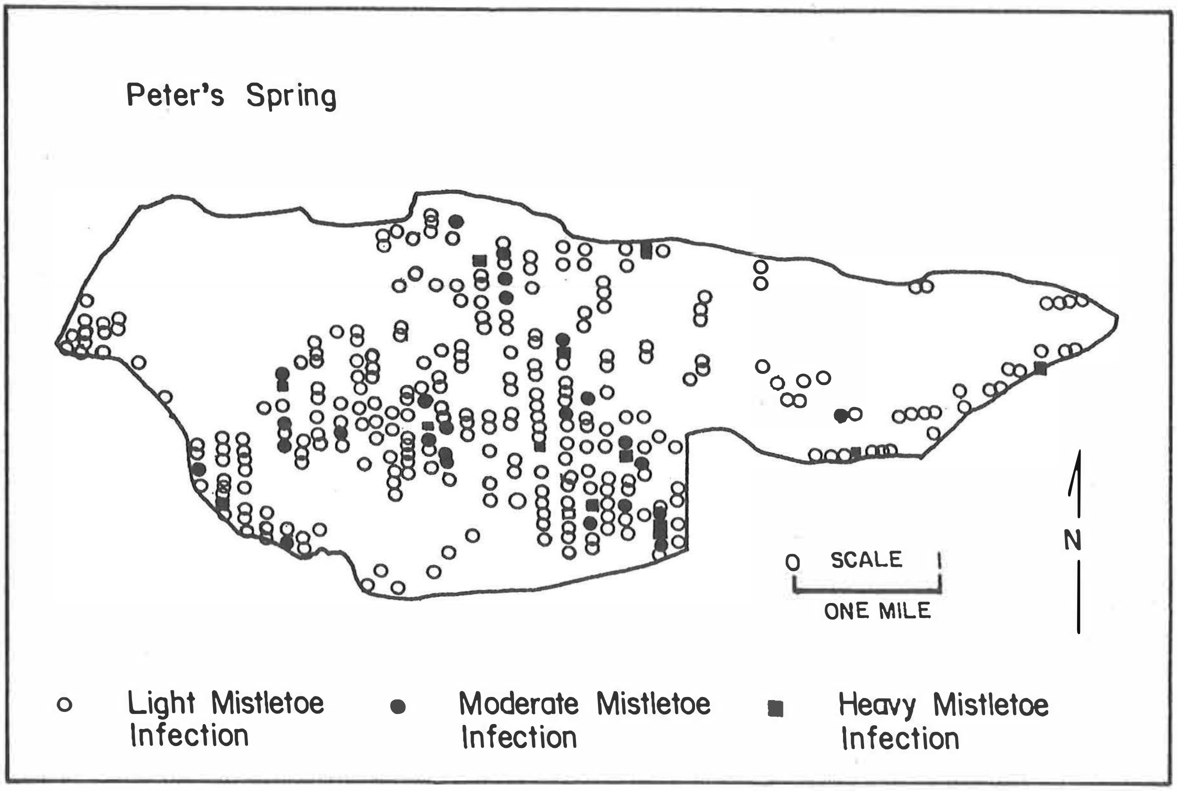


FIG. 2. Western pine dwarf mistletoe distribution by infection severity classes on the Peter's Spring Planning Unit. The total size of the unit is 7,690 acres. Each survey point square represents 2.5 acres (some of the irregular sized ones represent more). In areas with no survey point squares, trees are free of dwarf mistletoe.

By looking at the distribution of mistletoe and it's severity across the analysis area we can get a general idea of the treatment possibilities over the sale area as well as develop general priorities for treatment. For example, yield simulations done in conjunction with the roadside surveys in the Southwest (Hessburg and Beatty 1985) indicate that stands with moderate to heavy mistletoe cannot be managed to rotation without severe volume loss. Thus, if wood fiber production or growing big trees is your management emphasis, your options are probably limited to regenerating the stand. In the lightly infected areas however, an intermediate treatment (thinning, overstory removal etc.) can result in full rotation with little volume loss provided the stand is treated before it progresses to more severe infection levels (Hessburg and Beatty 1985). Besides the level of mistletoe infection and management objectives, priority and specific type of treatment can depend on size of the trees and location of adjacent areas of re-infection both of which can be determined from the dwarf mistletoe layer.

Integrating the mistletoe information with other resource layers such as the wildlife- and the harvest activity layer can also help with analysis and subsequent decision-making. For example, restrictions like wildlife cover requirements and maximum openings for watershed thresholds, can be analyzed and considered together with the need to treat dwarf mistletoe (Figure 2)

Mapping pine engraver risk

Pine engraver beetles (*Ips pini*) are not a problem everywhere on the Reservation. Usually, they only attack live trees where rainfall is 25 inches per year, or less. In these areas where risk is high, there is less flexibility in treatment scheduling and slash disposal. From where the Peter's Spring falls on the rainfall map (Figure 3), it appears we have to moderate our management activities to mitigate for pine engraver only on the eastern half of the sale (although this could change in a exceptionally dry or wet year).

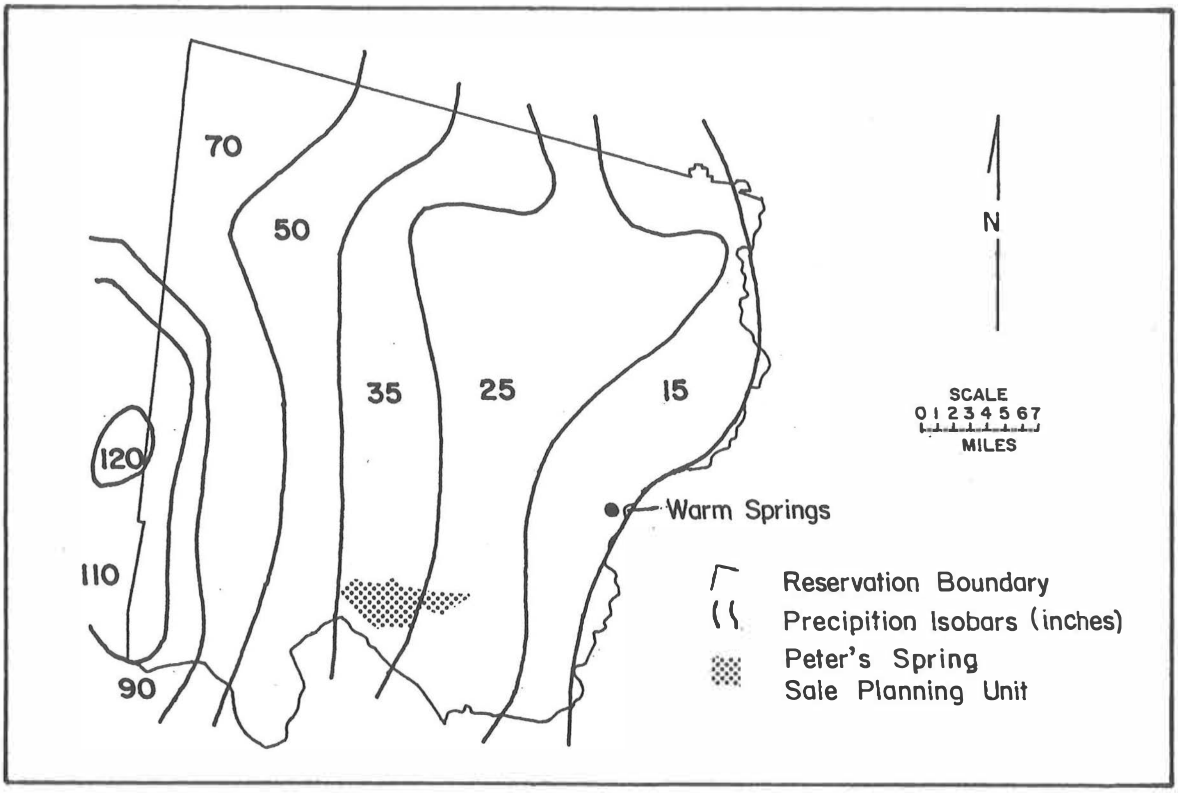


FIG. 3. Precipitation isobars (in./yr.) on the Warm Springs Indian Reservation and risk to pine engraver. Areas with 25 inches of rainfall per year, or less, are at high risk to fir engraver.

Mapping western spruce budworm risk

For another look at the application of risk ratings shift your attention to the mixed conifer and fir/hemlock forest types. Since western spruce budworm (*Choristoneura occidentalis*) defoliation has been a significant and re-occurring pest on the reservation, we developed a site specific defoliator risk map. Stands composed of greater than 30% host species, with high densities and southern exposures have been found to be high risk for western spruce budworm outbreaks on Warm Springs. These attributes are usually derived from the forest vegetation layer. Since this layer will not be installed until 1995 we are, for now, approximating the layer using the CFI plot summary information to predict general areas of high risk to western spruce budworm (Figure 4a). In comparing the risk layer in Figure 4a to present budworm activity (derived from the last two years of aerial survey) in Figure 4b, areas of high risk and budworm activity correspond well. Of course, if possible, the idea is to anticipate stand conditions of high risk; silviculturally treat them to lower the risk and prevent significant defoliator outbreaks!

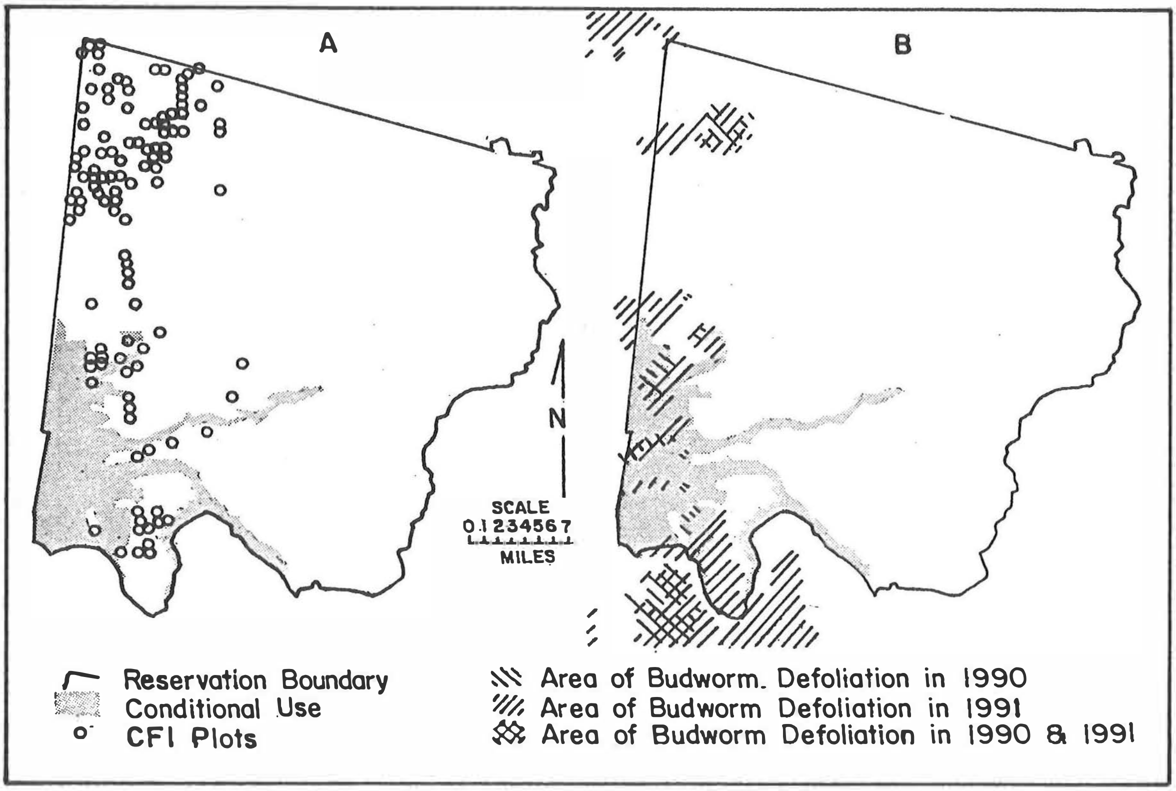


FIG. 4. a. Risk map for western spruce budworm outbreaks(developed using forest inventory plots, each square denotes high outbreak risk and represents about 250 acres); b. Distribution of western spruce budworm defoliation in 1990 and 1991 according to the aerial survey maps.

SUMMARY

In summary, we see the GIS system (complete with all resource layers, including the I&D maps) as a multiresource information system and an investment in the future. In order to perform the high level of integrated resource management required of us, we need tools which can deal with very complex analysis. GIS is such a tool and available to the Warm Springs Confederated Tribes. Once the pest layer is complete, the tribe will have an infinitely better picture of the the importance and role pests are playing in their forest, both at present and under various management scenarios. This will result in more informed land management decisions and a future which is much less likely to contain "unpleasant surprises".

LITERATURE CITED

Hawksworth, F. G. 1977. The 6-class dwarf mistletoe rating system. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-48.

Hessburg, P. F. and J.S. Beatty. 1985. Incidence, severity, and growth losses associated with ponderosa pine dwarf mistletoe on the Kaibab National Forest, Arizona. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 85-13.

Maffei, H. M., J.S. Beatty, and P.F. Hessburg. 1987a. Incidence, severity, and growth losses associated with ponderosa pine dwarf mistletoe on the Cibola National Forest, New Mexico. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 87-8.

Maffei, H. M., J.S. Beatty, and P.F. Hessburg. 1987b. Incidence, severity, and growth losses associated with ponderosa pine dwarf mistletoe on the Prescott National Forest, Arizona. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 87-9.

Maffei, H. M., J.S. Beatty, and P.F. Hessburg. 1987c. Incidence, severity, and growth losses associated with ponderosa pine dwarf mistletoe on the Gila National Forest, New Mexico. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 87-10.

Merrill, L. M., F.G. Hawksworth, and D.W. Johnson. 1985. Evaluation of a roadside survey procedure for dwarf mistletoe on ponderosa pine in Colorado. Plant Disease **69**: 572-573

USE OF A GEOGRAPHIC INFORMATION SYSTEM IN SOUTHERN PINE BEETLE MANAGEMENT

BRIAN M. SPEARS AND WESLEY A. NETTLETON
USDA Forest Service, Forest Pest Management, Region 8, 1720 Peachtree Road, N.W.,
Suite 925 North, Atlanta, Georgia 30367

Abstract. A geographic information system (GIS) is being used for southern pine beetle (SPB) management on the Oconee National Forest in Georgia and the Homochitto National Forest in Mississippi. Data were obtained from several sources including aerial photography, aerial detection surveys, the Southern Pine Beetle Information System, the Continous Inventory of Stand Conditions, and the Primary Base Series for the national forests. Maps were produced for proofing compartment and stand records, showing change in SPB hazard rating, and showing the threat of SPB outbreak to red-cockaded woodpecker colonies. Analysis included acreages of national forest affected within red-cockaded woodpecker zones of various radii, forest-type and age-class acreage calculations, and hazard rating susceptibility of stands to SPB attack. SPB is also one of the insect data layers in the Forest Health Atlas for the Southern Region.

INTRODUCTION

The southern pine beetle (SPB) is the insect most damaging to pine forests in the southeast. Numerous SPB outbreaks have occurred in the past 100 years causing widespread, often spectacular tree mortality for periods of two or more years. Such losses have upset management plans and reduced potential yields from managed forests.

In 1988, the USDA Forest Service established the SPB Demonstration Area Project on the 110,000 acre Oconee National Forest in Georgia and the 97,000 acre Homochitto National Forest in Mississippi. Both forests had experienced chronic SPB problems over the past twenty years. The project goal is to demonstrate how sound forest management practices and control strategies can minimize SPB and other pest-caused damage while still achieving overall management objectives (Nettleton, 1988). Emphasis is placed on utilizing available technology developed by research and integrating it into routine resource management.

DATA SOURCES

Forest Pest Management personnel in the Southern Region integrated several major databases into a geographic information system (GIS) to assist in the management of the Oconee National Forest in Georgia and the Homochitto National Forest in Mississippi. We obtained information on the location of SPB spots from aerial photography and aerial detection surveys. The Southern Pine Beetle Information System (SPBIS) and the Continuous Inventory of Stand Conditions (CISC) are large relational databases which have been tied to the stand and compartment boundary information implemented in the GIS. Development of the national forest GIS for these demonstration forests was completed according to the Region 8, GIS Implementation Plan (Dull, et al., 1989). The national forest primary base series (PBS) data provide the background for resource management. They include ownership, lakes and streams, roads, and stands and compartments. These data are organized in map libraries in our GIS, and we use them to produce maps of various scales such as page size, 1:24,000 7 1/2 minute overlays, or forest-wide maps at 1 inch per mile or 1/2 inch per mile.

Pages 15-24 *in* A.M. Liebhold and H.R.Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

DATA ANALYSIS AND PRODUCTS

An example of a page size map showing a forest compartment is shown in Figure 1. We produced similar maps for all compartments on both forests, and used them to proof compartment and stand records. They display both PBS and CISC data. We found it much easier to see errors when data were graphically displayed as compared to looking for errors in tabular information.

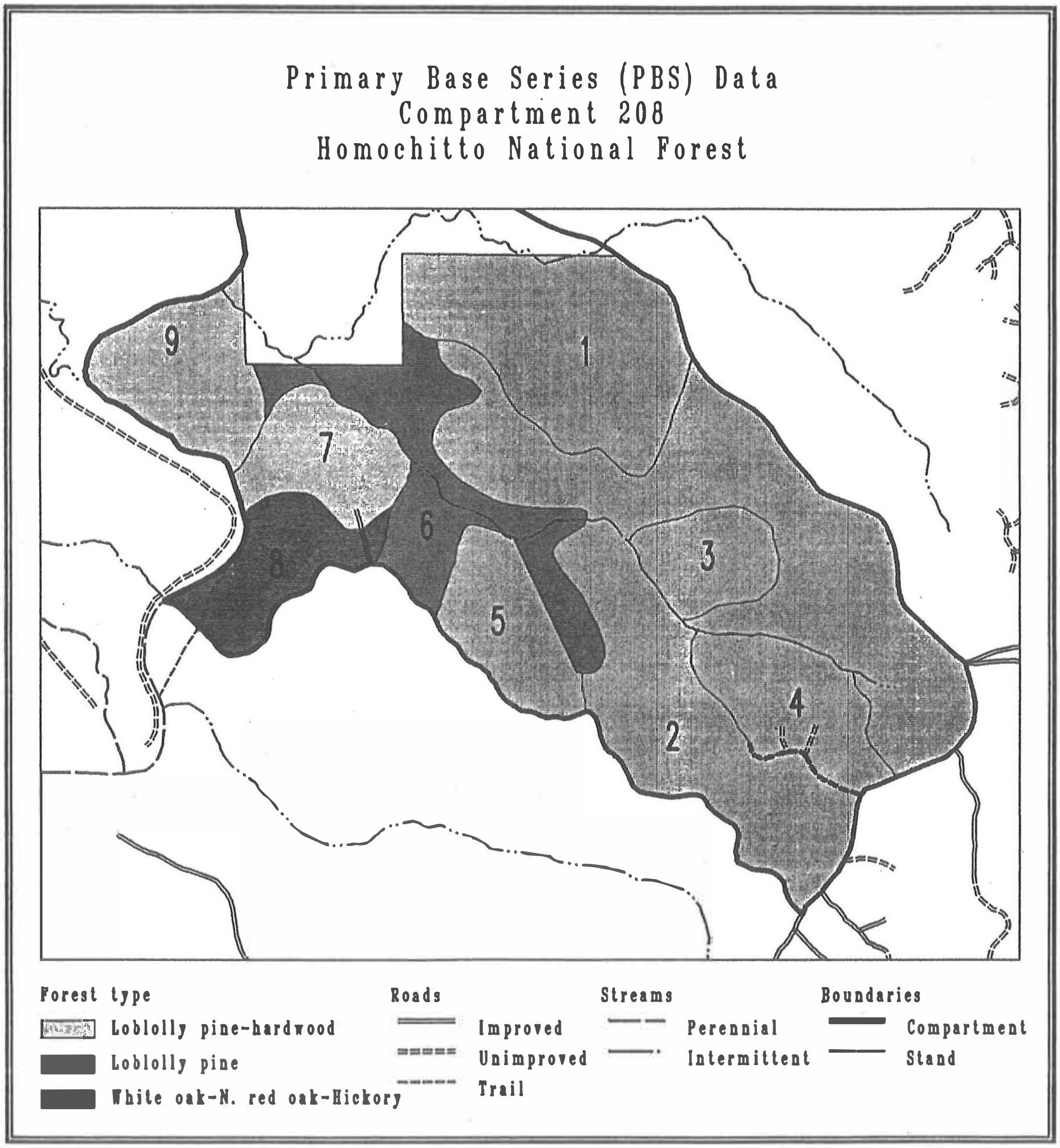


FIG. 1: Forest Types, Roads, Streams, and Stands for Compartment 208 of the Homochitto National Forest, Mississippi.

The GIS can be used to calculate acres or timber volume set aside for special uses much more quickly than conventional methods. Figure 2 shows one compartment from a ranger district map that was originally made at 1 inch per mile. We displayed SPB spots in relationship to red-cockaded woodpecker (RCW) colonies, and drew a 1/2 mile RCW foraging boundary around RCW colonies.

Understanding the relationship between SPB and RCW is important because the woodpecker nests in live pines which are susceptible to SPB attack. Figure 3 shows the acreage of national forest ownership affected if 1/4 mile, 1/2 mile, or 3/4 mile RCW foraging zones are allocated. Acreages for zones of other radii could be calculated in a matter of minutes if the above three were found to be inadequate for any reason.

Acres of general forest type (Figure 4), acres of each forest type (Figure 5), or acres of a forest type by age class (Figure 6) as well as other combinations can be quickly calculated. We used these types of analyses to hazard rate susceptibility of stands to SPB attack, and to map the hazard rating (Figures 7 and 8). Stand susceptibility was reduced after silvicultural treatments were applied. We mapped the changes in susceptibility following silvicultural treatments and updated the forest inventory data (Figures 9 and 10).

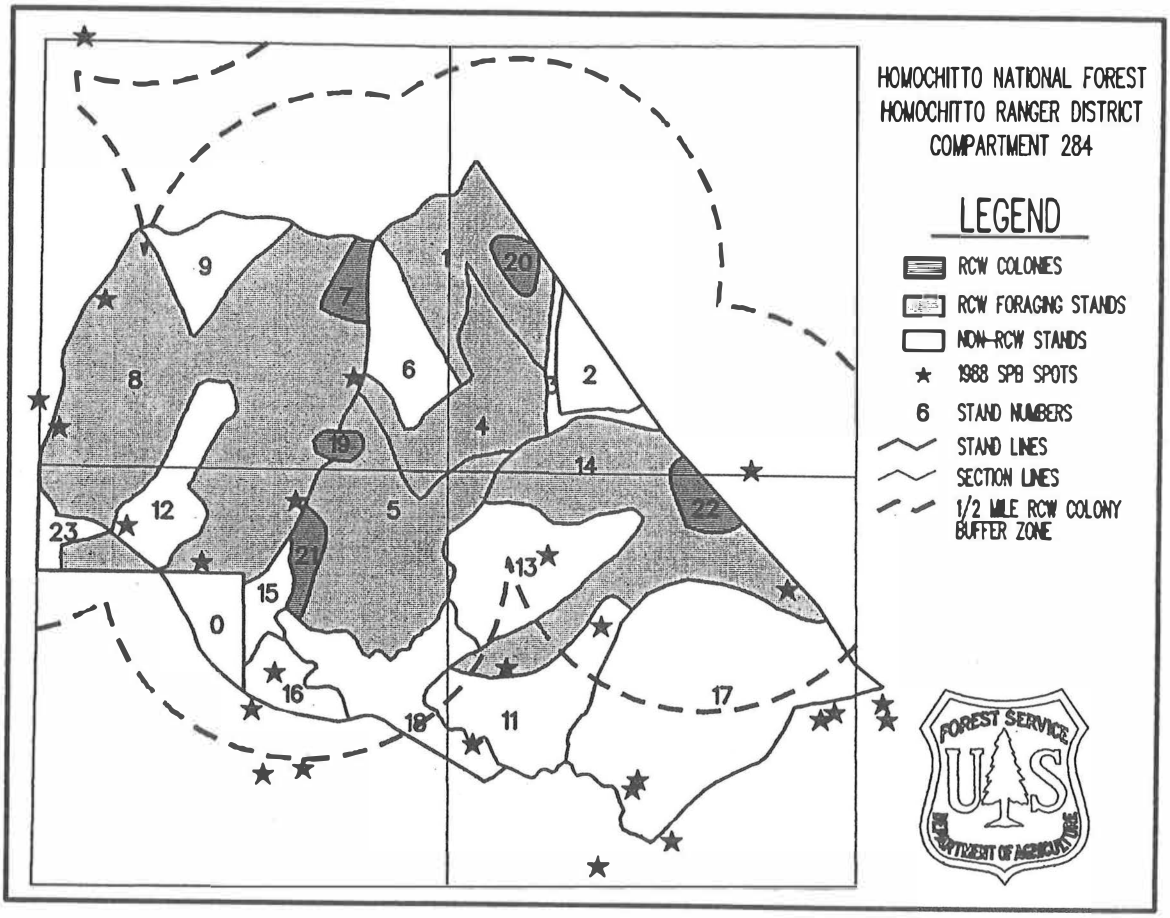


FIG. 2: Southern Pine Beetle Spots and Red-Cockaded Woodpecker Activity in Forest Compartment 284, Homochitto Ranger District, Homochitto National Forest.

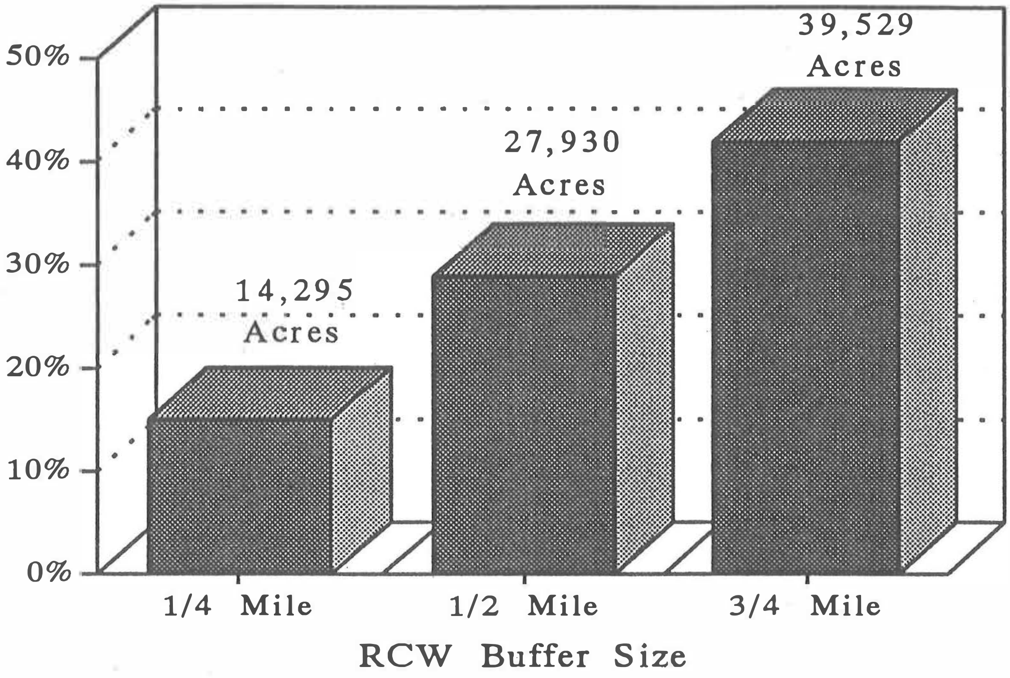


FIG. 3: Acreage of National Forest Ownership Affected on the Homochitto Ranger District, Homochitto National Forest, Mississippi, within 1/4, 1/2, and 3/4 Mile Red-Cockaded Woodpecker Buffer Zones.

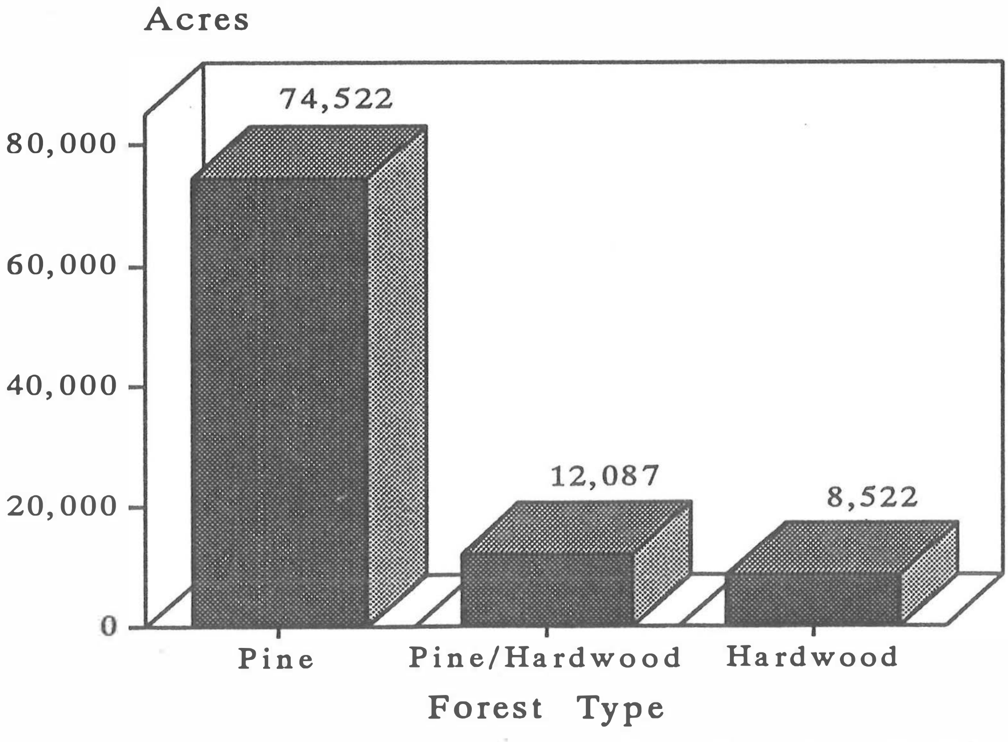


FIG. 4: Acres of General Forest Type on the Homochitto Ranger District, Homochitto National Forest, Mississippi.

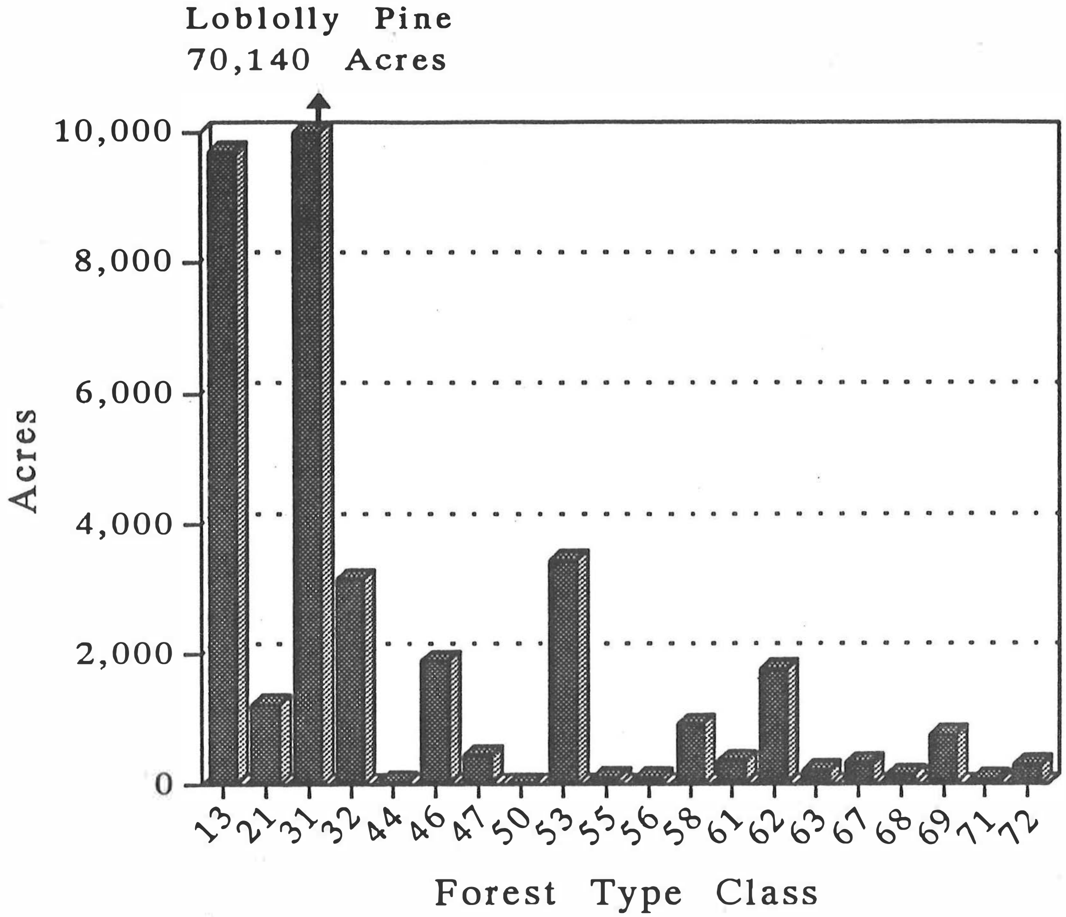


FIG. 5: Acres of Each Forest Type on the Homochitto Ranger District, Homochitto National Forest, Mississippi.

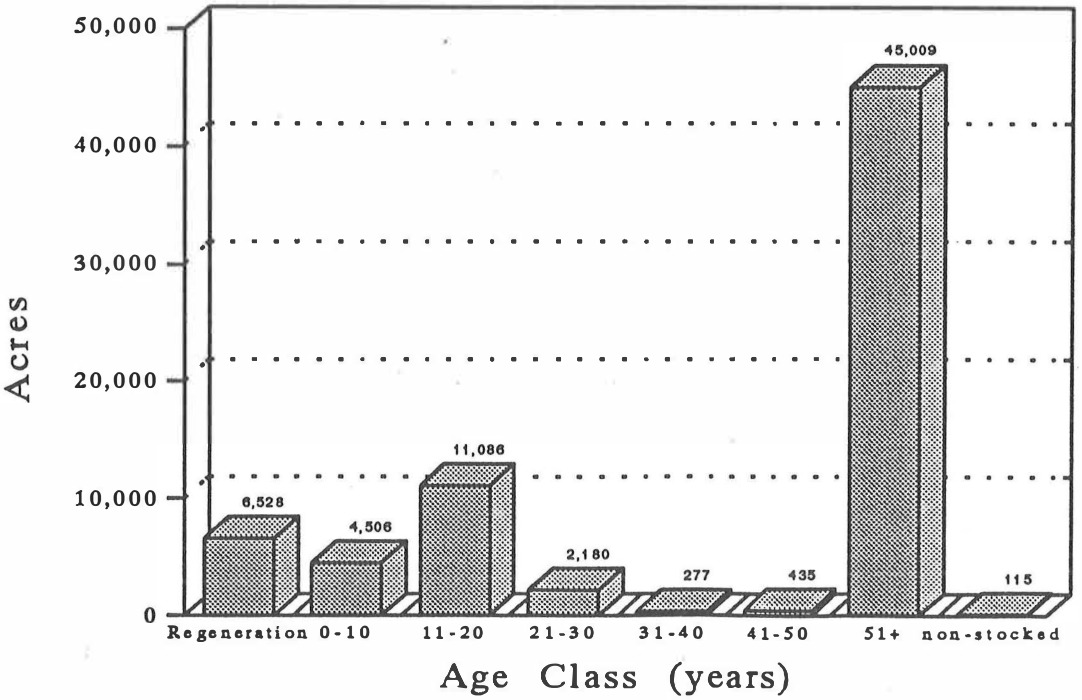


FIG. 6: Acres of Loblolly Pine by Age Class on the Homochitto Ranger District, Homochitto National Forest, Mississippi.

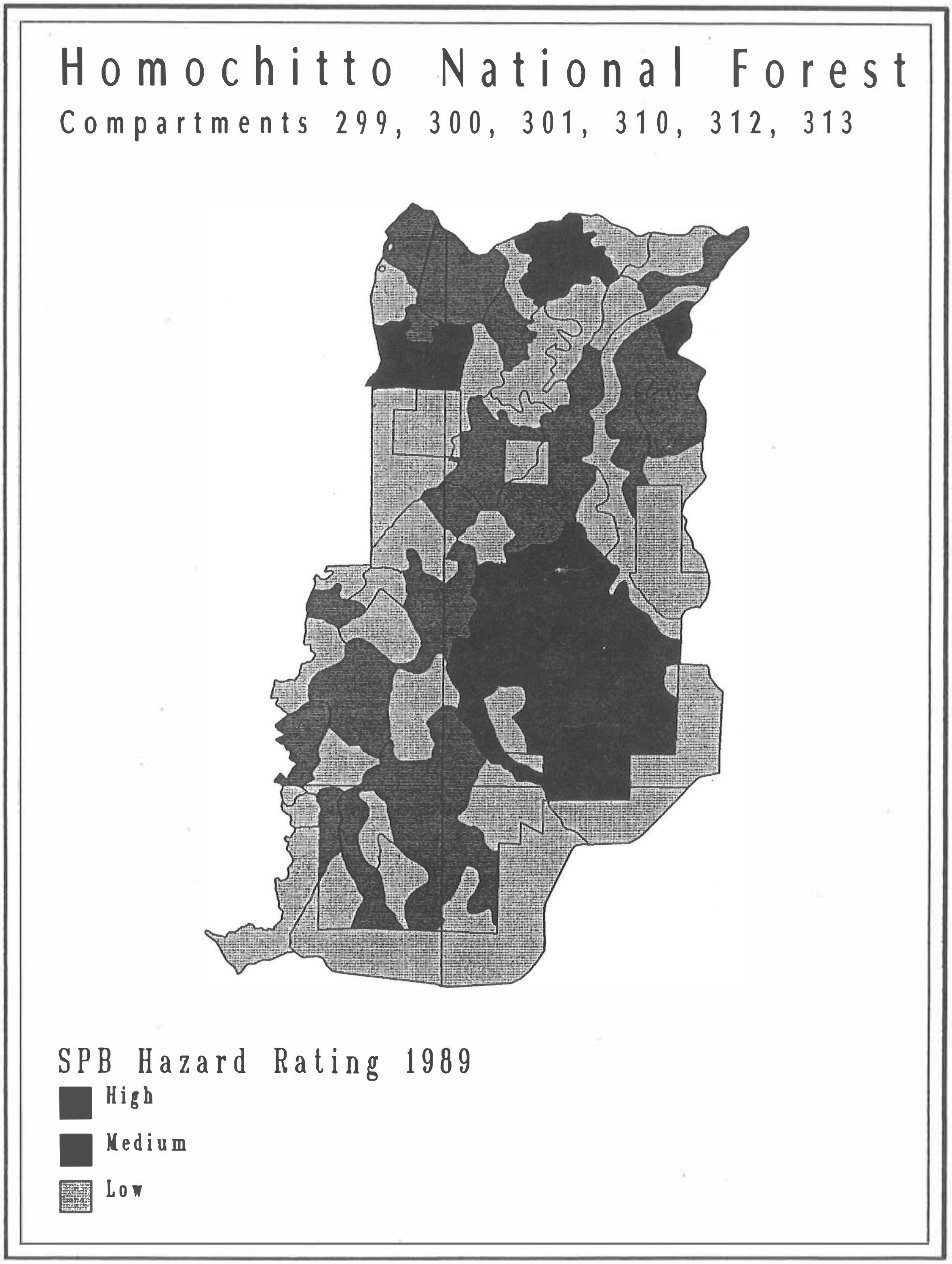


FIG. 7: 1989 Southern Pine Beetle Hazard Rating for Selected Forest Compartments on the Homochitto National Forest, Mississippi.

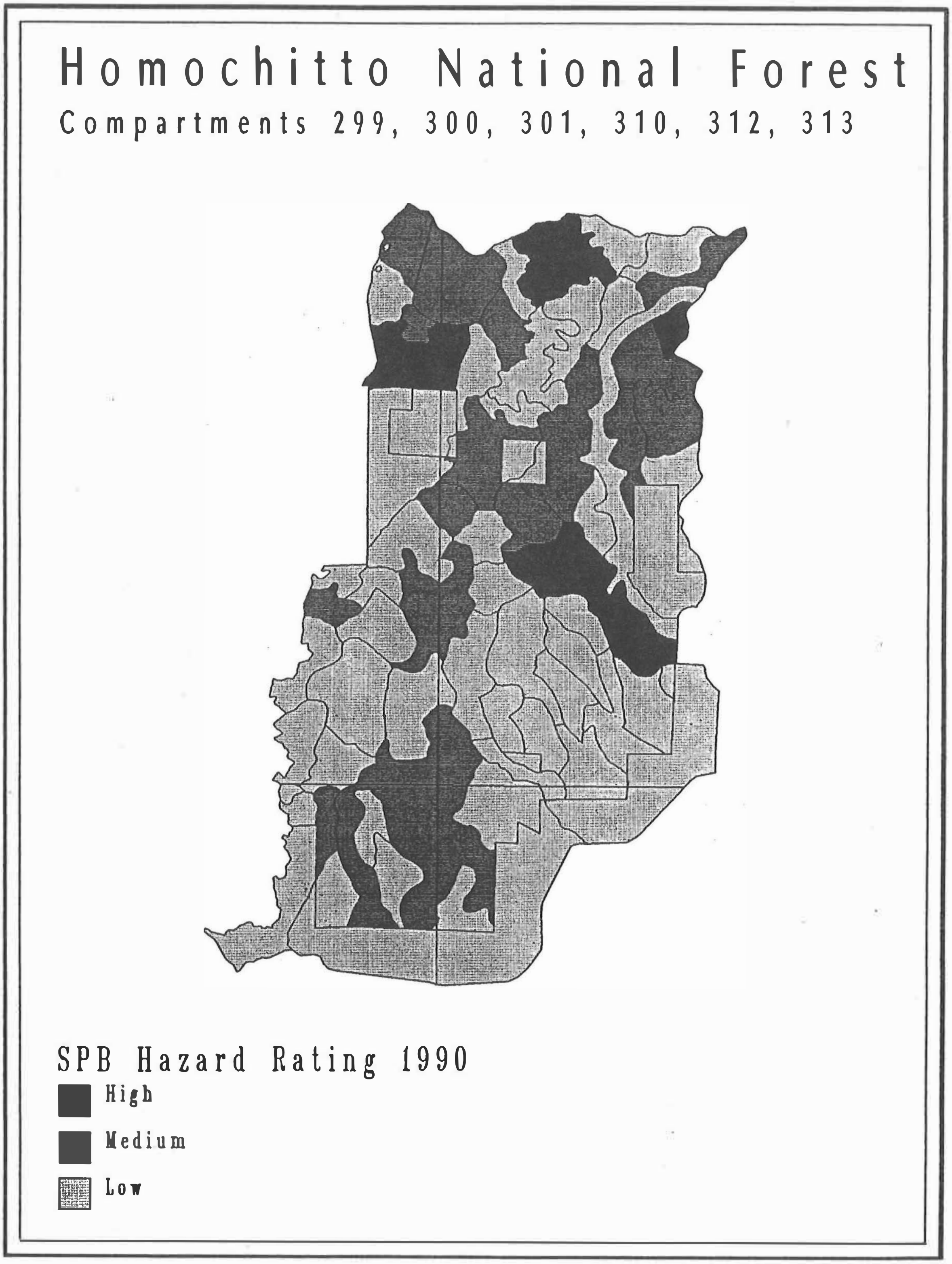


FIG. 8: 1990 Southern Pine Beetle Hazard Rating for Selected Forest Compartments on the Homochitto National Forest, Mississippi.

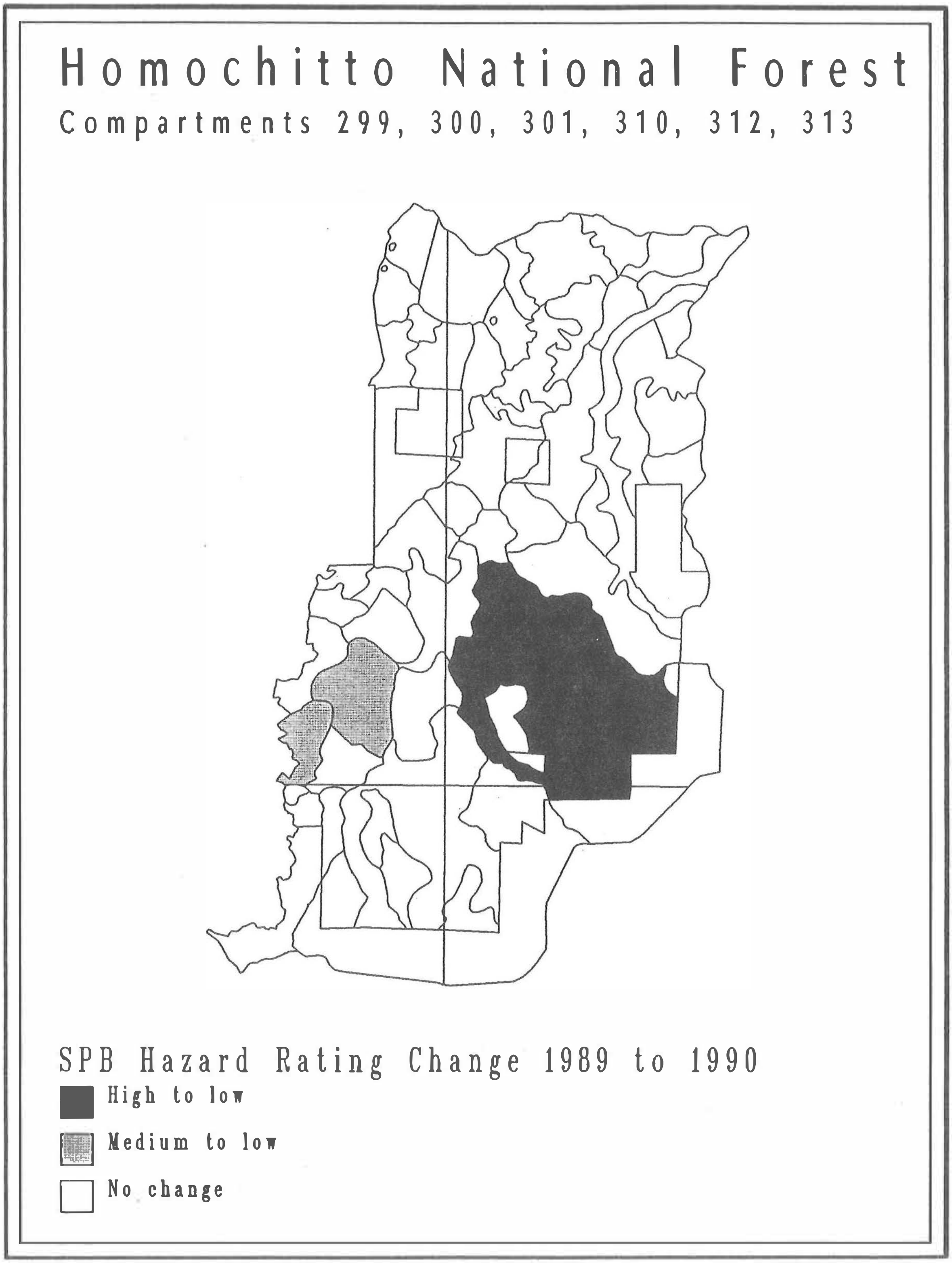


FIG. 9: Change in Southern Pine Beetle Hazard Rating Between 1989 and 1990 for Selected Forest Compartments on the Homochitto National Forest, Mississippi.

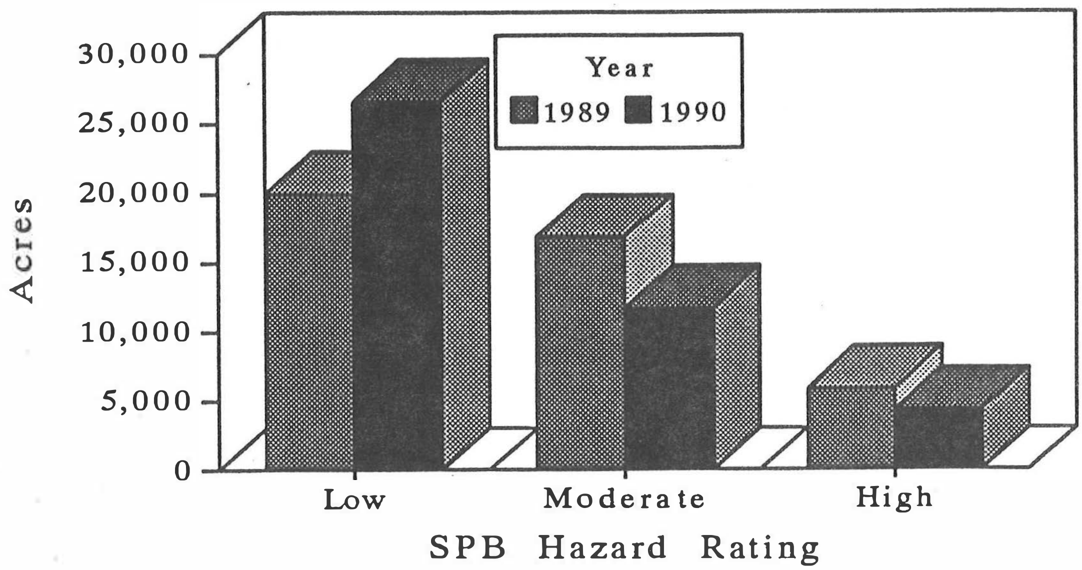


FIG. 10: Change in Southern Pine Beetle Hazard Rating Between 1989 and 1990 for the Homochitto National Forest, Mississippi.

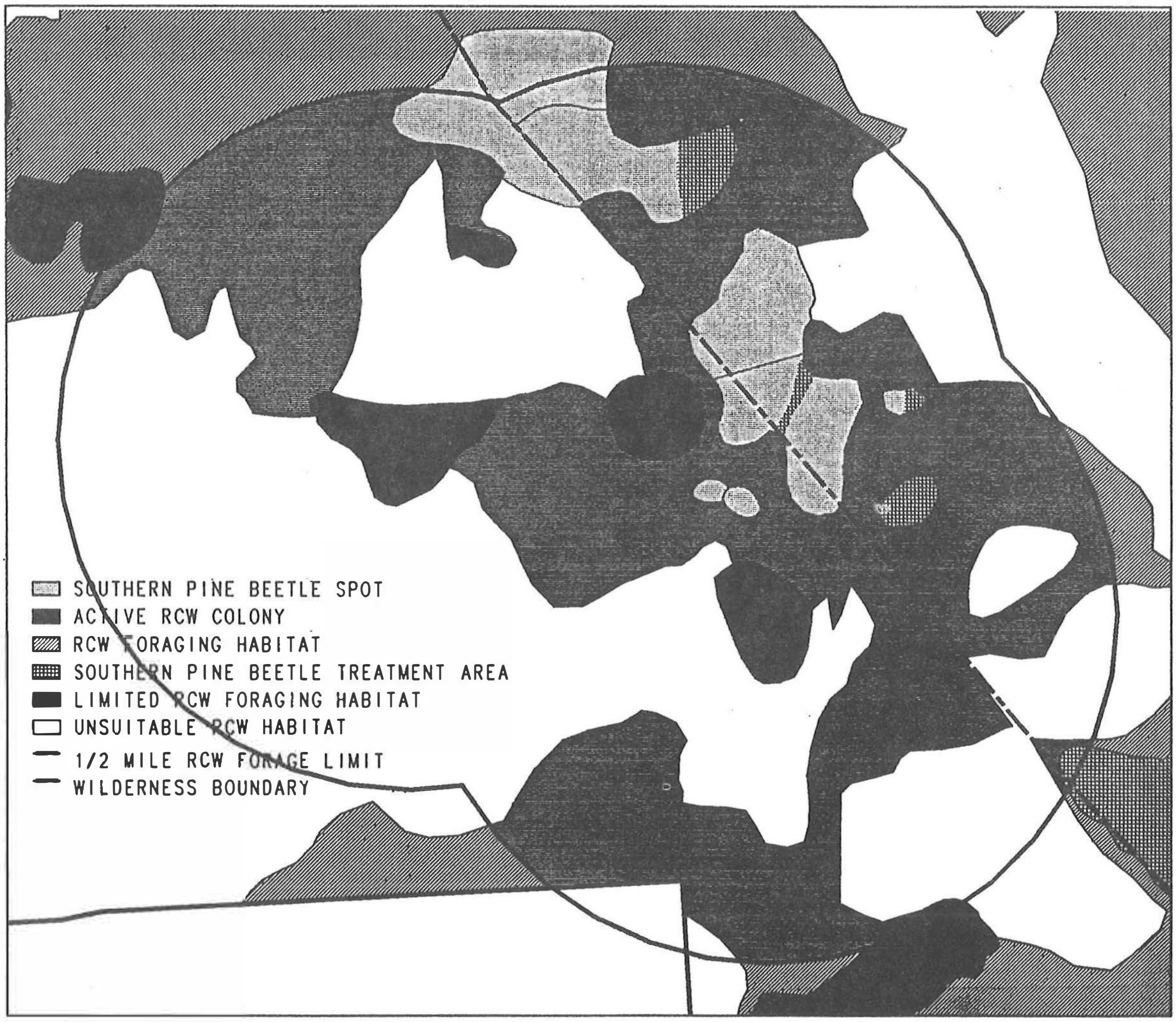


FIG. 11: Southern Pine Beetle Spots Threatening Red-Cockaded Woodpecker Colonies in the Little Lake Creek Wilderness in Texas.

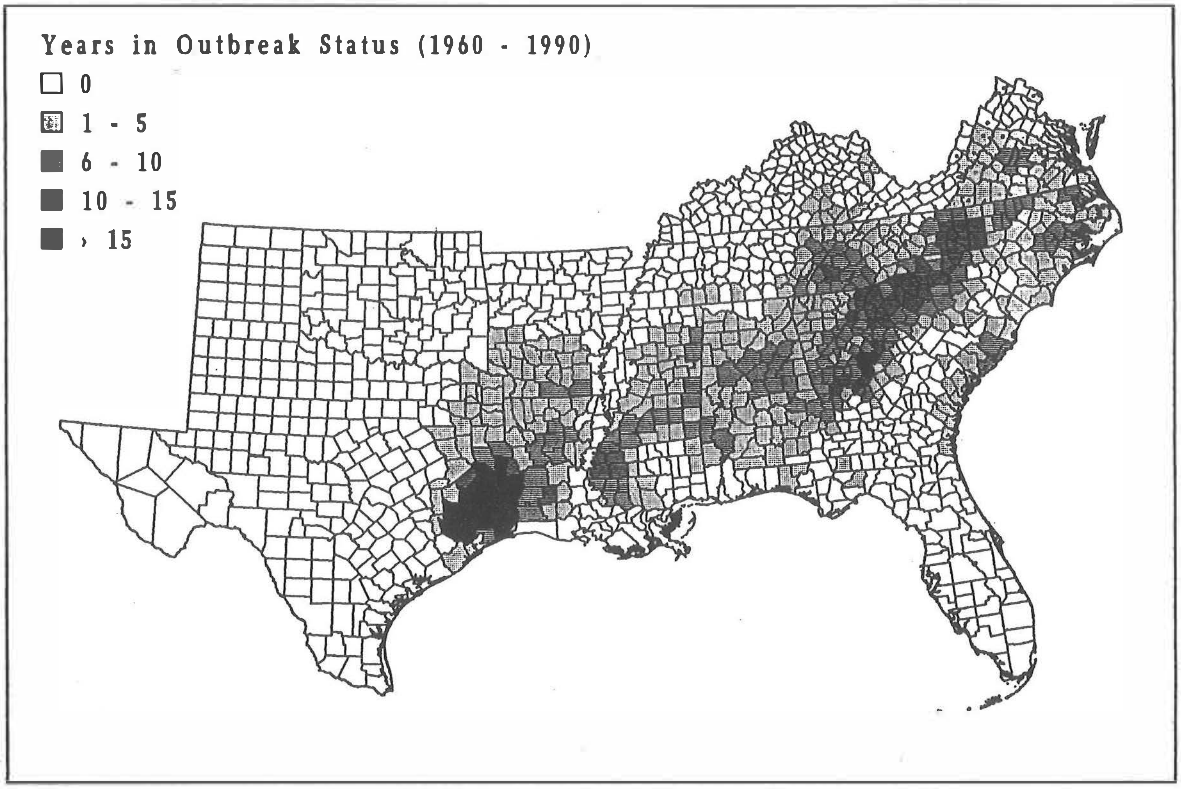


FIG. 12: Number of Years in Southern Pine Beetle Outbreak Status Between 1960 and 1990 for each County in the Thirteen Southeastern States.

One incidence illustrating the importance of analyzing data and producing graphics quickly was demonstrated when a SPB outbreak threatened RCW colonies within the Little Lake Creek Wilderness in Texas during 1990. The RCW must be protected according to the Endangered Species Act. The wilderness must be protected according to the Wilderness Act. We needed to cut SPB infested trees in the wilderness to protect the RCW so these two Acts would have been in conflict except thier is a provision in the Wilderness Act allowing treatment of pest outbreaks in wilderness areas. Therefore, the action chosen was to treat the SPB spots. We needed to treat the spots within a couple of weeks to keep them from spreading into RCW colony trees. Using the GIS, we quickly produced a map identifying which RCW colonies were threatened (Figure 11). The project resulted in successful treatment of SPB spots in the wilderness area and protected of the RCW colonies. We could not have produced the map in time to protect the colonies without the GIS.

We also have insect layers in the Forest Health Atlas for the Southern Region. Figure 12 shows southern pine beetle occurrence by county in the southern region. Tree stressors such as ozone, drought, fire, etc. which are in the Atlas can be analyzed in relation to SPB outbreaks.

LITERATURE CITED

Dull, C.W., R. Mead, E. Yockey, W. Clerke, R. Heins, J. Ashby, and R. Johnston. 1989. Geographic information system implementation plan, Region 8. USDA Forest Service, Atlanta, GA.

Nettleton, W. 1988. SPB update: southern pine beetle demonstration areas. USDA Forest Service, Atlanta, GA.

AIPM: A PROJECT DEMONSTRATING A GIS-BASED MONITORING SYSTEM FOR GYPSY MOTH

E. A. Roberts and F. W. Ravlin
Department of Entomology, VPI&SU, Blacksburg, VA. 24C61

Brian M. Spears
USDA Forest Service, 1720 Peachtree Road, N.W., Suite 925 North,, Atlanta, GA. 30367

Abstract. The Appalachian Integrated Pest Management Demonstration Project, a large gypsy moth pest management program, is survey intensive. Among the uses of GIS in the project is providing support for collection of male moth and egg mass data. In pheromone trap surveys for male moths, the GIS assists with management of trapping personnel as well as with quality control of survey data. Maps of male moth data are used to assist in determination of areas to survey for egg masses while maps of egg mass densities are used in delineation of potential intervention areas. Many aspects of the GIS are production-oriented and highly automated. The GIS/DBMS is centralized and future projects of this magnitude should consider a distributed system.

INTRODUCTION

Gypsy moth is a serious defoliator of oaks and other hardwoods in forested and residential areas of the northeastern and, more recently, eastern United States. Since its accidental release from Medford, Massachusetts in 1869, the insect has continued its inexorable spread south and west at a rate of several miles per year. The Appalachian Gypsy Moth Integrated Pest Management (AIPM) Demonstration Project is a large 5-year program begun in 1988 designed to use novel and existing management strategies to deal with this insect within 12.8 million acres in Virginia and West Virginia (Fig. 1). It is funded through the US Forest Service and involves several federal, state, and county agencies. Among the objectives of the program are: 1) minimize the spread and adverse impacts of gypsy moth within the project area, 2) develop a prototype integrated pest management program which can be implemented in areas outside the project, and 3) evaluate intervention methods for management of isolated and low-level populations. Over the lifetime of AIPM, a geographic information system (GIS) has proven to be a useful tool in many of the various program activities which comprise the workings of the project.

As a rule, population monitoring is a crucial component of IPM programs, and AIPM is no exception. Surveys for male moths and for egg masses account for a large portion of program resources and form the basis for most management decisions. This paper will discuss the use of GIS in providing support for the monitoring component of AIPM. We will discuss the use of GIS in a variety of aspects of the routine monitoring process, how the GIS has proven to be an effective tool for personnel management during periods of intense field activity, and how GIS assists in developing management strategies for areas of low-level populations.

AIPM GIS STRUCTURE

The AIPM GIS consists of Arc/Info software installed at four separate locations: USFS regional offices in Morgantown, WV; the Department of Geography and Geology at West Virginia University in Morgantown; USFS offices in Atlanta, GA; and the Department of Entomology at Virginia Polytechnic Institute and State University (VPI&SU) in Blacksburg, VA. Although each regional location assumes different responsibilities, activities typically are coordinated among the four groups. Because the AIPM data base is managed at VPI&SU, we at that institution have coordinated GIS efforts aimed at monitoring and data representation for management decisions.

Pages 25-36 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

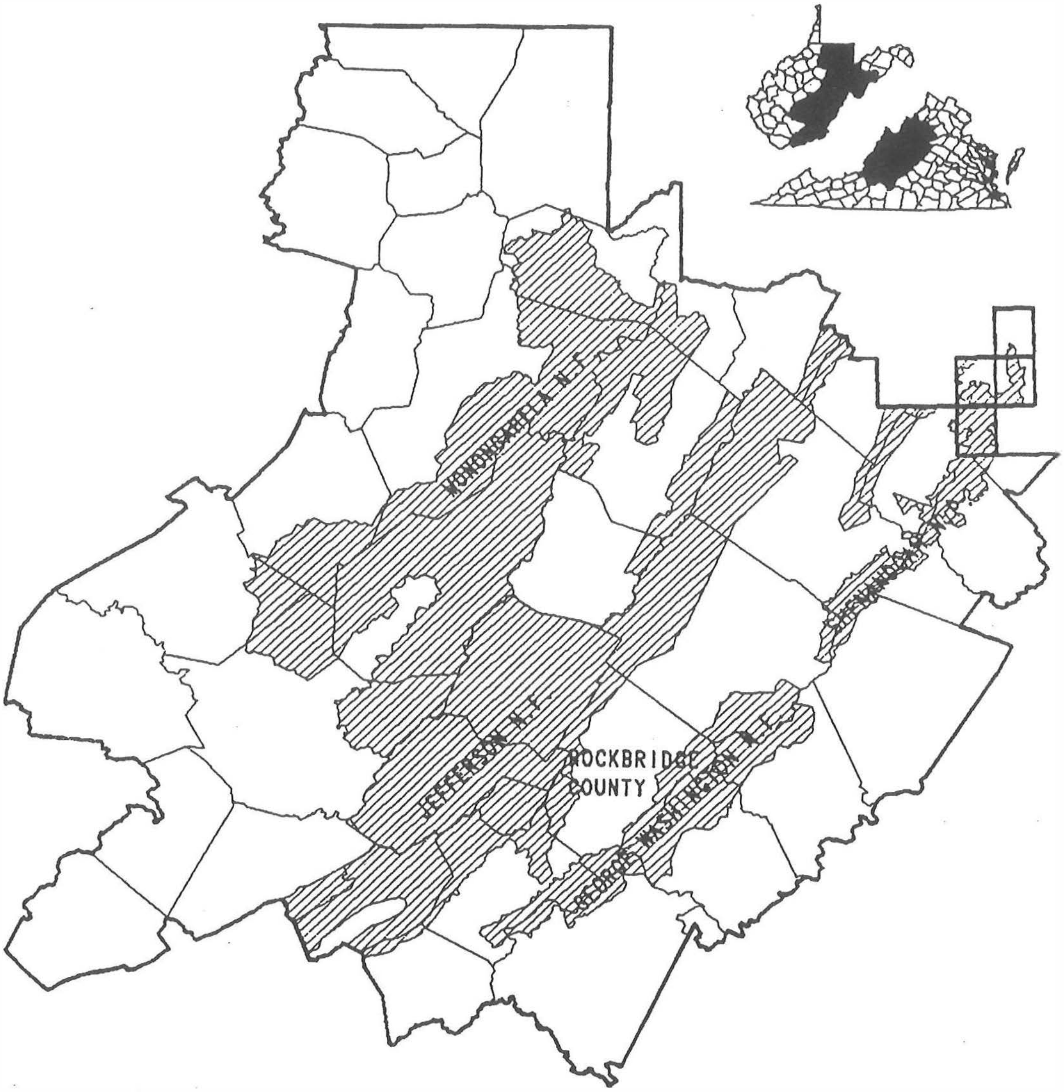


FIG. 1. The AIPM Project area. From Young, et al. 1991.

The emphasis of the AIPM GIS in support of monitoring activities has largely been on simplicity, and most maps involve no true GIS modelling. The philosophy associated with map production during the sampling phase of the program is to provide managers with information on what is happening on the ground and to let them make decisions based on that information. Many maps simply are depictions of point locations (sample sites) and their associated information, which is the type of information field personnel require most during the time when a survey is in progress. An advantage of these typse of maps is they are relatively easy and quick to produce and to interpret, which is important in rapid turnaround of data.

DATA FLOW AND AUTOMATION

Gypsy moth data are collected in the field on mark-sense forms and are mailed to VPI&SU. Each week the data are optically-scanned into the AIPM data base which is written in SPIRES data base management language on a large IBM mainframe computer. Positional data are recorded on the forms as UTM coordinates. After each weekly update flat files are created from the data base and transferred to a MicroVax 2000 which houses the GIS.

Essentially all operations which are performed more than once during the field season are automated with computer programs written in Arc/Info's macro language (AML). These include weekly creation of the point coverages and of the many types of maps produced over the season.

Map production at VPI&SU is limited by a lack of access to plotting devices suitable to production of large numbers of hardcopy maps. While maps produced on the available pen plotter are of good quality, it is not feasible to generate many copies of maps on this device. Thus, maps produced at VPI&SU are those requiring few copies (1 to 5) or are in a format which can be photocopied and distributed. Applications requiring production of tens or hundreds of maps are managed by sending digital files on tape to GIS operations in Atlanta, GA where they are plotted on an electrostatic plotter.

MALE MOTH SURVEY

Monitoring of male gypsy moths is accomplished through the use of pheromone-baited traps placed in the field prior to moth flight. Traps are placed on a regular grid in late spring and early summer. In West Virginia, traps are placed three kilometers apart while in Virginia traps are spaced every two kilometers. Traps in some areas are more closely spaced when higher resolution is needed to delimit populations or to assess treatment efficacy.

As a result of trapping on a regular grid, male moth data are essentially evenly-spaced across the entire project area. This uniform spatial distribution helps to make interpretation, analysis, and representation fairly straightforward.

PERSONNEL MANAGEMENT

Each year, approximately 175 field personnel, including trappers and supervisors, are involved in placing approximately 12,000 male moth traps within the AIPM region. These traps are placed within 38 counties in two states on federal, state, and private lands. The logistics of managing such an enormous field effort is compounded by the fact that different political jurisdictions have different management structures for field efforts. Often it is difficult for supervisors to maintain sufficient awareness of the spatial characteristics of trap placement, a situation which can lead to omission of traps in some areas or duplication of effort in others.

In attempts to prevent some of these problems, weekly data base updates include production of simple maps which depict locations of traps placed or monitored as the season progresses. Figure 2 depicts a map which provides trap location information relative to particular USGS quadrangles within a portion of the AIPM area. The project area is divided into seven regions which provide managers with more detail of their areas. Maps are made on 8.5 by 11 inch paper which facilitates handling. Figure 3 illustrates a series of small scale maps for the period of trap monitoring and removal for the entire project area. Managers readily notice those areas which have not been monitored and can investigate the causes of such neglect. Similar maps are produced during the time when traps are being placed in the field. Computer programs in Arc/Info are used to generate plot files of these maps which can then be either screen-dumped individually or plotted together on one large sheet of paper.

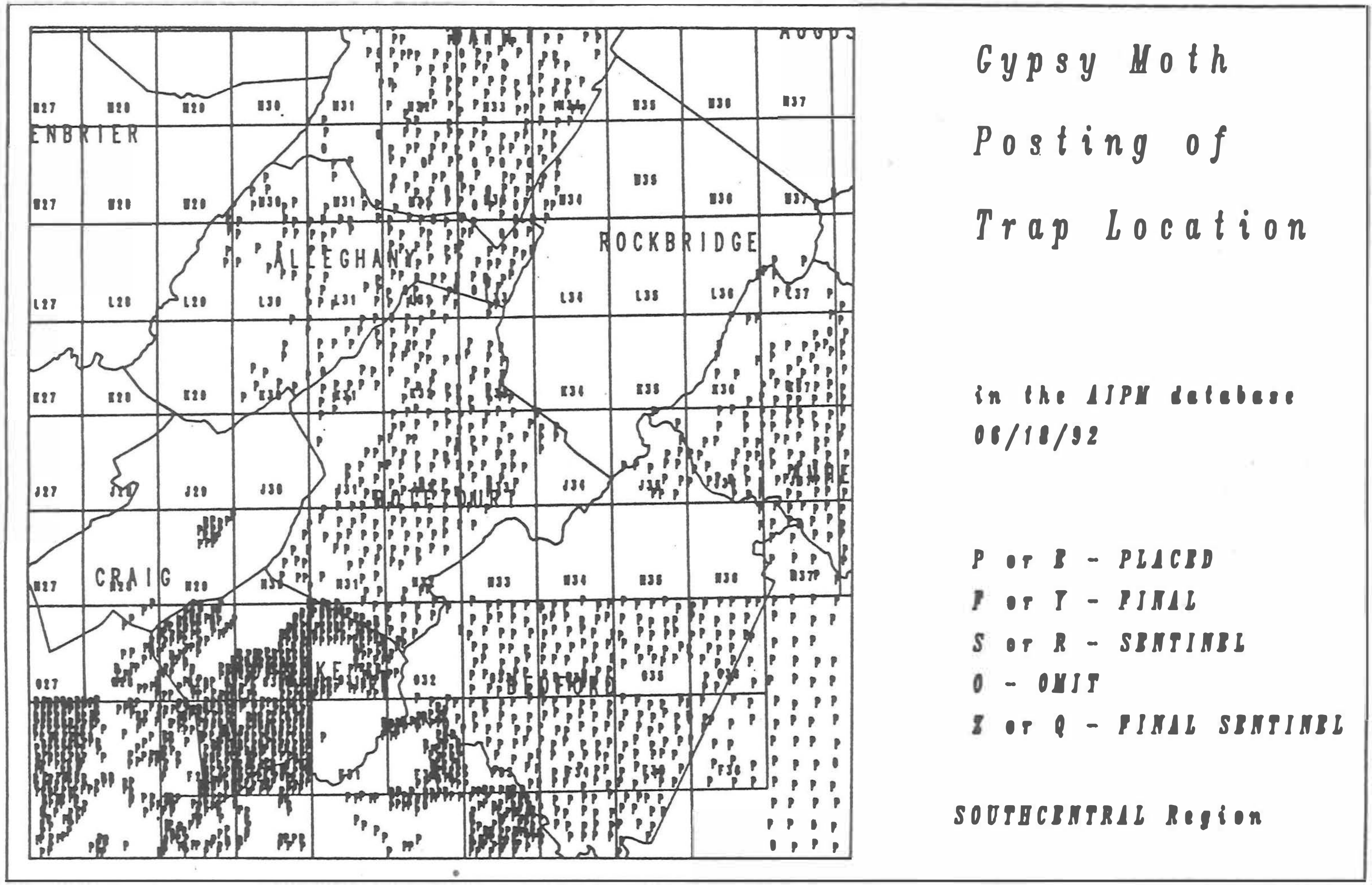


FIG. 2. Map of pheromone traps placed in early summer. Seven such maps are produced which represent the entire area.

FIG. 3. Map of pheromone trap and removal within the entire project area from August 28, 1989 through September 28, 1989.

Whenever possible, the GIS is used to respond to special situations which arise in the field and have a spatial component. For example, in 1990 there were a few areas in which traps were placed later in the season than desired. This precipitated concern that traps in these areas would not adequately represent moth populations because of the chance that first flight had occurred prior to placement. In response to this, we produced a simple map of trap placement sites with colored symbols corresponding to placement date. Field supervisors used this map as a subjective guide when interpreting moth catch at these sites.

MAPS OF MALE MOTH DATA

Logistically, nearly all monitoring activities in AIPM are associated with USGS 1:24,000 scale quadrangles. Maps of male moth survey data are created at this scale and used to assist in determining those areas in need of egg mass surveys (Fig. 4). At each pheromone trap site, catch values are posted along with information about trap monitoring procedures at that site. An interpolated surface of moth catch is represented as contour lines, often referred to as "isomoths". As a general guideline, any 1 km^2 cell wholly or partly within a 500 moth or greater contour interval is a candidate for egg mass surveys. Data themes which provide additional information include the previous year's egg mass survey locations with presence/absence of egg masses and a measure of yearly change in male moth catch values. Yearly change in pheromone trap catch is derived by associating the current year's catch with an interpolated catch at that same location from the previous year. A simple proportional increase or decrease is calculated and depicted on the map as a surface where each 1 km^2 contains a value for yearly change. Because maps are at 1:24,000 scale, field supervisors often overlay these maps onto USGS quad sheets on a light table.

Because of the large number (ca. 150) of maps produced during each field season, it is not feasible to plot them at VPI&SU. The computer programs which generate the digital map files were constructed to produce files compatible with the electrostatic plotter used by USFS operations in Atlanta. Digital maps are created at VPI&SU, written to tape, and mailed to Atlanta for hardcopy production and distribution.

Project-wide maps of moth catch are produced from interpolated surfaces of pheromone trap catch. These surfaces, termed lattice-polygons, are derived by first creating a triangulated irregular network (TIN) from the point data and then generating a raster surface of cells each having a categorical value for moth catch. Cell size is 500 meters and categories corresponded to management action thresholds. Whereas the 1:24,000 scale maps are designed to assist in survey and treatment decisions at the field level, these small scale maps are used most often to illustrate general population patterns within and among years (Fig. 5). Those interested should see Roberts *et al.* (1993) for more detailed discussion of surface representations of AIPM data.

EGG MASS SURVEY

Unlike monitoring for male moths where traps are placed on a predetermined grid over the entire project, surveys for egg masses are conducted only in areas which meet specific criteria. These are areas determined as a result of male moth data, landowner reports, intervention activities or some other method of prioritization. Egg mass samples are collected using a sequential sampling method devised by Fleischer et al. (1991). In areas selected for sampling, four to ten samples are taken in each 1 km^2 cell. Egg mass samples thus have a very clumped spatial distribution (Fig. 6) which makes some types of map representations involving interpolation more problematic than those for the evenly distributed male moth data (Fig. 3).

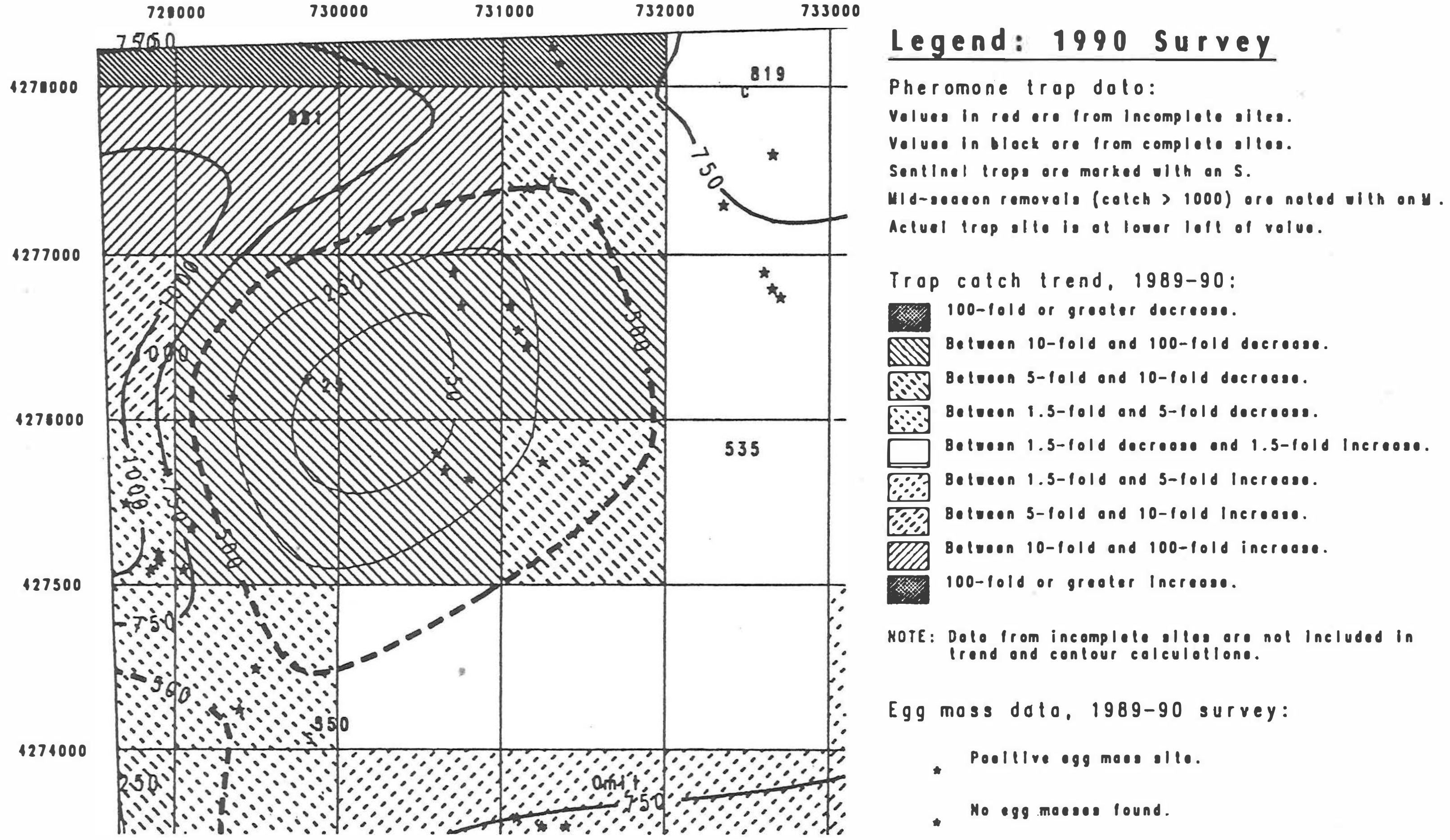


FIG. 4. A portion of a 1:24,000 scale map of male moth trap catch. Data layers include catch values, contours of catch, a measure of yearly change, and previous egg mass sample sites. The actual maps are in color.

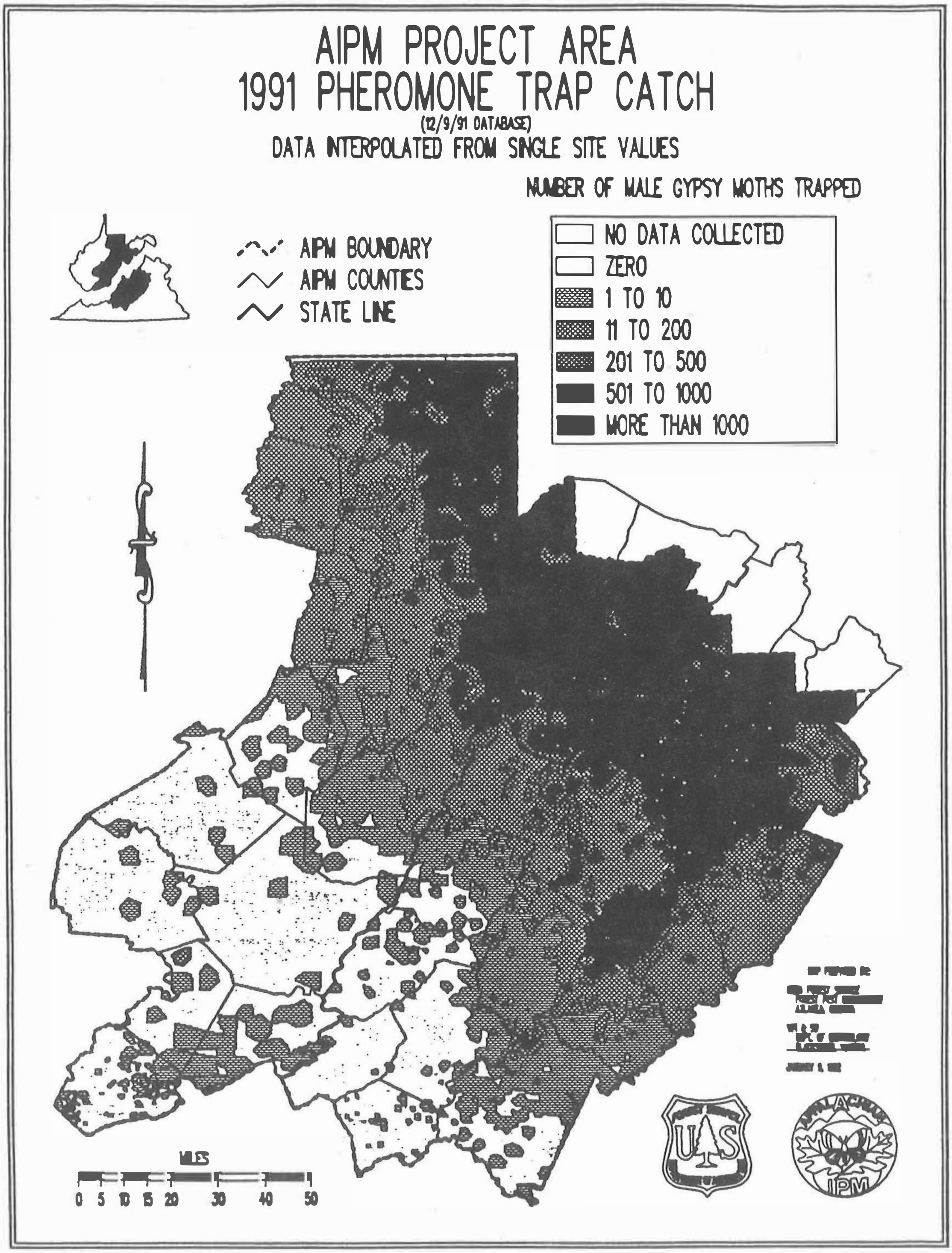


FIG. 5. Male moth catch over the entire project area. The representation is a lattice-polygon surface interpolated from a TIN of the sample data.

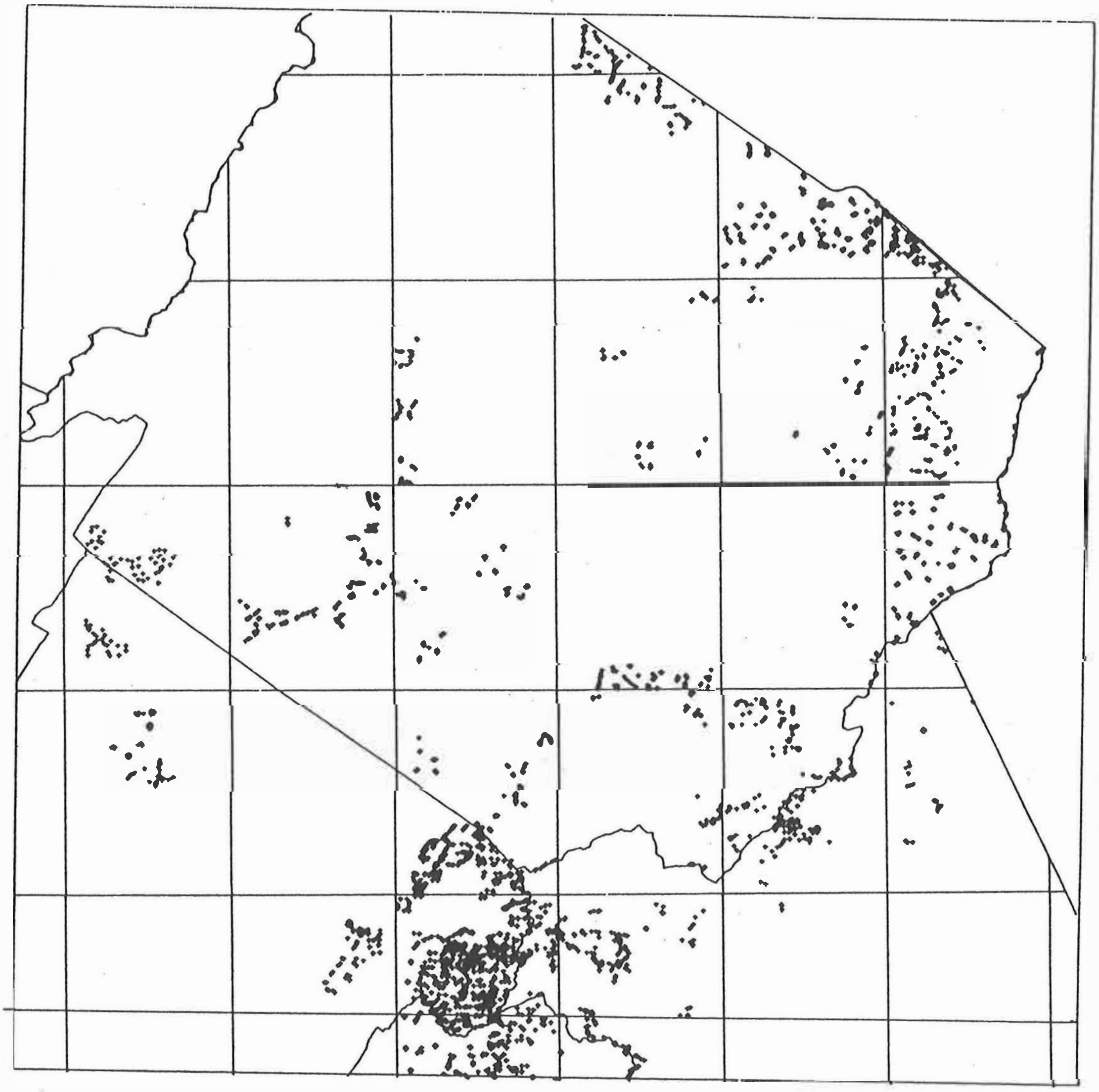


FIG. 6. Portions of Augusta, Rockbridge, and Nelson Counties in Virginia showing the clumped nature of egg mass sample sites. Data are from the 1991-92 egg mass survey.

Initial attempts at producing 1:24,000 scale maps of egg mass data analogous with the male moth maps proved frustrating. We felt uncomfortable interpolating across large unsampled areas, which occurred when interpolating from the TIN of the egg mass data. The displays of both the yearly change and egg mass sample surfaces were restricted to areas within 500 m of a sample site, but the resultant maps proved too complex to be easily interpreted. For this reason, as well as the long computation time (over 2 hours per map) and suggestions from the field, we opted for a simpler map showing only egg mass sample data and the most recent defoliation and treatment polygons. The lesson was one which anyone doing GIS will find familiar: just because you **can** do something in a GIS it doesn't mean that you necessarily **should** do it.

Unlike for the male moth survey, data base managers at VPI&SU have no means of knowing when a quadrangle is complete in terms of egg mass surveys and thus ready to map. For this reason, production of 1:24,000 egg mass maps is initiated upon the request of the field supervisor responsible for the area considered.

During the egg mass surveys, it often is necessary to provide maps to the field before the 1:24,000 scale maps are distributed. These "quick and dirty" maps depict political and USGS quadrangle boundaries, defoliation and treatment polygons, and egg mass sample values. They are produced at VPI&SU on a pen plotter and provide managers with relatively quick access to their data.

Like the display of the male moth data, the project-wide representation of egg mass data is a lattice-polygon of 500 m cells categorized into management action thresholds. The difference is that the egg mass display is restricted to only those cells which are within 1 km of a sample site (Fig. 7). This reduces risks associated with generalizing about egg mass densities in large unsampled areas.

SPECIAL PROJECTS

The applications discussed above were components of the standard monitoring program for AIPM operations and were in place for most or all of the duration of the project. In addition to these applications, the GIS has been used to assist in development of new approaches to gypsy moth management which involve monitoring and interpretation of survey results using unorthodox methodologies. One example of this is the work which has been done in areas of low population levels. Recent trends in gypsy moth management have focused attention on slowing the spread of gypsy moth into uninfested areas. Whereas intervention activities traditionally are based upon egg mass survey results, populations in areas under management to slow the spread of gypsy moth are too low to find egg masses; thus, population estimates used in decision-making must be made solely on the basis of male moth captures. This translates into trapping in intensive grids, pinpointing locations of low trap catches (1 to 25), and scrutinizing the spatial relation among positive traps and those which caught no moths. GIS has been used extensively in guiding management activities in these areas of low moth catch. Some of the most useful applications in this area involved using the GIS to play out a series of "what-if" scenarios. By constructing theoretical treatment or monitoring areas around locations of traps within certain catch categories it was possible to estimate the resource needs for different management scenarios.

Decentralization of the GIS/DBMS

While the GIS proved to be crucial to many AIPM management activities, there were instances where it was obvious that improvements were needed in the structure of information flow. Because of the centralization of the GIS/DBMS the time lag between data capture and its availability to field supervisors was too great for some applications. Indeed, some supervisors were copying egg mass data from data forms onto their own 1:24,000 scale maps before the forms were mailed to VPI&SU for entry into the data base. Although production of 1:24,000 scale maps is streamlined as much as possible, the delay caused by mailing of paper products (data forms, maps) and computer tapes is sufficient to hinder management decisions. This is particularly true for egg mass data which must be collected and processed quickly while managers are scrambling to meet time demands in proposal of treatment blocks.

It became clear that a centralized DBMS/GIS was inefficient in attending to many needs of the managers. In an attempt to provide managers with access to survey data in a decentralized system, Young, et al. (1991) began development of a county-based map display and analysis system which is composed of an interface to PC Arc/Info. The goal is to provide managers with the tools to manipulate a variety of spatial data themes in a GIS environment oriented toward gypsy moth management. While this system, called GypMap, was initially designed as dependent upon the mainframe DBMS/GIS at VPI&SU, ongoing efforts are to make the system autonomous within a county or USFS ranger district. This has been accomplished by incorporating data input and management capabilities. GypMap is in place in Rockbridge County, VA and the Glenwood Ranger District in the Jefferson National Forest. A system for Albemarle County, VA is under development. Hopefully, this approach will supplant the need for a centralized system and expedite management decisions.

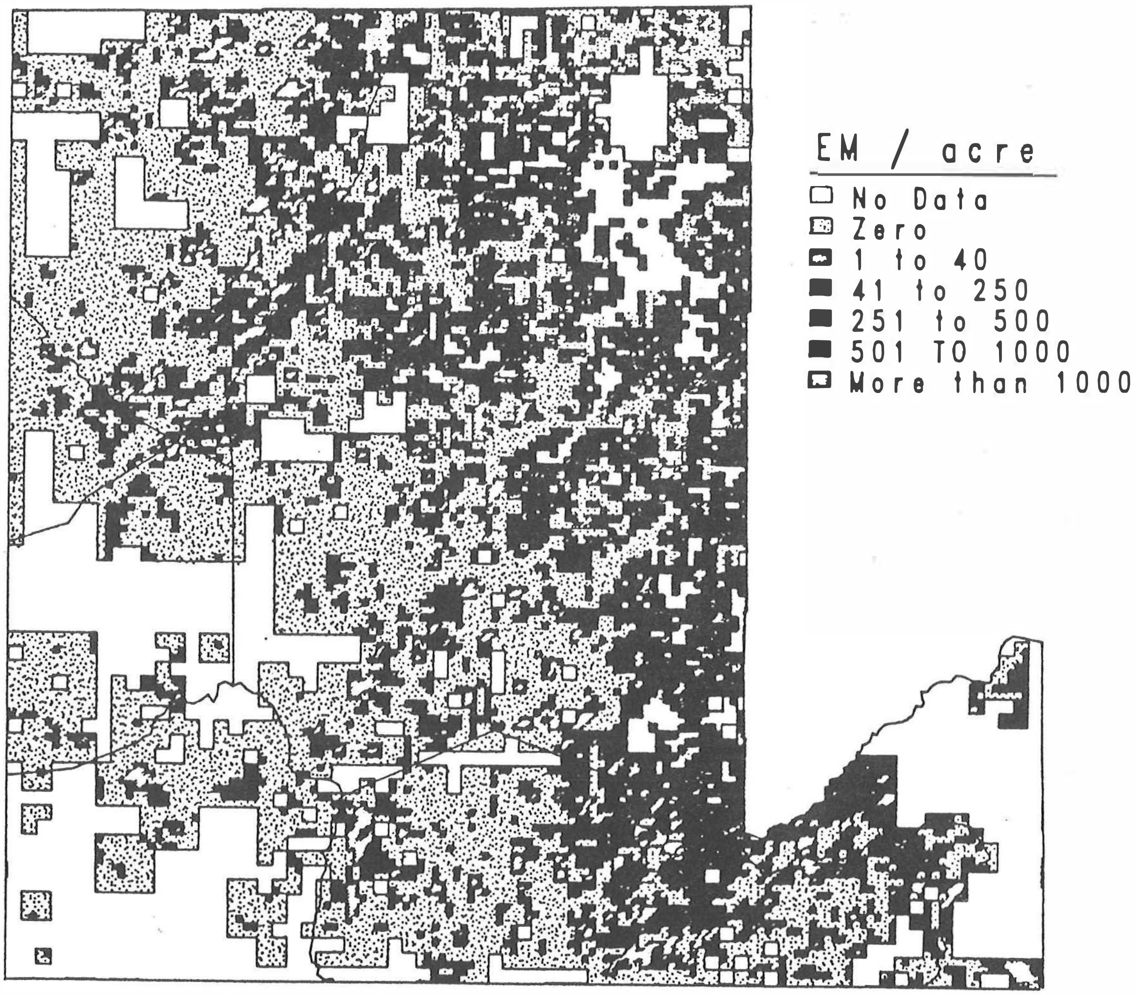


FIG. 7. A portion of the egg mass lattice-polygon surface in a several-county area of West Virginia. Cell size is 500 meters. Actual map is in color.

CONCLUSIONS

The AIPM Project has provided the opportunity to illustrate the role of GIS in a large pest management program. Although the AIPM GIS is involved in many more activities than just the monitoring program, the monitoring and survey component has developed into one of the most active uses of GIS in the project. With emphasis on simplicity and automation, the AIPM GIS has proven valuable in assisting in the management of project tasks such as personnel management which are not normally associated with GIS functions. Areas where the centralized GIS failed to meet project needs were addressed through development of a decentralized autonomous system for county-level management.

LITERATURE CITED

Fleischer, S.J., F.W. Ravlin, and R.C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (*Lepidoptera: Lymantriidae*) egg masses in eastern hardwood forests. Journal of Economic Entomology **84**:1100-1107.

Roberts, E.A., F.W. Ravlin, and S.J. Fleischer. *In press*. Spatial data representation for integrated pest management programs. Amer. Entomol.

Young, J.A., S.J. Fleischer, F.W. Ravlin, E.A. Roberts, S. Talley, R. McFarlane, and J. Repair. 1991. Development of a county-based map display and analysis system for gypsy moth management. pages 109-117 in B.S. Carroll and F.W. Ravlin, editors. The gypsy moth in Virginia 1990. VCES Publication 444-030.

THE NORTH AMERICAN SPRUCE BUDWORM PHEROMONE TRAPPING NETWORK

D. Barry Lyons And Chris J. Sanders
Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ontario, Canada P6A 5M7

Abstract. The North American spruce budworm pheromone trapping network and its sampling protocols are described. Historical pheromone trap capture data, dating back to 1984, are used to illustrate techniques for mapping and performing simple modeling of georeferenced point data. Geostatistics are then utilized to interpolate between data points to convert capture data to contour maps with complete spatial coverage. The resultant maps can be imported into GIS software packages for spatial analysis. Suggestions for incorporating these maps into early warning and predictive models are outlined. Problems resulting from year-to-year variation in lure potency and moth migration make the development of predictive models difficult, but future research to overcome these obstacles is discussed.

INTRODUCTION

The spruce budworm, *Choristoneura fumiferana* (Clemens), is a serious defoliator of spruces (*Picea* spp.) and balsam fir (*Abies balsamea* (L.) Mill.) in northeastern North America. Literature on the spruce budworm is extensive and has been reviewed by Mattson et al. (1988) and Sanders (1991). The insect occurs over a wide geographic area and undergoes periodic outbreaks. The period between outbreaks has ranged from 17 to 100 years and has been shorter during the current century (Blais 1983). The budworm is a threat to more than 60 million ha of susceptible forest in North America and during outbreaks causes growth loss, top kill, cone and seed damage and mortality to host trees. During the last three outbreaks, this defoliator attacked 10, 25 and 55 million ha (Mattson et al. 1988). To make management decisions concerning the spruce budworm, temporal and spatial population data on the this pest must be obtained.

Collection of population data for the spruce budworm is currently very labor intensive and costly. Current survey methodologies include branch sampling for various life history stages (see reviews by Sanders 1980, Dorais and Kettela 1982). Eggs of the spruce budworm are deposited in clusters on the needles of the host plant, which makes them a useful sampling unit for population estimates. Collection of branches from the mid-crown of host trees, using pole pruners, is one method of sampling for egg masses. Branch samples are collected from a representative number of trees and are returned to the laboratory, where they are intensively examined. The budworm overwinters as a second instar in a hibernaculum on the host plant, and another sampling method to assess population densities involves the soaking of sample branches in a NaOH solution to remove these overwintering larvae (Trial 1985). These overwintering larvae are available in the field for a considerable period of time, which makes the timing of sampling less critical.

At the end of the feeding period, reddish brown needles, severed from the twigs but still attached by silken webbing, are visible from the air. In some regions, aerial defoliation surveys are conducted to detect this discoloration, but these surveys only detect populations above some threshold level at which defoliation is observable and are costly in terms of aircraft time. At this stage, outbreaks are usually well established. These surveys do, however, produce population indices that have complete spatial coverage.

The use of pheromone traps to monitor spruce budworm populations should alleviate some of these sampling problems. The traps require less resources to deploy, recover and evaluate than do more traditional sampling methods. They also provide an early warning system for incipient outbreaks. Ideally,

Pages 37-48 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

the catch data could be used to predict future population levels with some degree of confidence and perhaps even future levels of defoliation or loss of wood supply. Some progress in predicting an index of defoliation level or a threshold, based on pheromone trap catch, has been made for other forest defoliators (Sartwell et al. 1985, Shepherd et al. 1985). Gage et al. (1990) had considerable success in predicting future gypsy moth populations based on pheromone trap catches, but the predictability was limited to an expanding population.

The purpose of this paper is to discuss the trapping network and protocols for spruce budworm, software tools for analyzing spatial patterns in the data, a preliminary analysis of the data, problems and future directions. Preliminary objectives are to develop techniques for constructing contour maps of the trapping data. Longer term objectives are to overlay successive years of data and detect changes, to overlay trap catch data on weather and forest type and to optimize trap distribution. From these analyses we intend to develop an early warning and predictive system for outbreaks and defoliation. This report describes the use of geostatistical techniques in spruce budworm research and their utility for converting data to a form suitable for geographical information system (GIS) analysis. The results are preliminary and are discussed for illustrative purposes.

PHEROMONE TRAPPING NETWORK

Mating of the spruce budworm occurs shortly after the moths eclose from pupae in late June to late July. Females of the spruce budworm produce a potent sex pheromone, which has proven to have multiple components (Silk et al. 1980). A synthetic pheromone lure, when combined with an efficient trap design (Sanders 1986), results in a low-cost, efficient system for monitoring populations of male spruce budworm moths.

TRAPPING SYSTEM AND PROTOCOLS

The network employs high-capacity non-saturating Multi-Pher® traps (Jobin 1985). The trap consists of a funnel leading into a collecting chamber with a lid covering the funnel. Initially, the pheromone was incorporated into a polyvinyl-chloride (PVC) lure, but after 1989 Biolures® (Consep Membrane Inc., Bend, OR) were used in the program. The lure is pinned to the lid of the trap and a strip of dichlorvos killing agent is placed in the chamber. At each trapping location, three traps are deployed 2 m above the ground and about 0.5 m from foliage (Allen et al. 1986). The three traps are placed in a triangle with about 40 m between traps and each trap is placed at least 40 m from the edge of an opening in the forest. The correlation among catches in the three traps at each location, as indicated by the Ontario data for 1984, 1986, 1987, 1988, 1989 and 1990, is very high (Table 1). Data from 1985 were not used in the analysis because of problems with the killing agents in the traps. The use of three traps at each location guarantees a sample in the event that individual traps are damaged or lost. Samples collected at a given location are therefore the average of three or fewer traps. Traps are deployed from the beginning of pupation in June throughout the 3- to 4-week flight period of the moth.

TABLE 1. Correlation coefficients for spruce budworm moth captures from the sets of three pheromone traps at the same locations in Ontario.

	Trap 2	Trap 3
Trap 1	0.92 (n = 479)	0.878 (n = 447)
Trap 2	-	0.879 (n = 447)

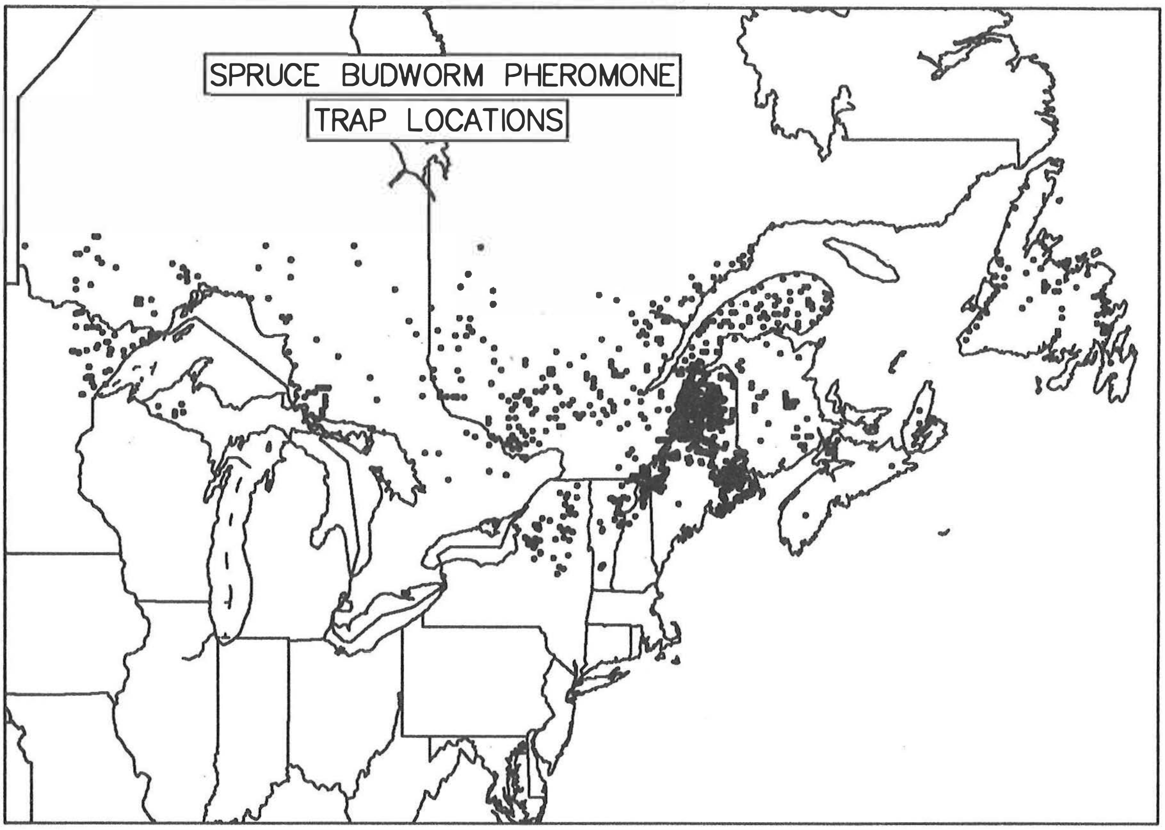


FIG. 1. Spruce budworm pheromone trapping locations in northeastern North America from 1984 to 1990.

HISTORICAL DATA

Figure 1 shows the distribution of trap locations in northeastern North America from 1984 to 1990. A few traps are also deployed in the three Canadian prairie provinces. Not all trap locations are sampled every year; the number of locations (Table 2) has varied considerably over the course of the project, depending in part on available resources. Staff of the Forest Insect and Disease Survey (FIDS) of Forestry Canada deploy and collect traps in the Maritimes, Newfoundland, Ontario and Northern Regions, while Forestry Canada researchers also place traps in Ontario and New Brunswick. In the Maritimes, these have been supplemented by traps deployed by the Nova Scotia Department of Lands and Forests and the New Brunswick Department of Natural Resources and Energy. In Quebec, trapping is carried out by the Ministère de l'Énergie et des Ressources. In the United States, traps are deployed by the states of Maine, Michigan, Minnesota, New Hampshire, New York and Vermont under the coordination of the USDA Forest Service. Private companies (J. D. Irving Ltd. and International Paper Co.) have also cooperated in trap placement. Table 2 shows the years for which data are available. The locations of the traps are stored as Universal Transverse Mercator (UTM) projection coordinates consisting of a zone number, a two-digit easting and a three-digit northing. Thus, the UTM coordinates denote the southwestern corner of a 10-km by 10-km grid square in a specific zone that contains the trap. By appending the digit "five" to the end of each coordinate, the reference point becomes the center of the square.

At some locations, associated population data are collected. Defoliation estimates are made in the Maritimes and Ontario regions; egg samples are collected in the Northern and Ontario regions; overwintering second instars (L2) are collected in the Maritimes, Newfoundland, Ontario and Quebec regions; and older larvae (L3-L4) are collected in the Maritimes, Newfoundland and Ontario regions. These associated data allow for comparisons to be made between trap catches and other estimates and indices of population density.

TABLE 2. The number of spruce budworm pheromone traps deployed in each region from 1984 to 1991.

	Year							
Region	1984	1985	1986	1987	1988	1989	1990	1991
Maritimes	0	40	39	39	34	13	23	21
Newfoundland	0	15	40	47	50	50	49	50
Northern	0	0	0	31	31	0	13	0
Ontario	25	30	51	78	75	55	74	85
Quebec	0	166	317	287	264	270	250	272
United States	0	242	300	369	427	248	121	92

SPATIAL ANALYSIS

Spruce budworm population data can be classified into two types: maps derived from aerial surveys, which represent complete spatial coverage, or point data from samples collected from a fixed location in space. Pheromone trap data, like branch sampling data, are represented by points in space.

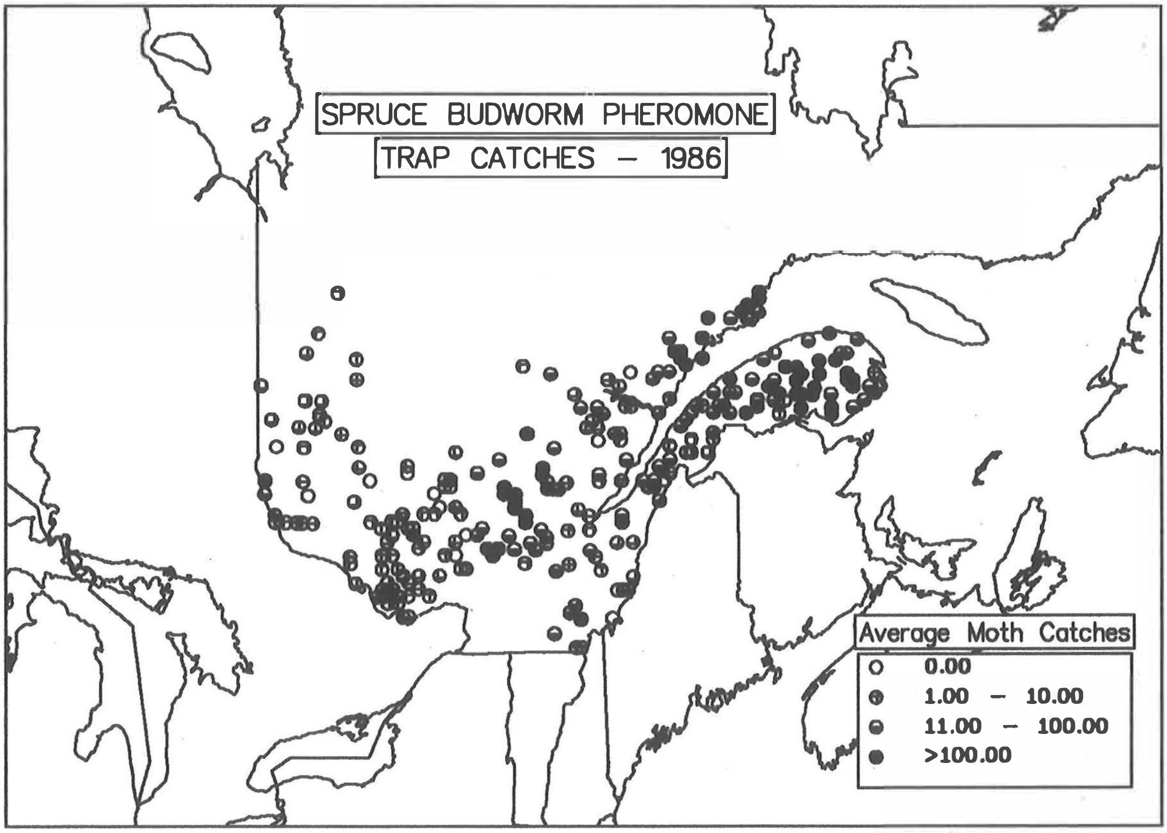


FIG. 2. Pheromone trap captures of male spruce budworm moths for Quebec in 1986, in four categories based on the number of moths caught.

The map in Figure 1 is an example of point data mapped using a software package called inFOcus® (Earth & Ocean Research Limited, Dartmouth, Nova Scotia). This is a simple GIS package that integrates QUIKMap® (Axys Software Ltd., Sidney, British Columbia) mapping software and FoxPro® (Fox Software Inc., Perrysburg, Ohio) relational database management software. In this example, the points are georeferenced (i.e., have map coordinates) but do not have attributes associated with the points. UTM coordinates for the original data were transformed to latitudes and longitudes using SPANS® (Intera Tydac, Ottawa, Ontario) software for use in inFOcus. However, not only are the map coordinates for the trap stored in the database, but also the number of male moths that were captured at that location each year. The database can thus be queried and the attributes (i.e., moth numbers) incorporated in the map. The attributes can be categorized with different symbols to indicate their magnitudes. Figure 2 shows the spruce budworm pheromone trap locations in Quebec in 1986 with the capture category indicated by different symbol types.

TABLE 3. Simple expert model for predicting the number (N) of spruce budworm moths captured in the current year (t) from captures in the two previous years (t-1 and t-2).

	$N_{(t-1)}$		
$N_{(t-2)}$	None	Low	High*
None	None	Low	Low
Low	None	Low	High
High	None	Low	Low

* High means > 100 moths

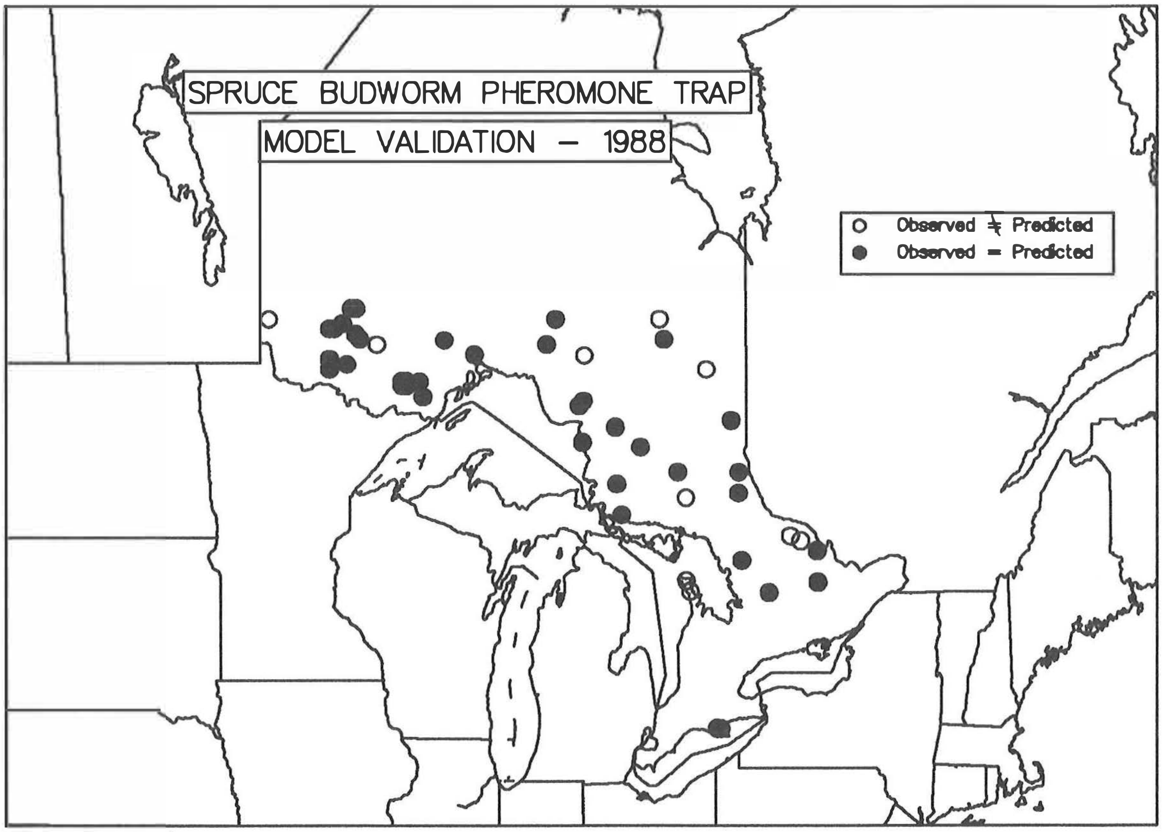


FIG. 3. Locations of correct and incorrect predictions of spruce budworm moth captures in Ontario in 1988 based on a simple expert model using moth captures in the two previous years as input.

Not only is this software useful for illustrative purposes and the visual detection of spatial patterns, but we can also do some simple modeling with point data. Table 3 indicates a simple expert model that predicts moth captures in the current year based on trap catches in the two previous years. For example, the model predicts low moth captures (i.e., < 100 moths) if moth captures were low in the two previous years. This is an intuitive model based on pheromone trapping experience. The inFOcus software can be used to generate predicted moth captures at each location and then to compare the predicted moth captures with actual moth captures at the same location. Figure 3 shows the distribution of correct and incorrect predictions of the model for Ontario in 1988. As indicated by the preponderance of black dots (i.e., correct predictions), the model predicted future moth captures fairly accurately. This simple model, however, probably behaves differently for increasing and declining populations. The representation of the data in the form of a map allows us to visualize areas in which the simple model performed well. If incorrect predictions were concentrated in a particular area, then failure of the model might have resulted from a spatial event such as an unusual weather pattern or moth migration. In the example provided (Fig. 3), however, the incorrect predictions are distributed evenly across the map.

The problem with point mapping is that the data represent points in space and we have no idea about what is happening in areas not represented by the data. To take full advantage of the analytical capabilities of GIS software, the data must provide complete spatial coverage. What we need is a means to interpolate between points, in a meaningful way, so that we have complete spatial coverage. Geostatistics provides us with the appropriate tools and GS+ (Gamma Design Software, Plainwell, Michigan) is an appropriate software package to perform geostatistical analysis of point data. The characterization of the spatial dependence for other insects using geostatistics has been effectively demonstrated (Kemp et al. 1989, Schotzko and O'Keeffe 1989, Liebhold et al. 1991).

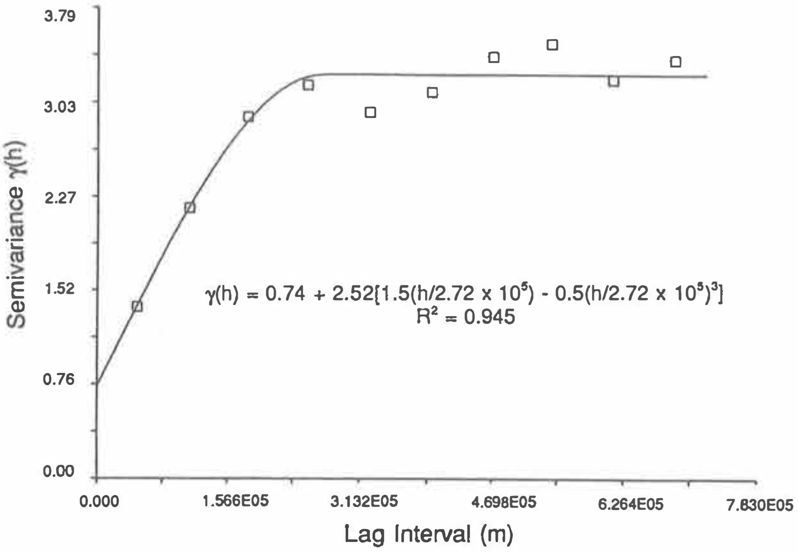


FIG. 4. Spherical semivariogram model for spruce budworm moth captures in Quebec in 1986.

The point interpolation routine used by GS+ is known as "ordinary kriging". Latitudes and longitudes for the Quebec data set were converted to x and y coordinates in metres, with 71.18^{o}W and 47.34^{o}N as the true origin, using an equidistant cylindrical projection in SPANS. The first step in the interpolation process is the construction of an autocorrelation model or semivariogram. The moth capture data for 1986 were transformed using ln(z + 1) to normalize the skewed distribution. Prior to mapping, the estimates were backtransformed using Haan's method (Gamma Design Software 1992). The semivariogram is essentially a plot of the variance between neighboring cells as a function of the distance between points. The software allows for the construction of either an omnidirectional (i.e., isotropic) or a unidirectional (i.e., anisotropic) semivariogram. Five different functions can be fitted to the scatter plot of lag distances using least-squares regression. The active lag used in the calculations was half the maximum lag, and the active step was one tenth the active lag (Liebhold et al. 1991). The isotropic semivariogram model for the pheromone trap data for Quebec in 1986 is shown in Figure 4. The curve is a spherical model, $\gamma(h) = C_0 + C[1.5(h/A_0) - 0.5(h/A_0)^3]$ where γ is the semivariance for distance h. C_0 is the "nugget" variance where the curve intersects the vertical axis and represents the variance attributable to local discontinuity

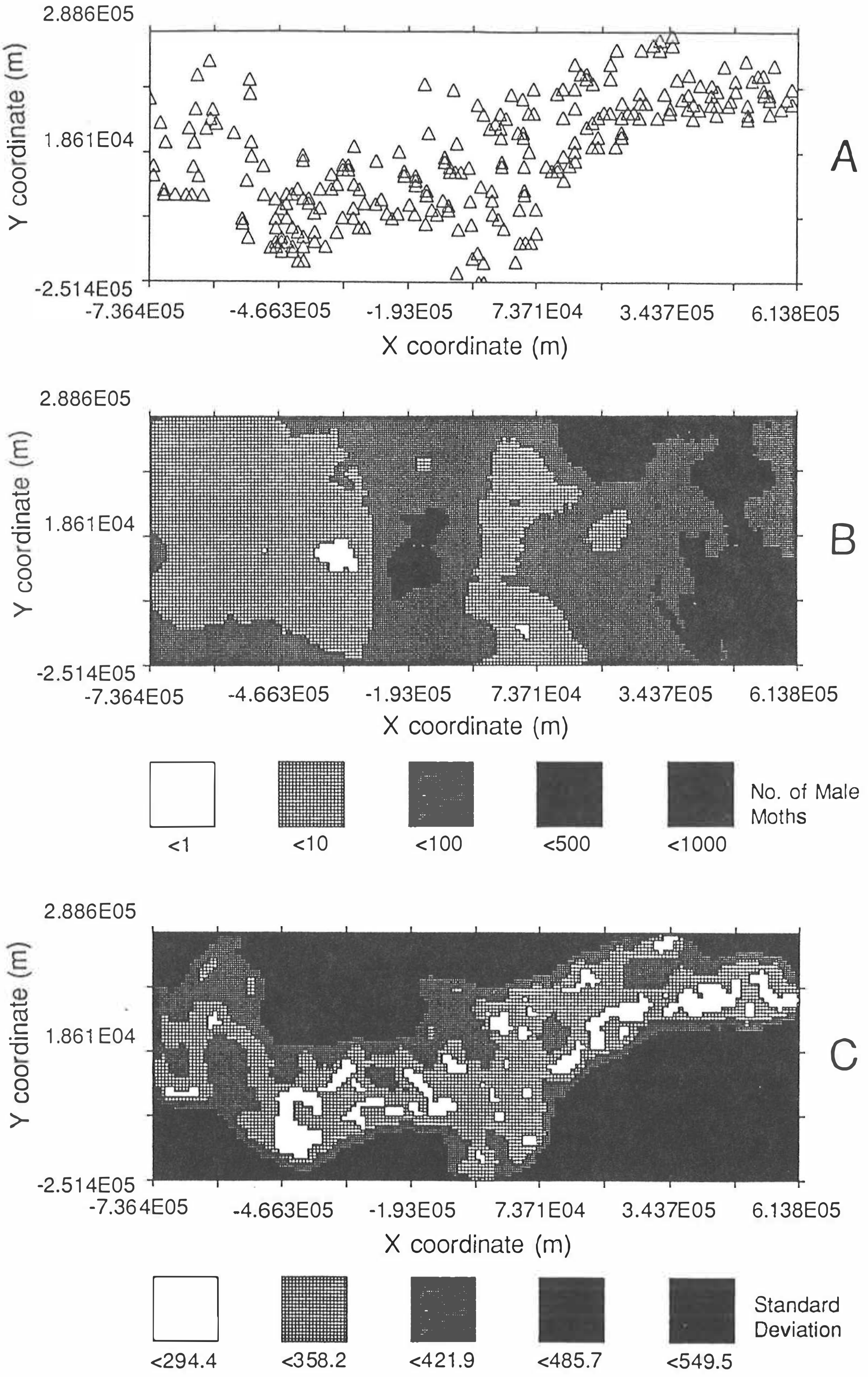


FIG. 5. Sample posting of spruce budworm pheromone trap locations (A); contour map of spruce budworm pheromone trap captures (B); and contour map of estimated standard deviations for spruce budworm pheromone trap data (C) in Quebec in 1986 using GS+ software.

or sampling error. The "sill" is where the semivariance reaches a plateau and is equal to the sum of C, the structural variance, and C_0. A_0 is the range of spatial dependence and its upper limit is where the curve reaches the sill. For the Quebec data, $C_0 = 0.74$, $C = 2.52$ and $A_0 = 2.72 \times 10^5$ m or 272 km ($R^2 = 0.945$). Once a semivariogram model has been calculated, the next step in the process of producing an isopleth of moth captures is interpolating between the point data using kriging. Kriging utilizes the weights determined from the semivariogram and the locations of the data points. Figure 5A is a sample posting of the point locations for traps, and Figure 5B illustrates the contour map of interpolated pheromone trap catches in the province of Quebec for 1986. GS+ also produces a contour map of estimated standard deviations (Fig. 5C). The distribution of sample points (Fig. 5A) reflects the distribution of the landmass of southern Quebec and the limit of the provincial border. The area in the southeast of the map is ocean and the southwestern part of the map is in the United States. The northern limit of the traps represents the limit of economically important budworm distribution. The smaller standard deviations (Fig. 5C) clearly delineate the outer limit of the sampling points.

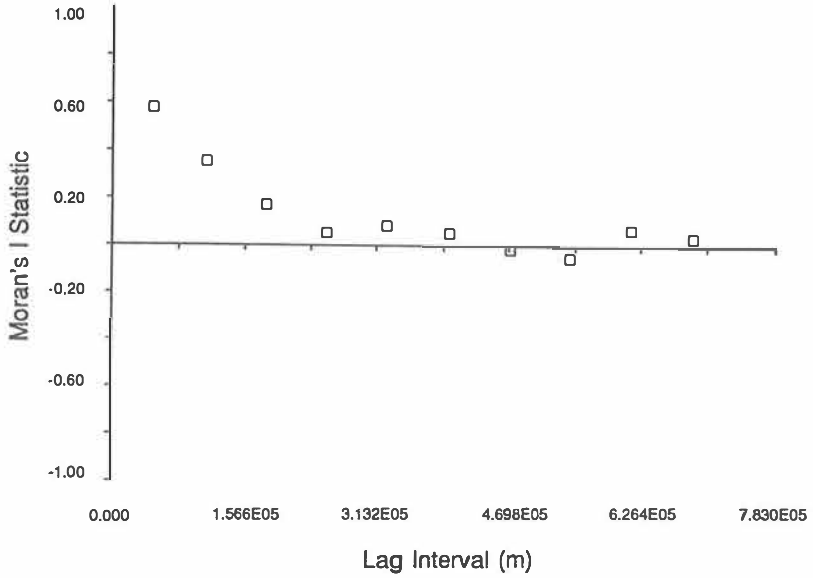


FIG. 6. Autocorrelogram of spruce budworm pheromone trap data for Quebec in 1986 using Moran's I statistic.

There are other methods for examining the spatial dependence of insect distributional data. Autocorrelations using Moran's I statistic is another technique provided in GS+ (Fig. 6). Parameters gleaned from autocorrelation analysis can also be utilized in a SPANS interpolation routine known as potmapping. These techniques have been used to evaluate grasshopper distributions in Alberta (Johnson and Worobec 1988).

Once contour maps of moth captures have been created they can be imported into GIS software packages. Areas that do not provide suitable habitat, such as bodies of water, can be stamped out of the maps. More complex GIS analysis, such as overlays, boolean algebra operations and modeling using maps as variates, are being undertaken using SPANS and IDRISI® (Clark University, Worcester, Massachusetts).

Table 4 shows a model of the empirical probabilities of defoliation derived from the Ontario data. Defoliation levels greater than 30% resulting from spruce budworm feeding are classified as equivalent to moderate-to-severe defoliation observed during an aerial survey. Contoured isopleths of moth catches can be converted to contours of defoliation probabilities using Table 4. Using SPANS, predicted maps can then be validated using digitized defoliation maps produced by FIDS from aerial sketch maps.

TABLE 4. The proportion of sites that will have defoliation levels greater than 30% in the current year for each category of trap capture of moths (N) in the previous two years (t-1 and t-2).

	$N_{(t-1)}$			
$N_{(t-2)}$	0	1 - 10	11 - 100	> 100
0	0.00 (n = 16)	0.00 (n = 23)	0.00 (n = 2)	- (n = 0)
1 - 10	0.00 (n = 18)	0.02 (n = 63)	0.05 (n = 20)	1.00 (n = 3)
11 - 100	0.00 (n = 8)	0.00 (n = 24)	0.30 (n = 27)	0.50 (n = 16)
> 100	0.00 (n = 1)	0.17 (n = 6)	0.45 (n = 31)	0.24 (n = 21)

PROBLEMS AND FUTURE DIRECTIONS

GIS and geostatistics allow us to visualize, manipulate and analyze spruce budworm pheromone trap catches in a spatial context. We have demonstrated the use of geostatistics to make meaningful contour maps of pheromone trap catches of male spruce budworm moths. One objective of the network is to provide an early warning for spruce budworm outbreaks based on trap catches. There is good evidence that this approach will be fruitful (Sanders 1988) and that we can do it spatially. However, an additional goal of the network is to predict future population levels or damage levels from the number of moths captured in traps in previous years. If we can develop predictive models of future population events, we can place these predictions in a spatial context using the techniques outlined. However, the relationships between moth capture and future events are not simple. Figure 7 shows the percent defoliation for sites in Ontario as a function of the logarithm of the number of male moths captured in pheromone traps in the previous year at the same location. The scatter of points suggests a weak relationship. When a Weibull function of the form $Y = 100(1-e^{-(X/A)**B})$ was fitted to the observed points using nonlinear regression analysis, the regression only explained approximately 34% of the variability. However, if we insert a vertical line at the point where we start to get defoliation above 30%, the result is a threshold for the number of moths that are sometimes associated with moderate-to-severe defoliation. This sort of threshold approach has worked for the Douglas-fir tussock moth, *Orgyia pseudotsuga* (McDunnough) (Shepherd et al. 1985).

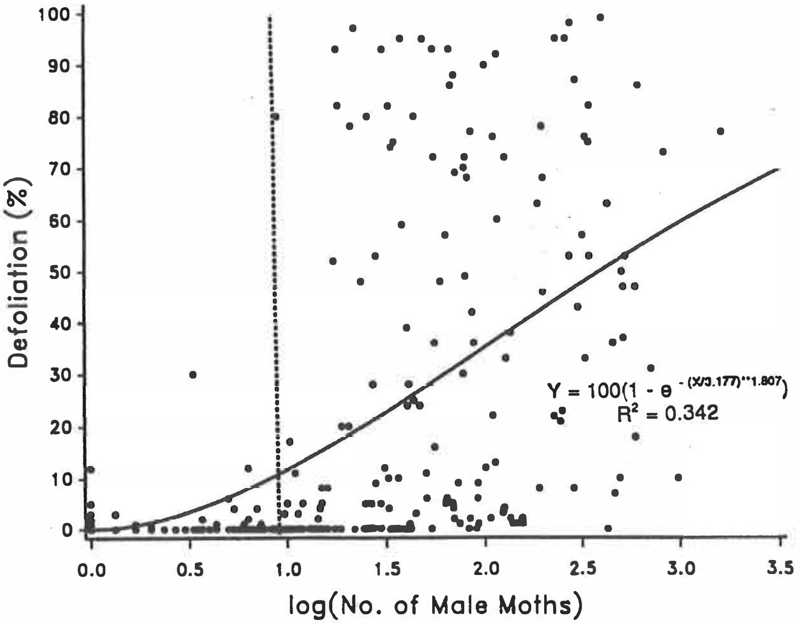


FIG. 7. Percentage defoliation as a function of log-transformed pheromone trap captures in the previous year. Dashed line indicates a threshold number of male moths greater than which is sometimes associated with moderate-to-severe defoliation (> 30%).

As previously stated, the utility of the network lies in its predictive ability. However, experiments conducted by one of us (CJS) indicate that there is considerable year-to-year variation in lure potency. Comparison of trap catches for 1989 and 1990 lures in 1990 at 12 locations indicated no significant difference ($R^2 = 0.948$, slope = 0.861) using linear regression analysis (Fig. 8). However, comparisons of 1989, 1990 and 1991 lures in 1991 caused some serious concerns. Significant and large differences among potency of lures was detected between the 1991 lures and those from the other two years (Table 5). Although we are not going to speculate on the cause of these differences here, the implication of this problem for a system that depends on year-to-year comparisons is catastrophic. Solutions to this problem currently being incorporated in the network include a bulk purchase of pheromone to help eliminate quality differences and continuous year-to-year comparisons of bait potency.

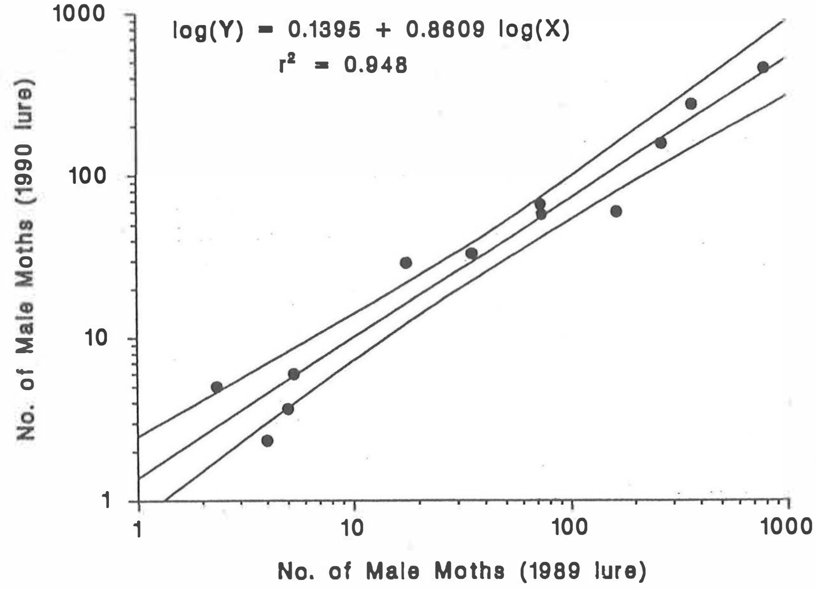


FIG. 8. Relationship between the numbers of male spruce budworm moths captured in pheromone traps using 1989 lures and 1990 lures in 1990. The lines are the linear regression and its 95% confidence limits.

TABLE 5. Mean number of spruce budworm moths captured in 1991 in traps (n=5) baited with lures from 1989, 1990 and 1991, and from unbaited traps at Black Sturgeon Lake, Ontario.

Lure	Mean number (SD) of moths
1989	57.0b (14.1)
1990	43.2b (13.6)
1991	289.8a (87.4)
Unbaited	15.0c (6.0)

Means followed by the same letter are not significantly different (Tukey's studentized range test; $P > 0.05$).

Moths often emigrate from heavily defoliated stands but probably do not disperse from sparsely or moderately defoliated stands. Distances traveled can be up to 600 km between origins and landing locations (Greenbank et al. 1980). Mass flights might initiate outbreaks in areas without previous high moth captures. Mass migrations of moths make correlations with other population indices difficult. Perhaps these observations can be assimilated into predictive models.

We would also like to know the level of trap density that provides us with the optimum amount of information to analyze trap catches spatially. Various grid sizes are being compared to address this question. These and other questions will direct future research.

ACKNOWLEDGEMENTS

We would like to thank all the cooperators for providing the network data. Thanks are also extended to George Lucuik and Gene Jones for technical assistance.

LITERATURE CITED

Allen, D. C., L. P. Abrahamson, L. Jobin, D. J. Souto and C. J. Sanders. 1986. Use of pheromone traps to monitor spruce budworm populations. Canadian Forestry Service, Ottawa. 16 p.

Blais, J. R. 1983. Trends in the frequency, extent, and severity of spruce budworm outbreaks in eastern Canada. Canadian Journal of Forestry Research. 13: 539-547.

Dorais, L. and E. G. Kettela. 1982. A review of entomological survey and assessment techniques used in regional spruce budworm, *Choristoneura fumiferana* (Clem.), surveys and in the assessment of operational spray programs. Eastern Spruce Budworm Council, Ministère de l'Énergie et des Ressources, Quebec. 43 p.

Gage, S. H., T. M. Wirth and G. A. Simmons. 1990. Predicting regional gypsy moth (Lymantriidae) population trends in an expanding population using pheromone trap catch and spatial analysis. Environmental Entomology. 19: 370-377.

Gamma Design Software. 1992. GS+ professional geostatistics for the PC. Ver. 2. Plainwell, MI.113 p.

Greenbank, D. O., G. W. Schaefer and R. C. Rainey. 1980. Spruce budworm (Lepidoptera: Tortricidae) moth flight and dispersal: new understanding from canopy observations, radar, and aircraft. Memoirs of the Entomological Society of Canada. No. 110. 49 p.

Jobin, L. J. 1985. Development of a large-capacity pheromone trap for monitoring forest insect pest populations. In: Sanders, C. J.; Stark, R. W.; Mullins, E. J.; Murphy, J. eds. Recent advances in spruce budworms research. Canadian Forestry Service, Ottawa: 243-245.

Johnson, D.L. and A. Worobec. 1988. Spatial and temporal computer analysis of insects and weather: grasshoppers and rainfall in Alberta. Memoirs of the Entomological Society of Canada. No. 146: 33-48.

Kemp, W. P., T.M. Kalaris and W. F. Quimby. 1989. Rangeland grasshopper (Orthoptera: Acrididae) spatial variability: macroscale population assessment. Journal of Economic Entomology. 82: 1270-1276.

Liebhold, A. M., X. Zhang, M. E. Hohn, J. S. Elkinton, M. Ticehurst, G. L. Benzon and R. W. Campbell. 1991. Geostatistical analysis of gypsy moth (Lepidoptera: Lymantriidae) egg mass populations. Environmental Entomology. 20: 1407-1417.

Mattson, W. J., G. A. Simmons and J. A. Witter. 1988. The spruce budworm in eastern North America. In: Berryman, A. A. ed. Dynamics of forest insect populations. Plenum Publishing Corporation: 309-330.

Sanders, C. J. 1980. A summary of current techniques used for sampling spruce budworm populations and estimating defoliation in eastern Canada. Canadian Forestry Service, Report O-X-306. Sault Ste. Marie, Ontario. 33 p.

Sanders, C. J. 1986. Evaluation of high-capacity, nonsaturating sex pheromone traps for monitoring population densities of spruce budworm (Lepidoptera: Tortricidae). The Canadian Entomologist. 118: 611-619.

Sanders, C. J. 1988. Monitoring spruce budworm population density with sex pheromone traps. The Canadian Entomologist. 120: 175-183.

Sanders, C. J. 1991. Biology of North American spruce budworms. In: van der Geest, L.P.S. and Evenhuis, H. H. eds. Tortricid pests, their biology, natural enemies and control. Elsevier Science Publishers, Amsterdam: 579-620.

Sartwell, C., G. E. Daterman and D. B. Twardus. 1985. Moth captures in pheromone-baited traps relative to subsequent defoliation of Douglas-fir by western spruce budworm. In: Sanders, C. J.; Stark, R. W.; Mullins, E. J. ; Murphy, J. eds. Recent advances in spruce budworms research. Canadian Forestry Service, Ottawa: 240.

Schotzko, D. J. and L. E. O'Keeffe. 1989. Geostatistical description of the spatial distributions of *Lygus hesperus* (Heteroptera: Miridae) in lentils. Journal of Economic Entomology. 82: 1277-1288.

Shepherd, R. F., T. G. Gray, R. J. Chorney and G. E. Daterman. 1985. Pest management of Douglas-fir tussock moth, *Orgyia pseudotsugata* (Lepidoptera: Lymantriidae): monitoring endemic populations with pheromone traps to detect incipient outbreaks. The Canadian Entomologist. 117: 839-848.

Silk, P. J., S. H. Tan, C. J. Wiesner, R. J. Ross and G. C. Lonergan. 1980. Sex pheromone chemistry of the eastern spruce budworm, *Choristoneura fumiferana*. Environmental Entomology. 9: 640-644.

Trial, H., Jr. 1985. Use of the overwintering-larvae soaking method for population prediction in Maine. In: Sanders, C. J.; Stark, R. W.; Mullins, E. J.; Murphy, J. eds. Recent advances in spruce budworms research. Canadian Forestry Service, Ottawa: 233.

COOPERS ROCK DEMOSTRATION PROJECT A DECISION SUPPORT SYSTEM FOR GYPSY MOTH MANAGERS

JAY HUTCHISON
Dept. of Geology and Geography, West Virginia University, Morgantown, WV 26507

SUSAN DELOST
USDA Forest Service, State and Private Forestry, Appalachian Integrated Pest Management Project, Morgantown, WV 26505

ABSTRACT. Gyspy moth managers are required to assess many factors when making the time-critical decisions about gypsy moth treatments. The Cooper's Rock Project was designed to demonstrate the capability of a GIS to automate some of the decision processes used by a gypsy moth manager. ARC/INFO GIS software and the ARC macro language were used to automate the decision protocols and generate suggestions for treatment type, location, and extent. A prototype of a graphical user interface was developed as part of the project.

INTRODUCTION

Geographic Information Systems are quickly becoming the technology by which spatial data is stored and manipulated and landscape decisions are made. In the management of forest pests such as the gypsy moth, treatment decisions are made considering the following spatial data: land cover (forest type); land use; management objectives; pest population densities; previous year's defoliation; previous years' treatments; topography (slope, aspect and elevation); infrastructure (roads, airports, etc.) and other information as applies to each unique situation. For example, surficial geology or soils information may be needed. The areas which are involved in such landscape scale management and analysis can be immense, easily covering hundreds if not thousands of 1:24,000 scale, 7.5-minute U.S. Geological Survey (USGS) topographic quadrangles, the traditional media for storing and analyzing this type of information. A GIS can efficiently store this information so that it is easily referenced and accessible, minimizing the time and frustration of sorting through thousands of maps and file folders. A GIS can be used to expand the types and depth of analysis that can be done by using only the traditional methods and materials such as hard copy maps and transparent overlays.

OBJECTIVES

In the first stage of the diffusion and acceptance of GIS technology, the GIS at first is often primarily used for storing map data and making customized maps. Only after the users are comfortable with the computer map environment and good spatial data in digital format is secured, do they use the analysis tools of the GIS. The Coopers Rock Project was designed to demonstrate how a GIS could be used in a gypsy moth management program to manage spatial information and to display the related data themes in a user-friendly environment. By using the GIS analysis tools, the land manager responsible for managing the gypsy moth infestations in his/her area would be able to access and use all available information in making the critical decisions concerning treatments to be used against the gypsy moth pest. The data needs for specific decision tasks and their analysis components in the GIS environment were formalized. Preliminary work to determine how a graphical user interface (GUI) could be implemented and used by the land manager was done. The use of a GUI would allow the land manager to concentrate on the decisions at hand, rather than learning the intricacies of the particular GIS software

---

Pages 49-55 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

(Note: at the inception of this project, the GIS software used was still in the "toolbox" stage, requiring the user to be familiar with the hundreds of individual commands and their interrelationships in order to perform even the most basic functions). By using the graphical user interface menuing system, the land manager can concentrate on the decisions that need to be made concerning gypsy moth treatment alternatives.

STUDY AREA

The study area for this project encompasses the Lake Lynn, West Virginia 7.5-minute topographic quadrangle and parts of four adjacent quadrangles. This area was chosen for a number of factors. A primary factor in the site selection were the locations of two managed forests in this area, the Coopers Rock State Forest and the adjacent West Virginia University Research Forest. An assumption was made that the land managers on these two forests would have good land use and forest cover information, which is often difficult to obtain. This area also gives a good representation of various management objectives and mitigating factors, from the existence of a threatened and endangered species in the area, the presence of recreation areas, open water and forested residential neighborhoods to public forests and private woodlots. Finally, the area has a broad variation in gypsy moth population densities, from fairly low levels to highly defoliating populations.

METHODOLOGY

The GIS software used in this project was ARC/INFO, developed by the Environmental Systems Research Institute of Redlands, California. The computer platform used was a Digital Equipment Corporation VAX minicomputer. The basic decision guidelines, which were formalized within the framework of the GIS, were those used by the project sponsor, the Appalachian Integrated Pest Management Project (Table 1, AIPM 1991). These protocols provide alternatives for intervention activities for differing management objectives. In the AIPM project area, a zone concept was initiated, which helped define possible alternatives based on the extent (from generally infested to isolated occurrences) of gypsy moth infestation within a delineated zone. The proposed treatment alternative is the manager's decision, after taking certain factors into consideration. One such factor is the federal Environmental Protection Agency's (EPA) restrictions for use of certain pesticides. As an example, the pesticide Dimilin can not be used near open water. This consideration forces the gypsy moth manager to consider alternative treatments, including the option of no treatment. Other factors must be considered by the manager in proposing the type, if any, of treatment, including landowner's concerns, special use of the land in question, and the presence of a threatened and endangered species.

By using the AIPM protocols as a guide and interviewing the AIPM Project Manager for clarification and refinement, the needed data layers were determined (Data Layers, Table 2 at end of paper). Because forest composition data is needed in most hazard rating models, the Coopers Rock area was chosen, assuming that this data was available. However, this was not the case, except in specific research plots, where the best classification available was the delineation of oak/hickory, yellow poplar and a few pine and hemlock stands. These data were supplemented outside of the West Virginia University and Coopers Rock State Forest by updating the forest and non-forest areas as shown on the topographic quadrangles with 1988-era NAPP (National Aerial Photography Program) infrared photography. This made up the forest cover layer. An egg mass density surface layer was created using the Fall 1990 egg mass survey data collected by the AIPM project. This data was interpolated using the Triangulated Irregular Network (TIN) function contained in the ARC/INFO GIS software. The surface was then classified into ranges corresponding to the AIPM protocol thresholds. Because of limitations of some of the treatments around water, open water areas and open canopy streams were buffered to 500 feet to limit the types of treatment around them. To obtain the management layer, areas were classified into forest production, forest research areas, recreation areas, scenic areas, and residential. Because the threatened and endangered species areas overlap many of these management areas, it was developed as a separate layer. A layer of elevation ranges was also produced to represent differing phenology but has not been used to date.

Using the vector GIS model implemented in ARC/INFO, all layers were combined using the UNION operation (Figure 1, Burroughs 1986). This produced what we chose to call minimum separable units, the smallest unit of area which has discrete values associated with it and which would be used in further processing. Each of these polygons (unit areas) has discrete values associated with it, corresponding to values associated with each input data layer.

The many sub-decisions about treatment possibilities were encoded in a macro of more than 1000 lines which takes into account the various thresholds for treatment, management objectives and restrictions. Some decisions were chosen just as a manager might choose some preferred treatments. A choice was made to limit treatment in the threatened and endangered species areas (Triodopsis platysayoides - snail) to either Gypchek or no treatment. After the model was tuned, it was run and a map of suggested treatment alternatives was produced. This was then compared to the manual decisions made by the gypsy moth manager.

TABLE 1. Decision protocols for use of intervention activities within the AIPM Project Area in 1991.

If management Objective is:	Egg Mass/Acre	Intervention Available
Zone I (Generally Infested Portion of Project Area)		
Minimize damage (defoliation impacts, tree mortality)		
Timber or mast production areas, uninhabited woodlots	Greater than 1,000	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
Forested residential communities	Greater than 500	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
High use areas (e.g. recreation areas, parks, along scenic highways/streets)	Greater than 250	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
Protect special values (e.g. trout streams, historic sites)	Greater than 250	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
Zones II and III (Transition Portion of Project Area)		
Minimize population buildup	Greater than 250	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
Minimize natural/artificial spread from high use areas, urban/suburban, etc. and protect special values	Greater than or equal to 50	No action, Bt (1 or 2 appl.), Dimilin, Gypchek
	Less than 10	Low level (pheromone flakes, inherited sterility, mass trap)
Zone IV (Isolated Portion of Project Area)		
Minimize natural/artificial spread from all areas: intensive detection		No action, Bt (2 appl.), Dimilin, Gypchek, Low leve (pheromone flakes, inherited sterility, mass trap)

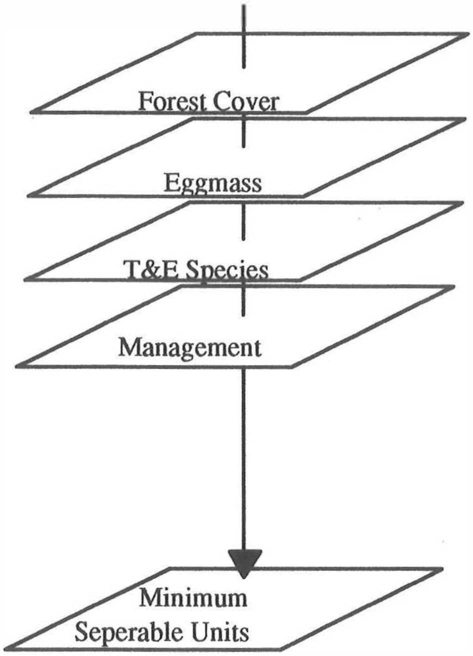


FIG. 1 The union operation

RESULTS

The areas suggested for treatment by the GIS and those of the gypsy moth managers corresponded very well. One area of disagreement was in the area near the research plots on the University Forest: in leaving a buffer around the forest research plots, the GIS used a discrete distance from the edge of the research plots as a delimiter, but in the decision made by the gypsy moth manager, subjective reasoning was used ("better not treat there, it looks too close to the research plots"). Another area of disagreement occurred where a single high count of egg masses forced the egg mass surface, produced by GIS operations, to skew the area into the high egg mass density range, indicating that a treatment was needed. The gypsy moth manager decided that the count was an anomaly (either wrong count or superficially high count on one tree) and decided against treatment. The exact boundaries of the suggested treatment areas differed frequently as the GIS is not predisposed to draw neat boxes or straight lines, however logistically for the type of treatment aircraft used by the state of West Virginia (DC-3), boxy areas are operationally more efficient.

For most of the forested areas of this part of the country there is minimal information on forest cover, so the model was run again using only a forest/non- forest delineation for the forest cover. The outcome of this operation added areas for treatment, but actually surprisingly little additional acreage compared to the originally suggested areas. The most common result was that suggested treatment areas increased in size and shapes became even less boxy and more nebulous.

Operationally, the vector model, used by the ARC/INFO GIS software, may not be the ideal method when faced with this type or other resource analysis type decisions which tend to incorporate many layers of information. In the vector model, the processes of unioning or intersecting these many layers to form the minimum separable units creates many very small polygons. These polygons may be spurious or may be smaller than the area of accuracy associated with the data. And, with each additional layer that is intersected, the number of small polygons increases exponentially. Ignoring the question of the value of the information in these small areas, the operational overhead occurring within the computer may slow the analysis to the point where manual analysis may be a better alternative. Therefore, in gypsy moth management as well as other resource analysis decisions, the raster model may be the more appropriate GIS approach. In the raster mode, the number of cells used to describe a particular phenomena are the same after a GIS operation as before the operation is performed. The number of cells making up the phenomena would be determined in advance by the manager as he/she deemed appropriate for the scale of that phenomena.

USER INTERFACE

One of the original ideas for the Coopers Rock project was to provide a "user-friendly" graphical user interface which would allow the gypsy moth manager to add or delete layers for the analysis and to change classification schemes, treatments and treatment thresholds without the need to learn the inner workings of a particular GIS. A rough conceptual prototype was programmed. However, during the course of this project, the need for this type of interface all across the GIS user community became glaringly apparent and the commercial suppliers of GIS software have now devoted vast amounts of resources to address this issue. By the time our prototype was operational, ESRI unveiled its Arcview product, which could, in the near future, become the core for a graphical user interface for gypsy moth and other resource managers. Further investigation of the Arcview product, which can be run on a high-powered microcomputer, is warranted.

CONCLUSIONS

It is clear that GIS technology can perform in more than a mapping capacity for the gypsy moth and resource manager. The analysis procedures used in this project are straight forward and follow closely those steps which a manager would normally use to make these types of decisions. The GIS is a more efficient means of storing map information, decreasing the chance that important information about an area is overlooked. The GIS is also a valuable tool, as relationships among data layers can be readily shown and incorporated as part of a decision matrix. The use of GIS points out where deficiencies in data occur, both in making it blatantly clear what is not available and what may be of poor quality or inappropriate. In this sense, the forest manager may be more comfortable doing business as usual. As the user interfaces to GIS software are more fully developed, become more user friendly and are adapted to specific purposes such as gypsy moth management, resource managers will have more opportunities to use a GIS to assist them in their decision-making.

TABLE 2. Coopers Rock Project Data Layers. **Bold Lettering** indicates layers which were unioned to make the minimum separable units layer. Underlining indicates layers used only as cartographic reference.

Layer	Description	Possible Values	Source
Forest Cover	Gross cover type aggregated from various sources	OH: Oak/Hickory, YP: Yellow Poplar H: Hemlock, P: Pine, F: Forested	Combined from WVU cover, Coopers Rock cover and Forested
WVU Cover	Cover type for the WVU experimental forest	Percent composition, Predominant species or no data	WVU Forestry via the GYPSES project
Coopers Rock Cover	Predominate species by stand	OH: Oak/Hickory, YP: Yellow Poplar or no data	West Virginia Forestry
Forested	Forested and non forest classification	F: Forested, blank: Non-forested, P:pine stands	From USGS 7.5' Quads updated from 1988 NAPP IR photography
Buffered Water	Open water buffered to 500 feet; two swath widths	1 or 0 for inside or outside the area	Buffered from Hydrology
Hydrology	Streams, lakes, and ponds	1 or 0 for open canopy or closed	USGS DLG Improved to Quad scale, updated from 1988 NAPP Photography
Buffered Research	Research Plots buffered to 1/4 mile	1 or 0 for inside or outside the area	Collected by AIPM from various sources
Buffered Threatened and Endangered Species	T and E areas blocked and buffered as to confuse exact location	1 or 0 for inside or outside the area	Buffered from Endangered Species
Endangered Species	Point location of endangered species in the study area	Type of species (One in study area) Triodopsis platysayoides -snail	Data from WV Natural Heritage Program
Egg Mass Densities	Classified surface created from egg mass survey data	Classes: 0 - 10, 11 - 50, 51 -250, 251 - 500, 501 - 1000, and over 1000 egg masses per acre	Generated from AIPM egg mass surveys
Egg Mass survey points	Point data from AIPM egg mass surveys	Actual sample values from zero to over 1000 egg masses per acre	From AIPM egg mass surveys
Elevation Ranges	100 meter elevation ranges from USGS 7.5' Digital Elevation Models	Values 2 through 8, value describes range. ie. 253 meters is in class 2	Generated from USGS 7.5' Digital Elevation Models
Management	Various management categories	Res: Residential, Rec:Recreation, Sce: Scenic, F: Forest	From various sources. WV Forestry, WVU Forestry, County Tax Maps, 7.5' Quads., 1988 NAPP IR Photography
Roads	Roads, streets and trails	Coded for interstate, primary, secondary and other roads, and trails	From USGS DLG data updated from NAPP IR Photography, and county road maps
Public Boundaries	Various political and management boundaries	County, state, park and forest boundaries	From 7.5' Quads and county tax map

LITERATURE CITED:

Burroughs, P.A. 1986. Principles of geographic information systems for land resource assessment. Oxford University Press.

U. S. Department of Agriculture, Forest Service - State and Private Forestry, Appalachian Integrated Pest Management Project. 1991. AIPM Project Area decision protocols. Morgantown, WV.

CREDITS:

ARC/INFO, TIN, Arcview and ESRI are trademarks of Environmental Systems Research Institute Inc., Redlands, CA.

GYPSES:
A DECISION SUPPORT SYSTEM FOR GYPSY MOTH MANAGEMENT

M.J. TWERY
USDA Forest Service, Northeastern Forest Experiment Station,180 Canfield St.,
Morgantown, WV 26505-3101

G.A. ELMES
Department of Geology and Geography, West Virginia University, Morgantown, WV 26506

L.P. SCHAUB
Department of Entomology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

M.A. FOSTER and M.C. SAUNDERS
Department of Entomology, The Pennsylvania State University, University Park, PA 16802

Abstract. GypsES is a decision support system for the management of gypsy moth using a knowledge-based geographic information system and multiple knowledge-based modules or 'advisors'. The advisors provide decision information on Forest Hazard Rating and Risk Assessment; Insect Monitoring and Prediction; and Intervention Decision and Implementation. System development is sponsored jointly by two branches of the USDA Forest Service: the Gypsy Moth Research and Development Program of the Northeastern Forest Experiment Station and the Forest Pest Management Technology Development Program through the Northeastern Area, State and Private Forestry. The basic objectives of GypsES are to model the sequence of evaluations necessary for gypsy moth management decisions and to provide active managers of the gypsy moth problem with a useful tool to make their work more efficient. This paper describes the knowledge bases included in GypsES and the state of the software development project which incorporates that knowledge.

INTRODUCTION

The gypsy moth is an insect that defoliates trees, often disturbing forest ecosystems and the people who inhabit or use the forest. When gypsy moth expands into new regions, as it is doing in the southeastern and midwestern United States now, the potential economic damage is extensive, compounding the existing substantial aesthetic damage and urban nuisance problems. To help forest managers deal with this threat we developed a computer program that can help managers determine how to set priorities for their forest lands according to relative risk from gypsy moth and how to improve the efficiency of their gypsy moth control efforts.

GypsES is a decision support system for the management of gypsy moth using a knowledge-based geographic information system and multiple knowledge-based modules or 'advisors'. The advisors provide decision information on: Forest Hazard Rating and Risk Assessment; Insect Monitoring and Prediction; and Intervention Decision and Implementation.

Pages 56 - 64 *in* A.M. Liebhold and H.R.Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

THE KNOWLEDGE BASES

Hazard Rating

Hazard rating is important because it allows efficient allocation of financial and other resources to meet challenges from particular dangers to the management goals. Rating of forests with regard to hazard from forest insects has been done extensively for many insects in many forest types (Hedden and others 1981) and is generally regarded as a useful management tool. To be useful, however, a great deal of information is needed about the forest stand and the pest insect. In general terms, the necessary stand information includes species composition, stocking level, tree vigor, and stress levels. The population levels of the pest insect also are important in estimating timing of potential damage, but are not necessary to estimate long-term hazard.

Gypsy moth hazard rating includes the determination of where a problem is most likely to occur given certain conditions and how severe any damage is likely to be. Although gypsy moth may be a problem across the entire Northeast at times, the specific areas of forest where it may be found vary from year to year. Also, however, individual stands within the same major forest type and in the same geographic area may have very different potential hazards. Under some management objectives, such as high-use recreation areas, damage may be defined differently and include the mere presence of high insect populations rather than any damage to the trees.

Definitions of four terms are necessary to understand the current hazard rating system for gypsy moth. Susceptibility is the term used for the likelihood of defoliation of a given tree or stand when and if the gypsy moth is present. Vulnerability is the probability that damage (mortality, growth loss, reduced scenic beauty, etc.) will result if defoliation occurs. Hazard combines the probability and severity of damage with its effects on management goals for a specific area. Risk incorporates insect population trends to predict the probability that such an event damaging to the management goals will occur.

Gypsy moth hazard rating is based on information of varying quality. It is well documented that gypsy moth larvae feed on particular host species (Mosher 1915, Montgomery 1991). Susceptibility is a straightforward function of species composition (Gansner and others 1987). Vulnerability is a more complicated relationship. The primary complicating factor is the amount of additional stress to which an individual tree has been subjected. Estimates of individual tree vulnerability have been compiled for many species in Pennsylvania (Gansner and others 1987, Hicks and Fosbroke 1987) and are still being refined. Stand-level vulnerability, which is a more useful scale to the forest manager, can be compiled from individual tree data or from stand level surveys. The stand-level survey is easier to manipulate, but is somewhat more variable because of the information it necessarily omits.

Forests of the Northeast have been classified as to their general susceptibility and vulnerability to gypsy moth. The various types of mixed oak forests are most susceptible because the trees are preferred hosts for gypsy moth. Classification of vulnerability is more difficult, because it must incorporate stand history, current stand conditions, presence of secondary mortality agents, insect population trends, and predictions of future conditions of the trees. Several attempts have been made to predict vulnerability of stands, but the equations do not fit other geographic areas or different stand conditions because of the specific characteristics used. After the biological factors influencing the impact of gypsy moth have been estimated, a useful hazard rating system must account for the objectives of the land managers and how the potential disturbance from defoliation will influence those objectives. As with most sociological factors, principles can be framed, but little real information is available. Highly reliable information on the relationship between defoliation levels and insect population levels is also still lacking.

Existing gypsy moth hazard ratings are based primarily on species and condition of individual trees. When such information is available, it is the best source from which to predict hazard to the forest. However, many areas of forest or partially forested land will not have such detailed information but a decision still will be needed on how to deal with the potential threat of gypsy moth.

Monitoring and Prediction of Insect Populations

Techniques and methodology for sampling gypsy moth and its associated natural enemies have been developed and in some instances tested and validated. The treatment threshold concept is central not only to sequential sampling but also to integrated pest management in general. Sampling for research purposes varies with the nature of the study and usually is more intensive than techniques used by managers. Managers usually require samples over large areas of variable habitat and are constrained by time and economics. For gypsy moth, egg mass, late instar larvae, male adult, frass, and head capsule sampling can be used but none have proven totally effective for making management decisions. Pheromone traps are a sensitive means of detecting male moths but are limited to detecting and delimiting new infestations. Egg-mass counts are routinely used by managers to decide on the need for suppression tactics. Currently used methods are prism points or fixed-radius plots and timed walks that provide only number of egg masses per acre and have not been a dependable predictor of defoliation. Factors such as forest site, foliar biomass, insect population vigor, and phenology are important components of predicting defoliation for purposes of initiating management action.

Currently, the implementation of truly integrated gypsy moth management programs is constrained by an inability to forecast outbreaks with adequate accuracy. There is substantial evidence that many areas designated for treatment never would reach damaging densities. Conversely, populations in stands that are rejected for treatment often irrupt to defoliating levels.

Several studies (Campbell and Standaert 1974, Gansner and Herrick 1985) have focused on predicting defoliation from gypsy moth egg mass density, estimated either from fixed-radius plots (Kolodny-Hirsch 1986) or fixed- and variable-radius plots (Wilson and Fontaine 1978). It is obvious that egg-mass density alone may not always accurately predict subsequent defoliation since gypsy moth dynamics, like that of most other insect species, is affected by a complex set of factors. Variability in fecundity, egg survival, first-instar dispersal, and larval survival may all contribute to variance in the relationship between egg mass density and defoliation (Campbell and Standaert 1974). More research is needed on the development of simple, yet precise, models that will forecast defoliation from variables that can be measured economically.

Intervention Decisionmaking and Implementation

Decisions regarding management of gypsy moth are always heavily influenced by political factors. The insect and the trees it attacks are highly visible to the public and draw much attention from the press.

Decisionmaking with regard to treatment involves three functions: decision, implementation, and evaluation. Treatment decision determines where to administer gypsy moth suppression activities. Implementation carries out the suppression process; that is, the details of aerial application and alternatives such as silvicultural options and natural enemies. Evaluation records the year's suppression program. This allows a comparison of the suppression program's efficacy with that of previous years. The goal of treatment decision is to determine which areas or polygons are to be treated. The logic flow can be divided into five main tasks: (a) determine which areas qualify for treatment, (b) split areas where justified by heterogeneity in risk or phenology (c) buffer or eliminate those areas with open water, objectors, aerial navigation hazards, or nontarget species, (d) assign treatment priorities to those that remain, and (e) identify the final set of treatment units that are affordable within the user's budget (in conjunction with state assistance).

The knowledge base for the treatment advisor is derived from two categories of government documents: Environmental Assessments and State Guidelines for gypsy moth cooperative suppression programs in Delaware, Maryland, Michigan, New Jersey, Ohio, Pennsylvania, Virginia, and West Virginia. The Environmental assessments describe gypsy moth suppression program objectives, biological criteria for areas to be included in a suppression program, alternative treatment options, and justification of recommended options. Guidelines describe the specific procedures to be followed by program staff in preparation and submittal of proposed treatments to the respective states.

Geographic Information Systems

Geographic information systems (GIS) enable gypsy moth management decisions to include, store, manipulate, and analyze geographical data in a spatial frame of reference. Although maps are the most commonly used product of GIS, the most important feature of a GIS is its ability to handle and analyze multiple layers of spatially referenced data. For example, map themes related to the determination of risk and hazard, the location of insect populations, and other data may be overlaid to produce measures of areal association. One of the most significant uses of GIS in GypsES is the creation of new data layers through reclassification or map overlay operations or both. In addition, the strength of influence of variables over distance may be calculated to provide otherwise unavailable information about a management unit from adjacent and surrounding areas.

Conceptually the intelligent functions of the GypsES GIS are separated into the graphical user interface and the spatial information management system. The graphical user interface guides an inexperienced user through the most efficient use of the system components according to their stated needs. More experienced users are provided with short cuts and tools to maximize system accessibility. The user interface also provides for concurrent access to different computer subsystems through multi-tasking and windowing. The spatial information management system is composed of several sub-systems for the management of: data error and lineage, cartographic output, and rules controlling spatial operations. Relevant knowledge of GIS experts and cartographers is being formalized to assist in: (1) geographic database maintenance, (2) map design, and (3) GIS operations. The knowledge bases feature the ability to obtain an explanation of the reasoning behind decisions that have been made; that is, the logic path is traced through the production rules to permit the user to determine the acceptability of the outcome provided by the expert system. An intelligent geographic information system (IGIS) comprises several interconnected components linked to knowledge bases in order to manipulate geographical data required for a given sequence of operations. A knowledge base has to be developed for each specialist area, embodying information that has been developed over many decades. In some instances, the knowledge required is on a research frontier and part of a research agenda and will be subject to revision.

A model approach to the development of the various IGIS knowledge bases falls into three categories: specification, design, and implementation. Understanding what knowledge is required is necessary before it is possible to determine how the knowledge should be represented in a formal or symbolic language structure. The principal issues are related to data quality and conveying such information to the user. Two major interrelated themes emerge as being central to the needs of users: lineage and error handling.

THE WORKING SYSTEM

Implementation of a fully functional system and its distribution to Ranger Districts and state gypsy moth control programs will significantly enhance the efficiency and efficacy of those programs. The current design of GypsES incorporates GIS capabilities compatible with those in the planned Forest Service GIS acquisition. It includes forest hazard rating and insect monitoring capabilities to focus on gypsy moth control efforts. It also incorporates the user's priorities in delineating recommended treatment areas. The algorithms and rule bases for use in the fully implemented system have been acquired from the literature and experts in the field, including the developers. These rule bases will continue to be refined during the ongoing development process.

The full GypsES system is being developed under the UNIX operating system. This system was chosen to use the Macintosh hardware already available to the developers and to prevent the end product from being obsolete before its release, which is currently planned for late 1993. The UNIX system allows use of the GIS program GRASS, which is a full-featured GIS in the public domain, a factor that helps minimize the cost to users. Hardware currently running GypsES includes Macintosh computers, Intel 80486 computers, Sun SPARC stations, and a DEC 5000 workstation, illustrating the portability of software developed in the X-Windows environment.

The Interface

The Graphical User Interface (GUI) is the part of the program seen by the user. It includes a system of windows, icons, menus, and pointers (WIMPs) that are designed to be easy to understand. The design of the GUI was complete by July 1990, and its basic programming has been accomplished since then. The individual modules within the GypsES system all use a set of four work windows in which different information can be displayed. Each opens with a simple flow chart to provide visual clues to the user about how the program's logic works and to simplify navigation through the program's many parts. Interactive use is guided by internal functions that simplify use and avoid excessive complexity to the user. An integrated help facility provides ready access both to information on how to use the system and on the knowledge bases behind it. Output to paper maps can be produced for any image that is visible on any screen in GypsES.

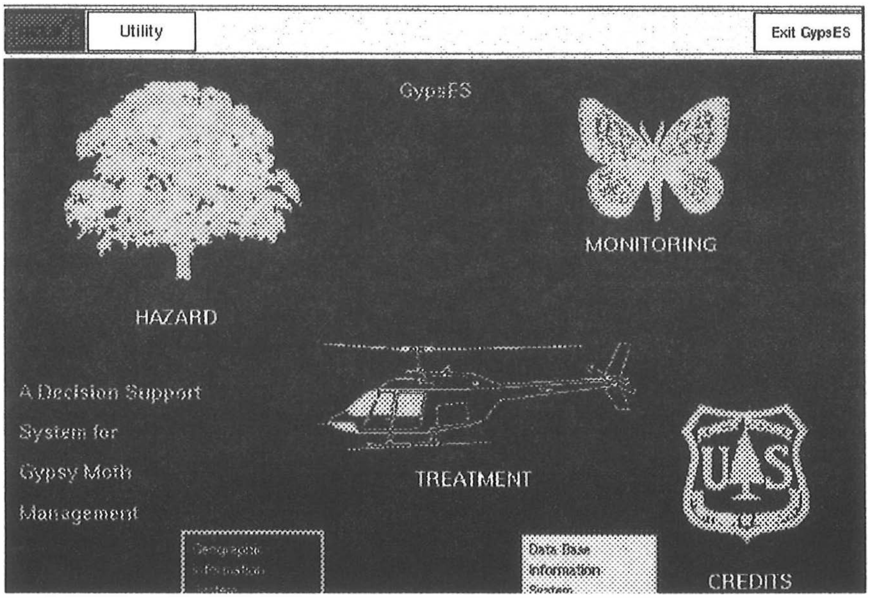


FIG. 1. The opening screen of GypsES showing the "point-and-click" interface with buttons and pull-down menus.

The Profile

Key elements in the system include the ability to store and recall information about the user and the areas under management. This function, known as the Administrative Profile, incorporates budgeting constraints, treatment priorities and preferences, and other individual characteristics, all of which are customized for or by each user.

Hazard Rating

The hazard rating module is designed to incorporate all the elements of the forest conditions and management considerations that are necessary as a precursor to any gypsy moth-related activity. This includes primarily information on the types of trees in the areas of concern, so that the system can determine the susceptibility to gypsy moth defoliation. Vulnerability to damage is then calculated based on the stocking, vigor, and prior disturbance history as described by the user. Management objectives are then incorporated to produce a hazard rating. This hazard rating can be used by the monitoring module to help determine sampling needs. In return, information from the defoliation prediction module is used within the hazard rating module to predict current risk of a gypsy moth infestation significant enough to need management intervention.

Monitoring and Prediction

Knowledge in the egg-mass sampling designer (EMSD) is derived from egg-mass sampling procedures applied in several county programs in Virginia and the Appalachian Integrated Pest Management (AIPM) Project and information available from other components in GypsES. The AIPM project developed sequential sampling plans for the forested areas in the AIPM project area (Fleischer and others 1991,.Rutherford and Fleischer 1989). The AIPM project implements a sequential sampling procedure for each 1-km cell. The EMSD adapts this approach to use sequential sampling procedures to estimate egg mass densities of management units. The parameters of sequential sampling are treatment (egg mass) threshold and acceptable error. The AIPM project leaves decisions on treatment thresholds and acceptable errors open to managers. The EMSD applies an average weighting scheme to combine input layers required to assign priorities to egg-mass sampling areas. The user chooses the weight she wants to associate with different input layers. Management units with a low Hazard Rating are associated with a high treatment threshold (1000 egg masses per acre) and management units with a high Hazard Rating receive a low treatment threshold (250 egg masses per acre). In an analogous fashion, acceptable errors between 15 and 35 percent are assigned to management units. The user has the ability to override the recommendations.

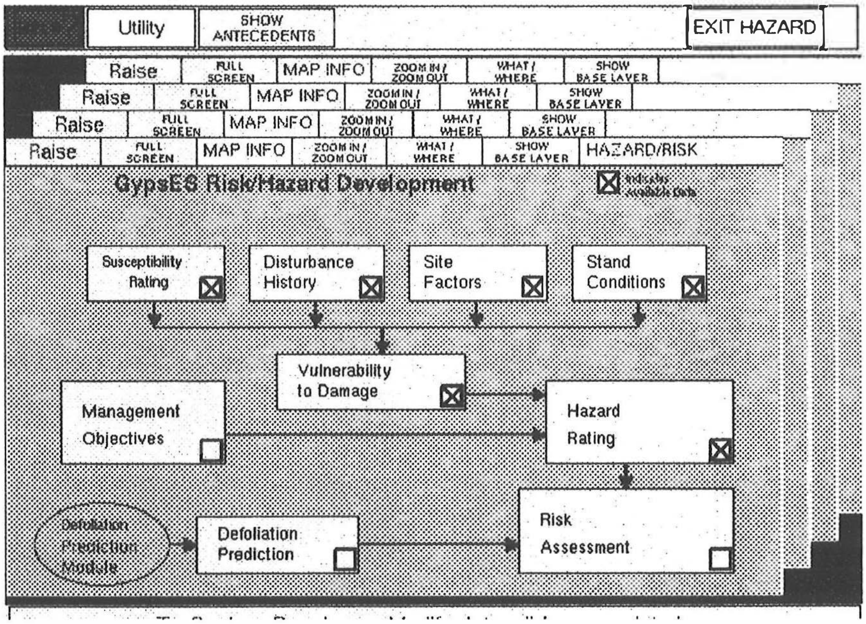


FIG. 2. The main Hazard Rating screen of GypsES showing the logic used to determine risk.

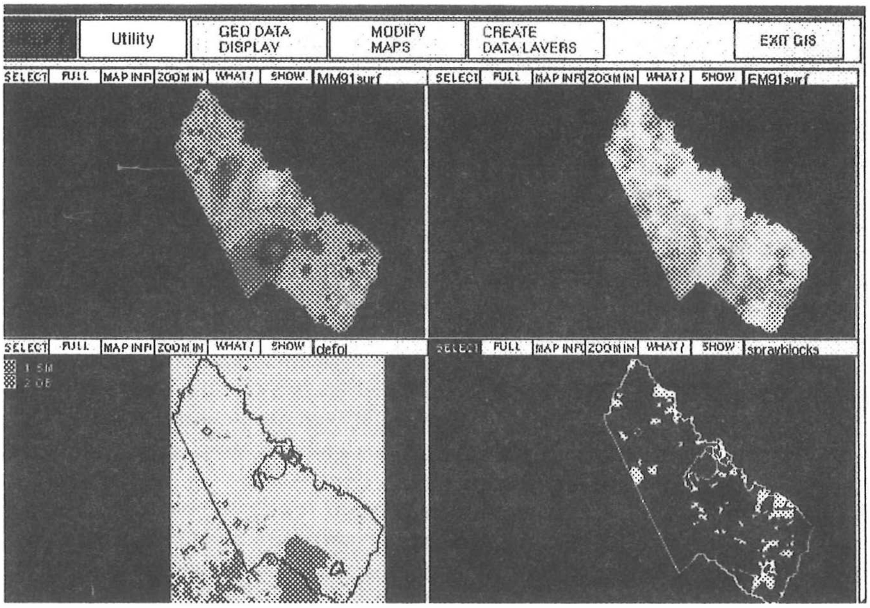


FIG. 3. Four input maps in tiled display as needed by the monitoring module.

The pheromone trapping system designer (PTSD) helps decide where and how many pheromone traps should be placed. These decisions are based on the monitoring priority resulting from the combination of the weighted input layers. Gypsy moth density estimates from pheromone traps have two purposes: (1) to provide the latest estimate of population densities in order to design egg-mass sampling and (2) to provide a low-cost, general survey of the population over a large area. The PTSD currently deals only with leading edge situations of gypsy moth populations.

The purpose of the phenology descriptor (PD) is to give the user a landscape-wide view of phenology (estimates of the timing of development of events such as gypsy moth egg hatch and larval development) and to provide information about phenology to the Treatment Component. Knowledge of phenology is important in planning spray operations and timing spray operations. To generate a map of phenology, the PD needs a map of elevation and temperature data from one location. The map of phenology is the basis for generating maps of expected phenology (mean and variability) of treatment blocks.

Treatment

The treatment module focuses on two functions in the treatment process: decision and implementation. Treatment decision assists a user in configuring potential treatment areas as suggested by the risk rating accomplished in the hazard rating module, assigning treatment priorities based on the risk assessment, and determining the final set of affordable treatment units. Treatment implementation advises on scheduling of aerial application activities, evaluation of aerial applicators' bids, and calibration of spray nozzles.

Potential treatment areas are identified through display of the risk rating generated in the Hazard module, and the user draws blocks on the screen to delineate areas of interest. The treatment module can then produce an estimate of the area to be treated. On the basis of cost estimates provided by the user, the module then assists in setting priorities for treatment that fit the fiscal constraints of the program.

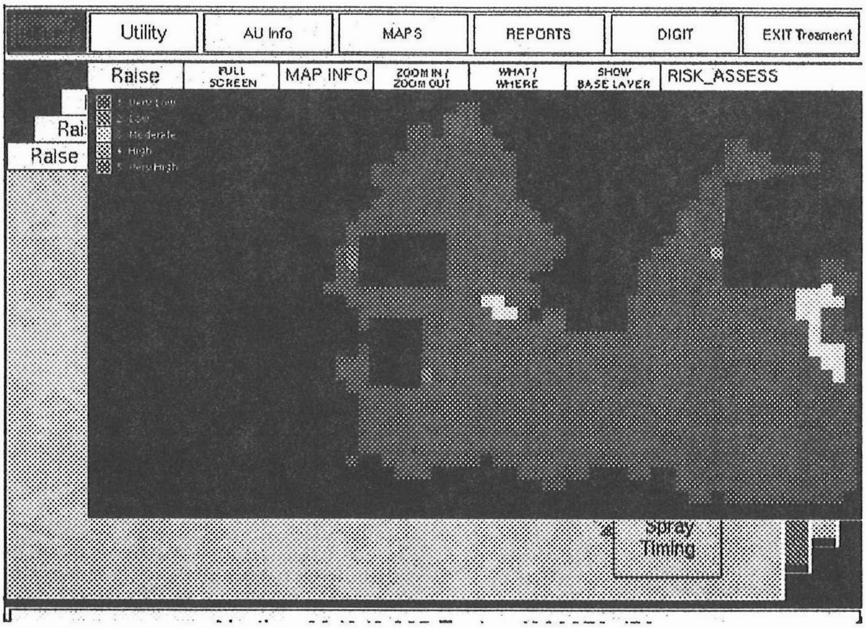


FIG. 4. Proposed treatment blocks drawn by a user on a sample area using the GypsES treatment module.

The scheduling of treatment blocks is based on information from the Phenology Descriptor. Predicted timing of larval development over each of the blocks produces an estimate of how much area needs to be treated during which time periods and how wide an effective window may be for each area and the overall program.

ACKNOWLEDGEMENTS

This work is supported by funding from the USDA, Forest Service, Northeastern Forest Experiment Station and Forest Pest Management Technology Development Program.

LITERATURE CITED

Campbell, R.W., and J.P. Standaert. 1974. Forecasting defoliation by the gypsy moth in oak stands. Forest Service Res. Note NE-193. U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA. 7p.

Fleischer, S.J., F.W. Ravlin, and R.C Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (*Lepidoptera: Lymantriidae*) egg mass in eastern hardwood forests. Journal of Economic Entomology **84**:1100-1107.

Gansner, D. A., and O.W. Herrick. 1985. A method for predicting gypsy moth defoliation from egg mass counts. Northern Journal of Applied Forestry **2**:78-79.

Gansner, D.A., O.W. Herrick, G.N. Mason, and K.W. Gottschalk. 1987. Coping with the gypsy moth on new frontiers of infestation. Southern Journal of Applied Forestry **11**(4):201-209.

Hedden, R. L., S.J. Barras, J.E. Coster, editors. 1981. Proceedings of Hazard-rating systems in forest insect pest management, 31 July-1 August 1980, Athens, GA. Gen. Tech. Rep. WO-27. U.S. Department of Agriculture, Forest Service. Washington, DC. 169p.

Hicks, R.R., D.E. Fosbroke. 1987. Stand Vulnerability: Can gypsy moth damage be predicted? Pages 73-80 *in* Fosbroke, S. and R.R. Hicks, Jr., editors. Proceedings on Coping with the gypsy moth in the new frontier, 4-6 August 1987, Morgantown, WV. West Virginia University Books.

Kolodny-Hirsch, D.M. 1986. Evaluation of methods for sampling gypsy moth (*Lepidoptera: Lymantriidae*) egg mass populations and development of sequential sampling plans. Environmental Entomology **15**:122-127.

Montgomery, M.E. 1991. Variation in the suitability of tree species for the gypsy moth. Pages 1-13 *in* Gottschalk, K.W., M.J. Twery, and S.I. Smith, editors. Proceedings of the USDA Interagency Gypsy Moth Research Review, 22-25 January 1990, East Windsor, CT. Gen. Tech. Rep. NE-146. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

Mosher, F.H. 1915. Food plants of the gipsy moth in America. Agric. Bull. 250. U.S. Department of Agriculture, Washington, DC. 39p.

Rutherford, S.L., and S.J. Fleischer. 1989. AIPM egg mass sampling and data entry handbook. Dept. of Entomology, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Wilson, R.W., Jr., and G.A. Fontaine. 1978. Gypsy moth egg mass sampling with fixed and variable radius plots. Agric. Handb. 523. U.S. Department of Agriculture, Washington, DC. 46p.

MODEL AND DATA-DRIVEN VISUALIZATION OF FOREST HEALTH DYNAMICS

BRIAN ORLAND, J. JAY OBERMARK, JEANINE LAFONTAINE, TERESA SUTER
Imaging Systems Laboratory, Department of Landscape Architecture,
University of Illinois at Urbana-Champaign

Abstract. Natural systems change slowly and impacts on them become evident only with the passage of considerable time. The ability of scientists and managers to comprehend such systems can be aided by the use of computer modeling accompanied by visualization of the resulting predicted changes. Visualization tools range from strictly scientific tools enabling specialists to better understand complex resource interactions, to visual simulation tools enabling non-experts to judge the acceptability of expected changes. This paper describes the use of different visualization techniques in the context of large-scale forest management. Use of such techniques in contentious settings results in the necessity to demonstrate the validity and accuracy of resulting imagery, as well as represent the dynamics of changing systems and the uncertainties inherent in computer modeling. This paper describes a visualization system in development to address these issues.

INTRODUCTION

Typically, forest health or productivity impacts occur sporadically and proceed slowly, making the understanding of system dynamics by forest scientists difficult to assimilate, and the appropriate management responses difficult to promote and initiate. Computer data visualization offers opportunities to rapidly review developing impacts and alternative responses by animations of the outputs of models such as those for stand growth or insect spread.

BACKGROUND

Data visualization has been recognized as an increasingly important aspect of the management of environmental resources (see Orland (ed) in press). Visualization tools have been used both by natural resource scientists seeking to better understand their science (e.g., Onstad, 1990; Larson et al., 1989; Cox, 1989), and by social scientists seeking to better understand human behaviors vis-a-vis those resources (e.g., Orland et al., 1990; Malm et al., 1980; Daniel et al., 1988). However, each group of users is willing to accept that their tools could bear considerable improvement, and that the wide range of tools in use would benefit from integration with comprehensive links between different modeling domains (Orland, in press). In addition, visualization users have identified several pressing needs in the development of new tools for environmental management. First, the reliability and validation of visualizations has been identified as an area needing attention (Daniel, in press) and, second, the necessity to support visualization at detailed as well as regional scales has been identified (Orland, in press).

Because of the complexity of their biology and their sensitivity to public opinion, the national forests have been the focus of extensive programs of modeling and visualization. There are comprehensive models of timber growth (e.g., Wykoff et al., 1986) and of pest damage (e.g., Stage et al., 1986) available for various parts of the forest system. Visualization tools have been developed to respond to those

Pages 65-72 *in* A. M. Liebhold and H. R. Barrett, editors. 1993. Proceedings: Spatial Analysis of Forest Pest Mangement. USDA Forest Service General Technical Report NE-175.

models (e.g., Heasley, 1990; Loh, 1990) and have been used in one or two pilot studies to assist public groups understand the forest dynamics at work in a management plan. Others (e.g., Daniel and Orland, 1991; Kruse et al., 1991; Orland, Vining and Ebreo, 1992) have used visualizations of forest conditions to elicit public reactions to forest policy issues and to alternative management plans.

CRITIQUE OF PREVIOUS VISUALIZATION TECHNIQUES

For each group there have been considerable drawbacks in the nature of the visualizations available. For example, the visualizations created by Heasley (1990) presented convincing perspective diagrams of forest conditions to facilitate understanding of forest growth, but were probably not sufficiently realistic to support valid evaluations of scenic quality. Moreover, they were based on timber stand data -- the common management unit for national forests. Since a timber stand is determined as a relatively homogeneous unit of variable size, there is no detailed information about the locations of individual trees -- Heasley's visualizations were probabilistic in their distribution of trees and thus not able to accurately depict detailed areas.

Modeling based on such coarse delineations lacks the ability to address detailed issues of forest management, failing to offer support for management actions which increasingly focus on tree-by-tree management, and failing to respond to current conceptions of forest ecosystem dynamics based on the behavior of individual stems. The opportunity to model and visualize forest systems in the desired detail has been missing for the lack of sufficiently detailed forest databases, and for the lack of visualization techniques able to handle the extremely large databases that would result.

In contrast, the visualizations created by Orland and collaborators (e.g., Orland, 1991) display high levels of detail and realism. However, their verifiable links to resource models have been weak, relying on expert appraisals rather than model output. This has mostly been an immediate consequence of there not being adequate models available (e.g., Orland et al., 1990), but the links of model to image would still present problems related to graphic system issues of geometry and perspective (see Orland and Kesler, 1991) as well as the data issue noted above -- that a stand map is too coarse to support detailed visualization.

Orland and Kesler (1991) suggested that the video-imaging technology being used for detail visualization was an intermediate technology -- precisely for the reasons noted above. The benefits of reliability and verifiability would accrue to the geometrically-modeled types of visualization if the necessity for sufficiently detailed databases could be met. The requirement for realism, while not as easily achieved, might be addressed through ever-improving graphic tools. Much of Orland's work for the last few years has focused on the development of image processing and sampling techniques able to create realistic images in response to calls from underlying forest system models (see Figure 1).

A SPATIALLY DEFENSIBLE VISUALIZATION SYSTEM

In the work reported here, an advanced graphically-oriented computer workstation has been used to develop a tree-by-tree visualization of forest databases. Computer capabilities have been evolving rapidly. When Heasley (see above) was developing his forest stand visualizations the graphics components of the computer system were limited by the US Forest Service Data General computer and associated Tektronix graphics displays. None of the devices was optimized, or even intended, for dynamic, shaded, three-dimensional displays. In addition to limited graphics capabilities, Heasley's visualizations were restricted by available computer power and time-sharing to image creation times of several to many minutes. Interaction with the screen image was impossible.

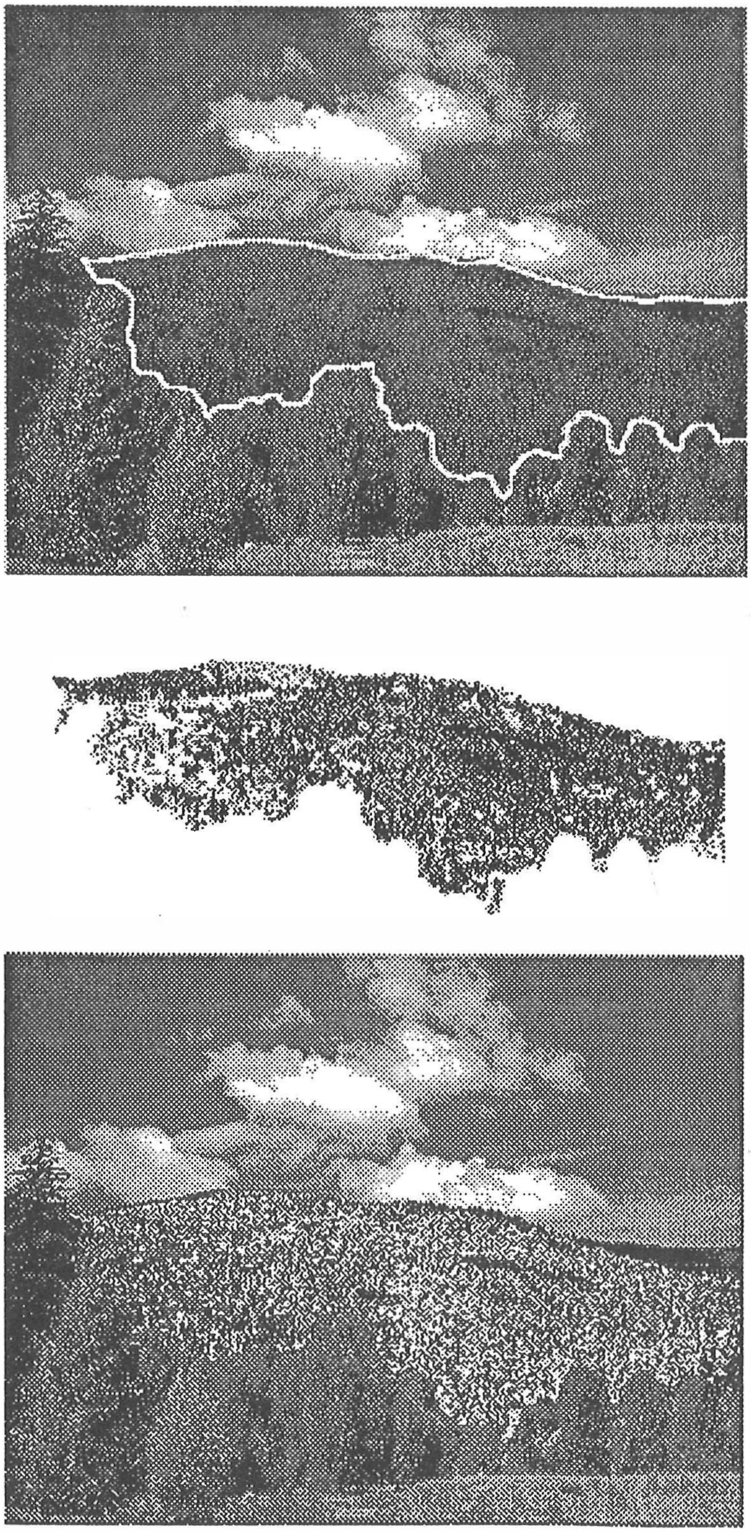


FIG. 1. Image processing was used to simulate the visual effects of Western Spruce Budworm damage on mixed conifer stands on the Carson National Forest, New Mexico. The first image shows the impacted stand delineated; the next image shows the digital filter used to manipulate the image; the third image shows the filter applied to the original image (changes greatly exaggerated for black and white reproduction).

These earlier visualizations were developed to display the data in forest stand tables. While that strategy was fitting to the agency's field operators the outcome must inevitably be an approximation to on-ground conditions. Stand data based on sampled data lack the spatial differentiation vital to many aspects of forest modeling. On-ground management of the resource results in decisions to thin particularly dense tree groupings -- or to preserve the resulting wildlife habitat -- but those decisions cannot be made based on the data held in the forest inventory. At the same time, the increasing burden of public accountability suggests new demands for detailed and concrete forest resource information to be used in management. Orland (in press) has described the emerging need for highly detailed and defensible data visualizations in forest management.

Three goals were identified for the visualization system described here:

1. To achieve sufficient speed in the modeling system to allow users to use the visualization as a decision support tool, rather than just to display decisions already made.

2. To develop forest visualizations where individual trees are represented and to take advantage of the most detailed single tree growth models and population dynamics models available.

3. To develop an interface which enables a user to import data tables from a variety of sources, to deal with data bases of differing resolution and abstraction, and to manipulate model parameters and instantly view the results.

SYSTEM DESIGN

To achieve the above goals demanded the identification of a suitable computer platform. The Imaging Systems Laboratory at the University of Illinois was mostly built around the use of personal computer equipment -- both IBM-PC and Apple Macintosh formats. The machines had been frequently up-graded and remain adequate for their main task -- image processing of single frame images. However, the equipment did not have sufficient processing speed or adequate memory for the rapid graphic modeling proposed here. A high-performance workstation, the Silicon Graphics Indigo, was acquired. This machine was a recently introduced, and inexpensive, dedicated graphics workstation. The computer uses the UNIX operating system, has 16Mb of memory and a 420Mb hard disk. The dedicated graphic processor of this particular machine is designed for 3-D visual modeling at speeds many times faster that with PC-DOS or Macintosh machines.

The modeling and visualization techniques adopted had been widely used and tested (e.g., Cox, 1990). However, much previous work in the area of resource management had focused on visualization tasks with relatively simple spatial characteristics. For example, growth models and pest population models had assumed flat terrain and evenly spaced host species. In addition, with interest focused on scientific visualization, the visual icons and techniques in use could be quite abstract.

In contrast, in the instances reported here the realism of the resulting imagery was critical, so some elaboration of previous visualization models was necessary to deal with irregular terrain, and to create visual icons sufficient to represent tree-forms when seen in the context of the modeled stand.

Programming of the visual modeling system has used the C programming language and the GL graphics library (a Silicon Graphics Inc. proprietary system). To date visualization models have been developed to allow the rapid and easy manipulation of the display (e.g., zooming and panning) using keyboard or mouse. Simplified timber growth and harvesting models have been developed which allow the user to readily alter model parameter or harvest prescriptions using standard forestry nomenclature. (Figure 2)

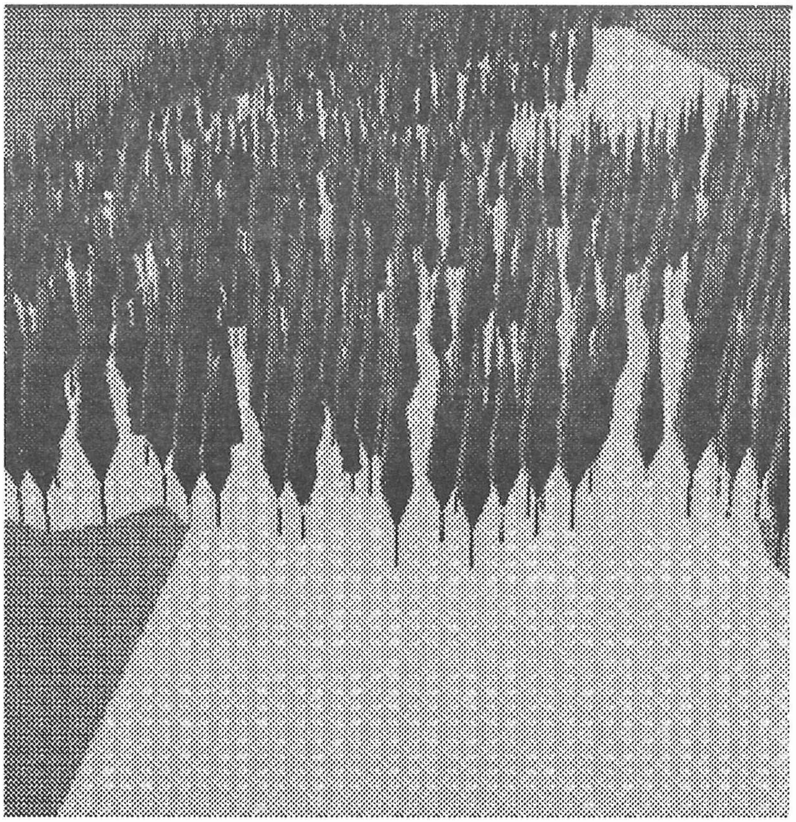


FIG. 2. A portion of a mixed spruce-fir stand on the Dixie National Forest, Utah. Image indicates the spatial distribution corresponding to locations from on-ground inventory data.

The implementation of these tools on two forest case studies is described below. The intention is to incorporate models for pest impact and stand recovery as resources become available, and to create animated visualizations that illustrate the changes expected in that stand over time, under a variety of different stand management prescriptions.

TWO CASE STUDIES

Chugach National Forest

In the course of other funded research two highly detailed forest inventories have been assembled. The first was an inventory of a Lutz spruce-white spruce-hardwood stand on the Kenai Peninsula in Alaska (Orland et al., 1990). The location is within an area which has suffered intense bark beetle attack in recent years, resulting in widespread tree mortality and offering ample opportunity for later validation of model outputs. Three years of research in the area has focussed on the application of computer visualization techniques to solicit public preferences for various public policy options facing the Kenai. The spatial data was collected using a laser range finder device, enabling the collection of accurate location (in x, y, and z dimensions), height, dbh, condition and species data.

We will conduct a validation study to measure the effectiveness of the visualizations by reference to existing conditions elsewhere on the Kenai peninsula. The area exhibits examples of forest stands of numerous different compositions and age structures, at different stages of insect attack and recovery. We will evaluate the utility of the visualization approach vis-a-vis the visual simulation approaches previously employed by Orland, (a) by expert panel scrutiny conducted by forest entomologists and silviculturists, and (b) by a pilot study comparison of preference judgements for graphic modeled vs. edited video visual simulations.

Dixie National Forest

The second case study is a mixed Engelmann spruce-subalpine fir stand on the Dixie Forest in southern Utah. The location is suffering an active outbreak of spruce beetle in large diameter trees, and is expected to lead to widespread mortality. Current visualization projects are focusing on the historic and long-term future effects of insect outbreaks on the forest. The spatial data were collected by stereoplotter using high resolution aerial photography of the stands.

In the absence of detailed ground data for this stand the validation issue becomes one of evaluating the relationship between estimated forest conditions represented by the visualization vs. on-ground conditions. As above, the evaluation will comprise both expert appraisals and preference judgements.

BENEFITS OF THE VISUALIZATION APPROACH

The principal applications benefits of the project were described above. In addition there are significant benefits to on-going research programs:

1. The visual simulation techniques employed previously have suffered from inadequate geometric control. While it has been possible to guide the image editing processes by overlaying wire-frame topographic grids, certain physical constraints of the computer display systems (e.g., the thickness of displayed vector lines) have restricted the accuracy that can be attained. The approach described in this paper offers much better geometric control, although at the expense of some realism in the final picture. The issue of when or whether that loss is sufficient to impact the usefulness of the imagery in decision-making is an important research question (see Daniel, in press). This pilot study will enable the investigation of such issues at a time when the direction of visualization of forest systems is in need of such information.

2. The systems previously addressed in scientific visualization, while complex in the number and interactions of variables portrayed, have focused on relatively simple data sets -- for example, individual corn plants on a flat field, evenly spaced, and all starting at the same age. This study offers the opportunity to add several levels of complexity -- the stand in question contains four species, unevenly spread on uneven topography, in numerous age classes, both healthy and insect-impacted. As a visualization exercise it offers many previously unaddressed complexities and will have important ramifications both for visualization and for modelers working in complex systems.

ACKNOWLEDGEMENTS

This work has been supported by the University of Illinois, Research Board and Department of Landscape Architecture. Data collection has been courtesy of USDA FS, State and Private Forestry FPM, Region 10, Anchorage; the Dixie National Forest, Cedar City, UT; State and Private Forestry FPM, Region 4, Ogden; State and Private Forestry FPM-MAG, Fort Collins.

LITERATURE CITED

Cox, D.J. 1990. The art of scientific visualization. Academic Computing, **4**(6):20-56.

Daniel, T.C., G. Long, J. Heasley, A. Lynch, B. Orland, and D. Wunneburger. 1988. Computer simulation methods for representing and manipulation forest vistas. *in* Resource Technology 88 - International Symposium on Advanced Technology in Natural Resource Management. Fort Collins, CO.

Daniel, T.C., B. Orland, A. Lynch, J. Hetherington, and J. LaFontaine. 1990. Integration of GIS and video imaging technology for data-driven visual simulations. *in* USDA Forest Service Remote Sensing Applications Conference, Tucson, AZ. Society for Photogrammetry and Remote Sensing.

Heasley, J. 1990. Simulating the visual effects of timber harvest practices. *in* Resource Technology 90 - Second Symposium on Advanced Technology in Natural Resource Management, Washington, D.C. American Society for Photogrammetry and Remote Sensing.

Larson, S.M., G.R. Cass, K.J. Hussey, and F. Luce. 1988. Verification of image processing based visibility models. Environ. Sci. Technol. **22**(6):629-637.

Malm, W., K. Kelley, J. Molenar, and T. Daniel. 1981. Human perception of visual air quality (uniform haze). Atmospheric Environment **15**(10/11):1875-1890.

Orland, B. 1991. Digital image processing aids for visual simulation of forest management practices. Pages 73-86 *in* T. Daniel and I. Ferguson, editors. Integrating Research on Hazards in Fire-prone Forest Environments, Proceedings of the US-Australia workshop, 1989, Melbourne, Australia. US Man and the Biosphere Program, Washington, DC.

Orland B. I*n press.* Evaluating regional changes on the basis of local expectations: a visualization dilemma. *in* B. Orland, editor. Data Visualization in Environmental Management, Special Issue of Landscape and Urban Planning.

Orland, B., editor. *In press.* Data visualization in environmental management, Special Issue of Landscape and Urban Planning.

Orland, B., T.C. Daniel, J. LaFontaine, and C. Goldberg. 1990. Visual effects of insect damage in western mixed coniferous forests, Final Report, Cooperative Research Project: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Work Unit 4501. Imaging Systems Laboratory, Department of Landscape Architecture, University of Illlinois, Urbana. 33p.

Orland, B. and G. Kesler. 1991. Computer video-imaging for training land design applications. Final Report. No. U.S. Army Construction Engineering Research Laboratory. Imaging Systems Laboratory, Department of Landscape Architecture, University of Illinois, Urbana, IL.

Orland, B., J. LaFontaine, and T.C. Daniel. 1990. Visualizing alternative futures for forested landscapes. in Resource Technology 90 - Second International Symposium on Advanced Technology in Natural Resource Management, American Society for Photogrammetry and Remote Sensing. Washington, D.C.

Stage, A.R., N.L. Crookston, and M.R. Wiitala. 1986. Procedures for including pest management activities in forest planning using present or simplified planning models. Pages 202-215 *in*. Bailey, R.G., technical coordinator. Lessons from using FORPLAN, Proceedings of a planning and implementation workshop, 29 April-1 May 1986, Denver, CO. USDA Forest Service Land Management Planning Systems. Washington, D.C.

Vining, J., and B. Orland. 1989. The video advantage: a comparison of two environmental representation techniques. Journal of Environmental Management **29:**275-283.

Wykoff, W.R. 1986. Supplement to the user's guide for the stand prognosis model-version 5.0 No. INT-208. United Stated Department of Agriculture.

ASSESSMENT OF POTENTIAL IMPACT OF GYPSY MOTHS ON GREAT SMOKY MOUNTAINS NATIONAL PARK

HOPE R. BARRETT
USDA Forest Service, 180 Canfield St., Morgantown WV 26505-3101

STEPHEN C. NODVIN
NPS-CPSU, 274 Ellington Plant Sci. Bldg, University of Tennessee, Knoxville TN 37901-1071

Abstract. In assessing the potential impact of gypsy moth on Great Smoky Mountains National Park (GRSM), forests in GRSM were rated for defoliation potential, sensitivity to environmental stress, and tree mortality potential. Maps of the GRSM vegetation cover, human access, elevation, slope, and aspect were obtained in digital format at 90-meter pixel resolution. These parameters were incorporated into a geographic information system modeling program.

Ratings of forest-type preference for defoliation by gypsy moth resulted in five major classes: most preferred (6% of GRSM, 11,551 hectares); highly preferred (15%, 32,030 hectares); moderately preferred (30%, 61,376 hectares);, less preferred (11%, 22,250 hectares); and least preferred (2%, 4,765 hectares). Twenty-three percent of GRSM (47,807 hectares) was sensitive to gypsy moth defoliation due to slope, aspect, and elevation. Combinations of forest preference with forest sensitivity produced estimates of potential forest mortality. Fifteen percent of GRSM (30,416 hectares) was predicted to be vulnerable to forest mortality within the first 2 of gypsy moth introduction.

Both forest and human management of GRSM may be influenced by the invasion of gypsy moth. Infestation in GRSM may prompt mitigation actions by the National Park Service should defoliation reach an unacceptable level and/or if resultant changes in forest composition are unacceptable or public safety is threatened by dying or falling trees in recreation or visitation areas.

INTRODUCTION

The gypsy moth, *Lymantria dispar*, is one of the most significant forest pests in North America. Larvae of this species can feed on the foliage of more than 300 tree species, and gypsy moth often causes extensive defoliation of forests that can result in tree mortality. Migrating gypsy moths are present in Tennessee, southwest Virginia, and North Carolina, but their populations are not dense in the Great Smoky Mountains National Park (GRSM). Since 1984, GRSM personnel have used pheromone traps to monitor the park for the presence of male gypsy moths. To date, only a few male moths have been caught annually (Leonard 1991), so gypsy moth does not yet pose a threat to the park.

This study was the first attempt to assess the forests of GRSM for potential impacts from the inevitable gypsy moth invasion. Three questions were addressed: What areas of GRSM are likely to become infested and thus defoliated by gypsy moth within 2 years of gypsy moth introduction? What forested areas would likely suffer mortality if defoliated by gypsy moth considering topographic features of the park? What specific park areas are both likely to be infested with gypsy moth and suffer forest mortality within 2 years of gypsy moth introduction into the park?

Pages 73-84 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

METHODS

The following variables were evaluated: short-term susceptibility to defoliation, forest sensitivity to gypsy moth defoliation, and short-term vulnerability to forest mortality. The evaluations were completed using a geographical information system (GIS) and together provide a hazard assessment for GRSM forests likely to be affected by gypsy moth.

Short-Term Susceptibility Evaluation

Susceptibility of forests in GRSM was determined on the basis of ratings of feeding preference by gypsy moth larvae and proximity to sites of probable gypsy moth introduction. The degree of feeding preference was based on species composition within nine forest types in the park. In this paper, defoliation refers to 100% leaf loss from a tree that is infested with gypsy moth larvae. A GRSM vegetation cover map developed by MacKenzie (1991) categorized 90- by 90-meter (0.81 hectare) digital GIS picture elements (pixels) into various forest types.

Foliage Preference Index. - The susceptibility evaluation required the development of a foliage preference index to rank the nine forest types into preference categories. The term "preferred" in this study refers to forested areas favored by gypsy moth due to the high palatability of the tree leaves. The 63 tree species included in verifying the vegetation cover map were weighted according to foliage preference by gypsy moth. Each species was assigned a 0, 1, 2, or 3 with zero indicating that no information was available and 3 indicating the highest preference. Because food preferences by gypsy moth larvae may vary among geographic locations, the foliage preference weights assigned to tree species were unique to GRSM (Table 1). Preference weights were assigned to tree species following a review of the preference weights used in each of the following studies: Kegg (1971), Gansner and Herrick (1985), Houston and Valentine (1985), and Shumway and Bowersox (1987). Within each of the nine forest types, species weight was multiplied by the species mean basal area following MacKenzie (1991). The products were summed across species and forest types with similar sums were placed in the same preference class (highest, high, moderate, low, lowest) (Table 2).

Dispersal Zone. - The second step in determining GRSM susceptibility ratings entailed locating pixels that represented areas where gypsy moths were assumed to be introduced. Frequently, this pest invades uninfested areas by attaching itself to transportation vehicles. Developed campgrounds, environmental education centers, visitor centers, picnic areas, and heavy- or medium-duty roads were determined to be the sites of assumed gypsy moth introduction into the park. Point data (campgrounds, education and visitor centers, and picnic areas) were digitized using a 1:125,000 resolution topographic map, while vector data (roads) were transformed from a digitizer to a raster GIS at a 90-meter pixel resolution. An equal probability of gypsy moth introduction was assumed at each point and along each vector. A dispersal zone around all sides of all introduction locations was created and represented the assumed distance (5 km) in which gypsy moths were expected to disperse within 2 years of their introduction to GRSM. This linear dispersal distance was based on an assumed dispersal rate of 2.5 linear kilometers per year. This rate generally is used to represent the expansion of low-density gypsy moth populations (Doane and McManus 1981).

TABLE 1. Ratings of Individual tree species for gypsy moth preference in the Great Smoky Mountains National Park

Scientific name	Rating	Scientific name	Rating
Acer pensylvanicum	1	*Liquidambar styraciflua*	3
Acer rubrum	2	*Liriodendron tulipifera*	1
Acer saccharinum	1	*Magnolia acuminata*	2
Acer saccharum	1	*Magnolia fraseri*	2
Acer spicatum	1	*Morus rubra*	1
Amelanchier arborea	2	*Nyssa sylvatica*	2
Amelanchier laevis	2	*Ostrya virginiana*	2
Aralia spinosa	2	*Oxydendron arboreum*	2
Aesculus octandra	2	*Picea rubens*	2
Betula lenta	2	*Pinus echinata*	2
Betula lutea	2	*Pinus pungens*	2
Betula spp.	2	*Pinus rigida*	2
Carpinus caroliniana	2	*Pinus strobus*	2
Carya cordiformis	3	*Pinus virginiana*	2
Carya glabra	2	*Platanus occidentalis*	1
Carya ovalis	2	*Prunus pensylvanica*	2
Carya pillada	2	*Prunus serotina*	2
Carya spp.	2	*Quercus alba*	3
Carya tomentosa	2	*Quercus coccinea*	3
Castanea dentata	2	*Quercus falcata*	3
Cladrastris kentukea	0	*Quercus prinus*	3
Cornus florida	1	*Quercus rubra*	3
Fagus grandifolia	2	*Generic red oak*	3
Fraxinus spp.	1	*Quercus velutina*	3
Halesia carolina	0	*Rhododendron maximum*	2
Hamamelis virginia	3	*Rhododendron spp.*	1
Ilex montana	1	*Robinia psuedocacia*	1
Ilex opaca	1	*Sorbus americana*	2
Juglens cinerea	2	*Sassafras albidum*	2
Juglens nigra	1	*Tilia heterophylla*	2
Juniperus virginiana	1	*Tsuga canadensis*	1
Kalmia latifolia	1		

0 = no information 1 = low preference 2 = moderate preference 3 = high preference

TABLE 2. Forest-type preference ratings for the Great Smoky Mountains National Park

Preference	Forest Type
Highest	Mesic oak
High	Pine-oak
High	Pine
High	Xeric oak
Moderate	Northern hardwood
Moderate	Cove hardwood
Moderate	Spruce-fir
Low	Mixed mesic hardwood
Lowest	Tulip-poplar

Susceptibility Ratings. - The third step in determining gypsy moth susceptibility ratings entailed the development of a program to locate forest-type preference ratings of pixels within gypsy moth dispersal zones. Forests outside of the dispersal zone were assumed to be nonsusceptible to defoliation during the first 2 years after introduction of gypsy moth. The model predicted what forests within the dispersal zone were likely to be defoliated within 2 years of introduction, and assigned ratings of highest to lowest susceptibility to the pixels.

Forest Sensitivity Evaluation

Forest sensitivity in this study refers to the likelihood that forests exist under environmental stress based on pixel location within distributions of particular topographic factors. Stress was measured by the associations of a forest type with the topographic factors (GIS map layers) of elevation, slope, and aspect. The rationale for this approach was based on preliminary observations that each of the nine forest types were normally distributed over the gradients of each of the three topographic factors. The assumption was that the majority of trees in the pixels located toward the center of the Gaussian (normal) distributions were experiencing lower stress compared to trees located in pixels at the extremes of the distributions. Each topographic variable was cross tabulated with each of the nine forest types and data were plotted on an XY graph. The plotted distributions represented frequencies of the nine forest types over an elevation gradient, seven slope classes, and eight aspect directions. An iterative Marquardt-Levenberg nonlinear least-squares curve fitting algorithm was used to fit Gaussian curves to the distributions (MicroCal, Inc., 1991). Goodness of fit was calculated and a 95% confidence interval was estimated from each Gaussian distribution. Lower and upper limits of each confidence interval were used to determine the "optimal" and "suboptimal" growing range for each forest type. "Optimal" referred to pixels representing a forest type assumed to be experiencing lower amounts of stress; "suboptimal" pixels representing a forest type that was experiencing higher stress. A model was developed to determine suboptimal forest growing sites due to all or any of three map layers. The model was applied to all nine forest types and determined high, moderate, and low forest sensitivity for all possible combinations of elevation, slope, and aspect.

Vulnerability Evaluation

Vulnerability was defined in this study as the likelihood that forests in GRSM would suffer mortality (the death of all trees in a pixel) within 2 years of gypsy moth defoliation. The vulnerability evaluation was based on the assumption that defoliation will weaken the stands and would indirectly kill the trees. The predicted degree of mortality for the park was based on all possible scenarios of combined forest susceptibility and sensitivity ratings.

The vulnerability evaluation was completed in one modeling step that combined the susceptibility ratings and forest sensitivity ratings. A program was developed to choose all possible combinations of forest susceptibility and sensitivity by following the rules outlined in Table 3. Pixels in each combination represented a specific degree of potential mortality (vulnerability rating) that was predicted to occur within 2 years of gypsy moth defoliation.

RESULTS

Susceptibility Evaluation

Foliage Preference Index. - Individual tree species that were assigned a foliage preference weight of 1, 2, or 3 influenced the overall forest-type preference rank (the likelihood that a forest type will be defoliated by gypsy moth). *Hamamelis virginia*, *Liquidambar styraciflua*, and all species of *Quercus* were highly preferred by gypsy moths, so these species were assigned a 3 (Table 1). Species of *Amelanchier*, *Betula*, *Carya*,, *Magnolia*, *Pinus*, *Prunus*, and several individual species were assigned a 2, indicating a moderate foliage preference. During the application of the selection index, 17 species were considered low in foliage preference. Among these were *Fraxinus* spp., *Ilex* spp., *Juniperus virginiana*, *Liriodendron tulipifera*, *Morus rubra*, *Plantanus occidentalis*, *Robinia pseudoacacia*, and *Tsuga canadensis*.

A foliage preference value of zero, indicated that a species did not influence the rank of the forest type. Two of the 63 tree species (*Cladrastris kentukea and Halesia carolina*) weighted for foliage preference were assigned a of zero because they were not ranked in the following studies: Kegg (1971) Gansner and Herrick (1985) Houston and Valentine (1985) and Shumway and Bowersox (1987) (Table 1).

Susceptibility Ratings. - Sixty-four percent of GRSM (131,972 hectares) were sufficiently close to assumed introduction sites to be defoliated within 2 years of the arrival of gypsy moth (Table 4). Approximately one-quarter of that land area consisted of forest types that were ranked as highly preferred by gypsy moth; about half consisted of moderately preferred forest types.

TABLE 3. If/then rules that use susceptibility and sensitivity ratings to determine vulnerability ratings for pixels that represent forests of the Great Smoky Mountains National Park

If susceptibility rating is:	And if sensitivity rating is:	Then vulnerability rating is:
Highest	High	High
Highest	Moderate	High
Highest	Low	Moderate
High	High	High
High	Moderate	Moderate
High	Low	Moderate
Moderate	High	Moderate
Moderate	Moderate	Moderate
Moderate	Low	Low
Low	High	Moderate
Low	Moderate	Low
Low	Low	Low
Lowest	High	Low
Lowest	Moderate	Low
Lowest	Low	Low
None	None	None

TABLE 4. Area based on preference ratings and composition of the Great Smoky Mountains National Park

Preference rating	Hectares (no.)	Percentage of GRSM
Highest	11,551	5.56
High	32,030	15.4
Moderate	61,376	29.6
Low	22,250	10.7
Lowest	4,765	2.29
Total	131,972	63.6

Forest Sensitivity Evaluation

Twenty-four percent of GRSM (47,807 hectares) were sensitive to gypsy moth defoliation based on the distribution of forest types across elevation, slope, and aspect: 0.32% of (662 hectares) had high sensitivity, 4.26% (8,852 hectares) had moderate sensitivity, and 18.4% (38,293 hectares) had low sensitivity (Table 5). A rating of high meant that the pixel was found to be a suboptimal growing site in all three map layers. A rating of moderate meant that the pixel was a suboptimal growing site in any combination of two data layers. A rating of low meant that the pixel was a suboptimal growing site in only one of the three layers.

Distributions of forest type/elevation, forest type/slope, and forest type/aspect were accepted within the determined degrees of freedom and chi square values in all nine forest types (Figures 1, 2, and 3). Normality was determined by the goodness-of-fit tests calculated for each Gaussian distribution. Distributions of forest type/elevation for xeric oak, pine oak, and spruce-fir types were distributed in a non-normal manner as were the slope distributions for all forest types. With the available data it was difficult to visualize where the peak of the distributions of xeric oak, pine-oak, and spruce-fir elevation might lie beyond the extremes of the elevation range sampled. When the peak of a normal distribution is near or beyond the ends of the sampled range, it often is difficult to fit the data to a normal distribution from mathematical algorithms. In such cases, it can be assumed that the peaks are at the end of the sampled range of elevation. Given the nature of the curve-fitting program used, it was possible to assign a peak to the distributions and thus assume their normality.

TABLE 5. Area based on sensitivity ratings and composition of the Great Smoky Mountains National Park

Sensitivity rating	Hectares (no.)	Percentage of GRSM
High	662	0.32
Moderate	8,852	4.26
Low	38,293	18.4
Total	47,807	23.0

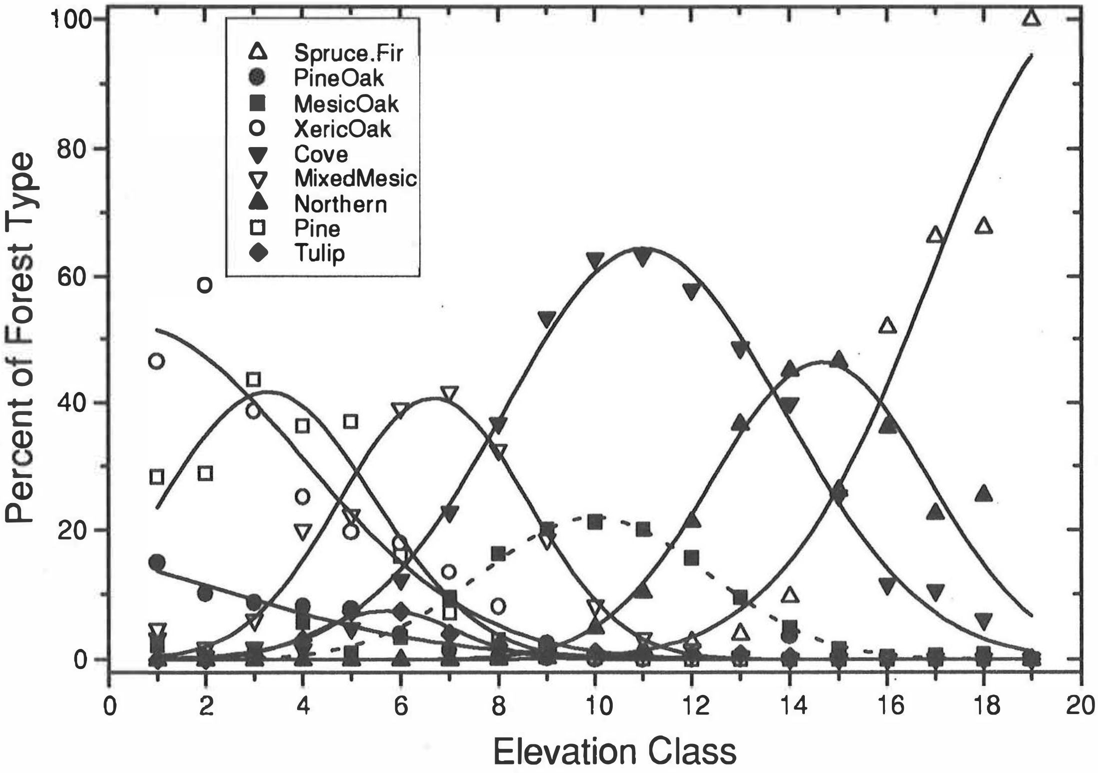


FIG. 1. GRSM Forest Type - Elevation Distributions

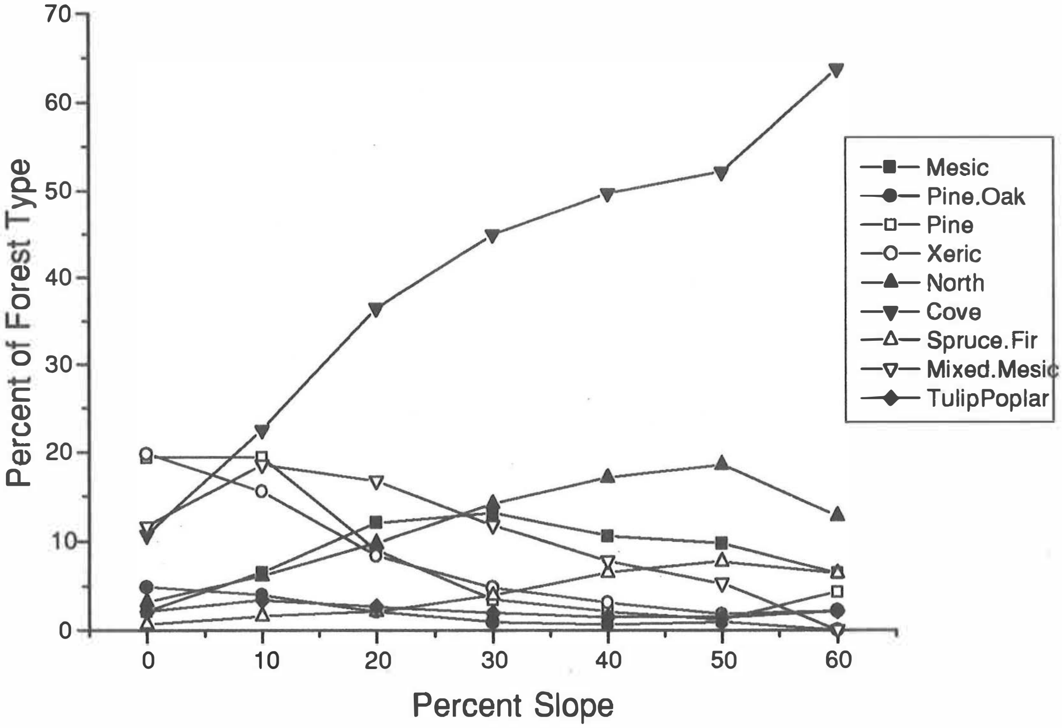


FIG. 2. GRSM Forest Type - Slope Distributions

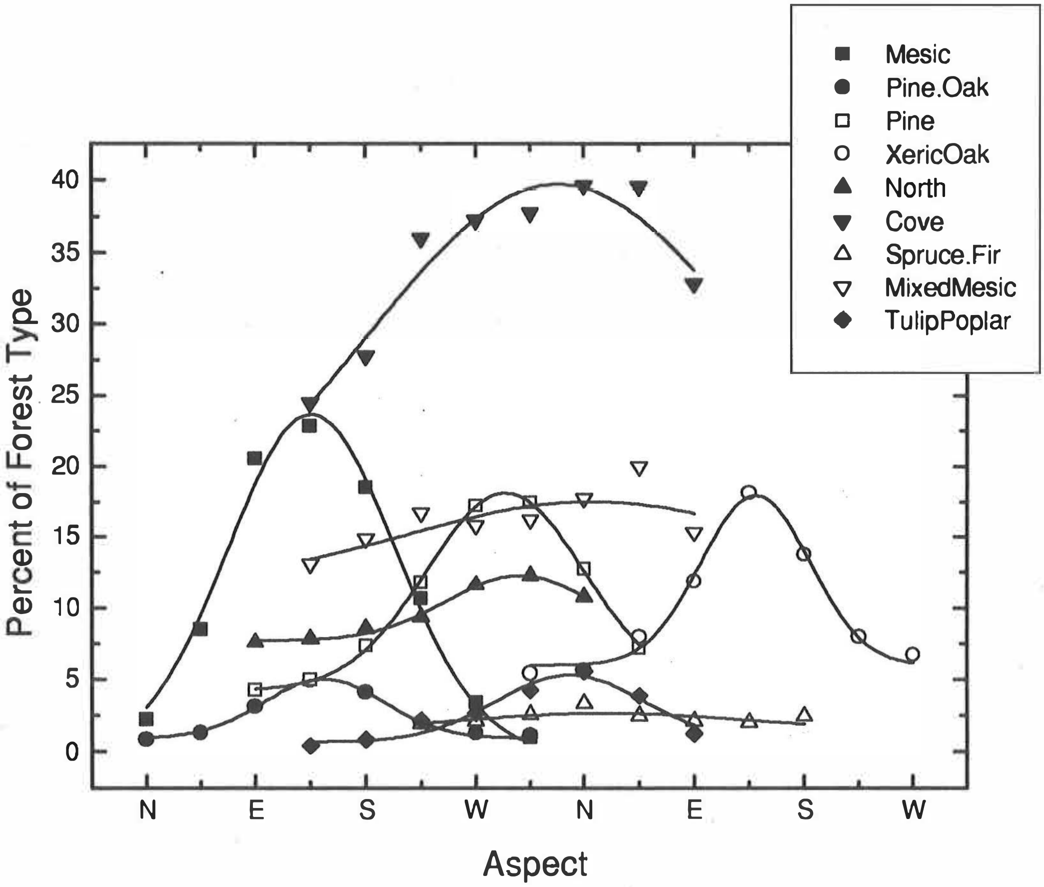


FIG. 3. GRSM Forest Type - Aspect Distributions

Vulnerability Evaluation

Fifteen percent of GRSM forests (30,416 hectares) were projected to be at some risk to forest mortality within 2 years of gypsy moth defoliation (Table 6, Figure 4). Most of this acreage was moderately vulnerable to mortality while less than 1% was highly vulnerable.

TABLE 6. Area and composition of forests that are high, moderate, or low in vulnerability to mortality within 2 years of gypsy moth introduction to the Great Smoky Mountains National Park

Vulnerability rating	Hectares (no.)	Percentage of GRSM
High	349	0.16
Moderate	18,279	8.80
Low	11,788	5.68
Total	30,416	14.7

CONCLUSION

The results of the present study have several management implications and can be used for initiating additional ecological research. Both forest and human management in the park can be influenced by results of the present study. Park managers could use the comparison to support management decisions such as the approval of the use of gypsy moth suppression techniques (*e.g.*, applications of Dimilin or Bt) in the old growth forests. The decision to alter the management of highly visited areas of the park may be influenced if defoliation occurs in those areas, and the results of the present study could be considered during the further development of visitor management in GRSM with respect to gypsy moth invasion. Interpreters and education specialists may develop an educational program in anticipation of gypsy moth invasion to explain that gypsy moth populations may indirectly cause forest mortality in the park. Such a program could also include rationale for the potential use of suppression techniques for reduction of gypsy moth population density.

There are five possible areas of research that might follow from this study: 1) ecological model development, 2) vegetation map development, 3) gypsy moth effects on wildlife of GRSM, 4) gypsy moth effects on GRSM forest types and understory, and 5) gypsy moth populations as affected by current GRSM Lepidoptera populations. Strategies that incorporate new computer technology in developing new gypsy moth modeling techniques could enhance those used in this study. The production of a finer scale GRSM vegetation map could be more useful as a basis for ecological research and forest management. The literature suggests that there are few interactions among gypsy moths, birds, and small mammals in North America; thus, there may be only minor indirect effects on plant and wildlife populations in the GRSM. Forest composition in the GRSM may be changed relative to both dominant species and understory structure if tree mortality follows gypsy moth defoliation. However, to date, no predictions have been developed to estimate specific effects of gypsy moths on GRSM plant or wildlife populations. Lepidoptera competition for available habitat and food may not be intense in areas that are newly infested with gypsy moths, yet there is no current investigation that might confirm this hypothesis.

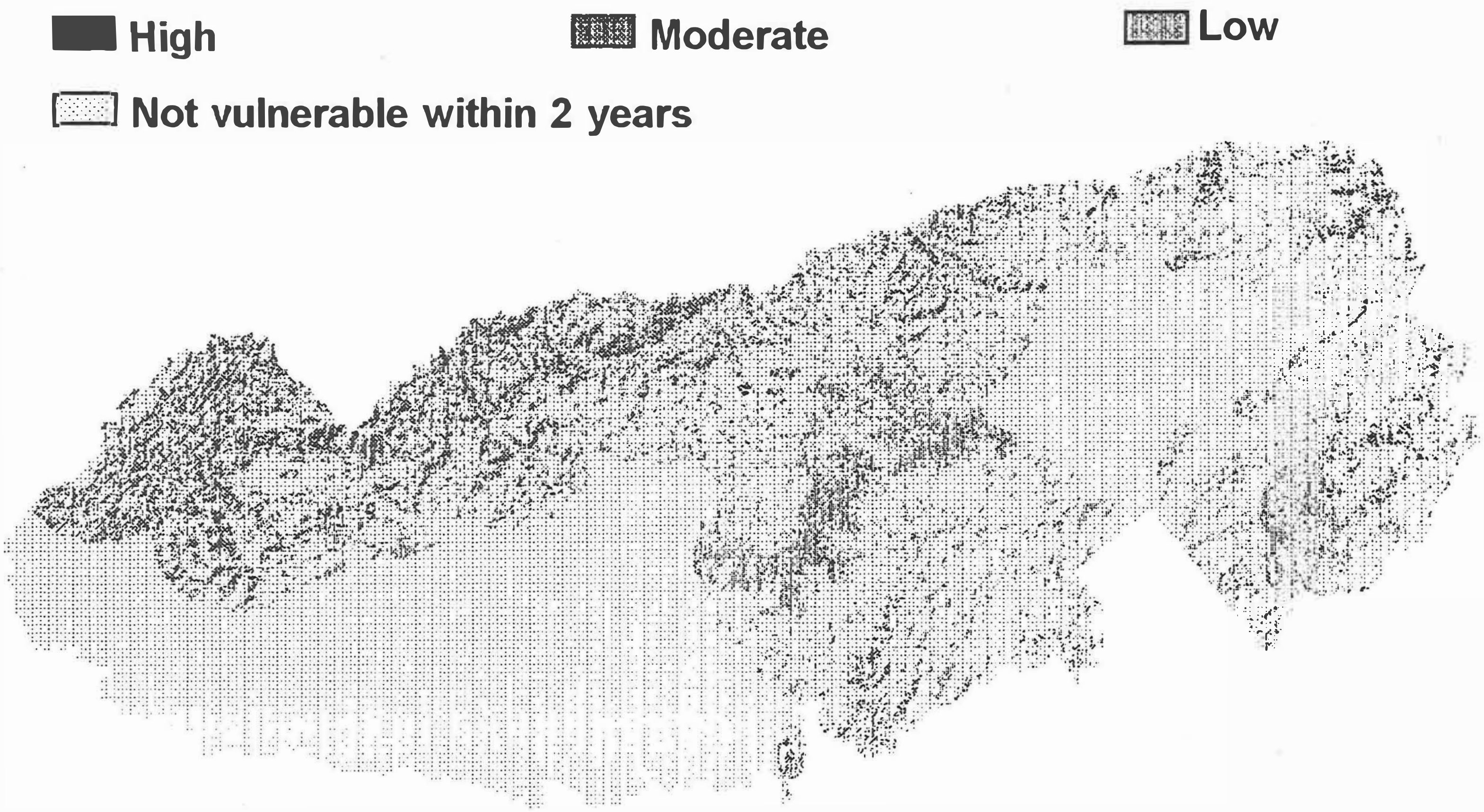


FIG. 4. High, moderate, and low ratings of forest vulnerability to mortality within 2 years of gypsy moth introduction to the Great Smoky Mountains National Park.

ACKNOWLEDGMENT

This work was supported by funding from the USDI National Park Service's Cooperative Park Studies Unit at The University of Tennessee at Knoxville (UTK), and was conducted while the senior author was a graduate student at UTK. This work represents partial fulfillment of a Master's of Science degree in Ecology for Hope R. Barrett.

LITERATURE CITED

Doane, C.C. and M.L. McManus. (EDITORS). 1981. The gypsy moth: research toward integrated pest management. USDA Forest Service Technical Bulletin 1584. Washington, D.C.

Gansner, D.A., and O.W. Herrick. 1985. Host preferences of gypsy moth on a new frontier of infestation. USDA Forest Service Research Note NE-330.

Houston, D.R., and H.T. Valentine. 1985. Classifying forest susceptibility to gypsy moth defoliation. USDA Combined Forest Pest Research and Development Program Agriculture Handbook 542.

Kegg J.D. 1971. The impact of gypsy moth: repeated defoliation of oak in New Jersey. Journal of Forestry **69**:852-854.

Leonard, D. 1991. Summary report for the southeastern region: gypsy moth trap catches on federal land. USDA Forest Service Forest Pest Management. Asheville, North Carolina

MacKenzie, M.D. 1991. Vegetation map of Great Smoky Mountains National Park based on LANDSAT thematic mapper data: accuracy assessment and numerical descriptions of vegetation types. A Report to the National Park Service.

MicroCal, Inc. 1991. Origin - the ultimate solution to scientific plotting version 1.2. MicroCal, Inc. Northampton, MA.

Shumway, D.L., and T.W. Bowersox. 1987. Gypsy moth risk assessment for Shenandoah National Park. NPS Research/Resources Management Report. 28 p.

INFORMS-TX OVERVIEW

STEPHEN B. WILLIAMS
*USDA Forest Service, Forest Pest Management, Methods Application Group, 3825 East Mulberry Street,
Fort Collins, Colorado 80524*

Abstract. INFORMS-TX is an integrated software application which attempts to provide the forest resource manager with a powerful yet easy to use tool for assessing and solving complex resource management problems. INFORMS-TX, an acronym for Integrated Forest Resource Management System - Texas version, is based on the concept that the power and utility of several commercial and public domain software packages can be linked together through a user-friendly interface to provide the user with a set of commonly needed functions to perform specific tasks. In the case of INFORMS-TX, the components tied together for the benefit of the forest manager include a geographic information system (GIS), relational database management system (RDBMS), various forest resource models, and knowledge base (i.e., rulebase) software.

INFORMS HISTORY

A strategic goal of the U.S. Forest Service (USFS) Forest Pest Management (FPM) is to promote and improve integration of forest pest management with forest planning processes. To address this goal, FPM has been sponsoring the development of integrated technologies through the Integrated Forest Resource Management System (INFORMS) project (Andersen 1989a). INFORMS-TX is one of several integrated technology projects related to INFORMS objectives. FPM managers believe that the design concepts present in INFORMS-TX can help integrate forest pest considerations into forest resource decision processes. By incorporating pest models and pest knowledge into a software package that is easy to use and relevant to management tasks, it is more likely that forest resource managers will consider pest impacts when developing management alternatives.

FPM's early efforts in providing resource managers with a set of computer software tools for assessing the forest environment can be traced to the early 1980s. The first prototype was developed between 1980 and 1983 and was called the Integrated Pest Impact Assessment System (IPIAS) (McNamara et al. 1990). This effort came out of Virginia Polytechnic Institute and State University with support and cooperation from the U.S. Forest Service and the U.S. Fish and Wildlife Service. The system ran on an Apple II+ computer.

The concepts and ideas generated by IPIAS were moved to the Data General computing environment (i.e., the service wide computing environment of the Forest Service) in 1987. This software version was renamed INFORMS-DG. Work continues today on this version with support and development contracted through Management Assistance Corporation of America for the FPM Methods Application Group (MAG). INFORMS-DG contains a large amount of custom code, manipulates and displays MOSS-formatted spatial data, and contains the unique ability to display three-dimensional forest scenes as affected by various management alternatives. This software has been used to develop environmental assessments on the Deerlodge National Forest in Montana and on the Wallowa-Whitman National Forest in Oregon.

Pages 85-92 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

In 1988, these integration concepts were tested on a microcomputer in a project called IRMAÑIntegrated Resource Management Automation (Loh et al. 1988). This demonstration project was conducted by the Nicolet National Forest in Wisconsin and Texas A&M with cooperation and support from FPM, USFS-Timber Management, USFS-Land Management Planning, the U.S. Fish and Wildlife Service, and the USDA-National Computer Center.

In many ways, the IRMA project spawned the INFORMS-TX project. Following the IRMA experience, the USFS recognized the need to integrate several commercial packages utilizing a workstation computing environment (Andersen 1989b). The workstation would allow multitasking as well as align this software for easy integration into the expected future computing environment of the USFS.

Based on these above ideas, FPM in 1990 sponsored a Technology Development Project in cooperation with the National Forests in Texas and Texas A&M's STARR Lab (Oliveria et al. 1991). The project remains active through March of1993. This project has resulted in the INFORMS prototype known as INFORMS-TX. INFORMS-TX integrates the ORACLE relational database management system, the ARC/INFO geographic information system, the CLIPS rulebase processing engine, various USFS models, and the OpenWindows interface on a SUN SparcStation. Texas A&M researchers have and continue to work very closely with the Neches Ranger District in Texas in integrating these products and providing key GIS, RDBMS, rulebase, and modelling functions necessary in performing project level planning on a ranger district.

INFORMS-TX: SPECIFICS

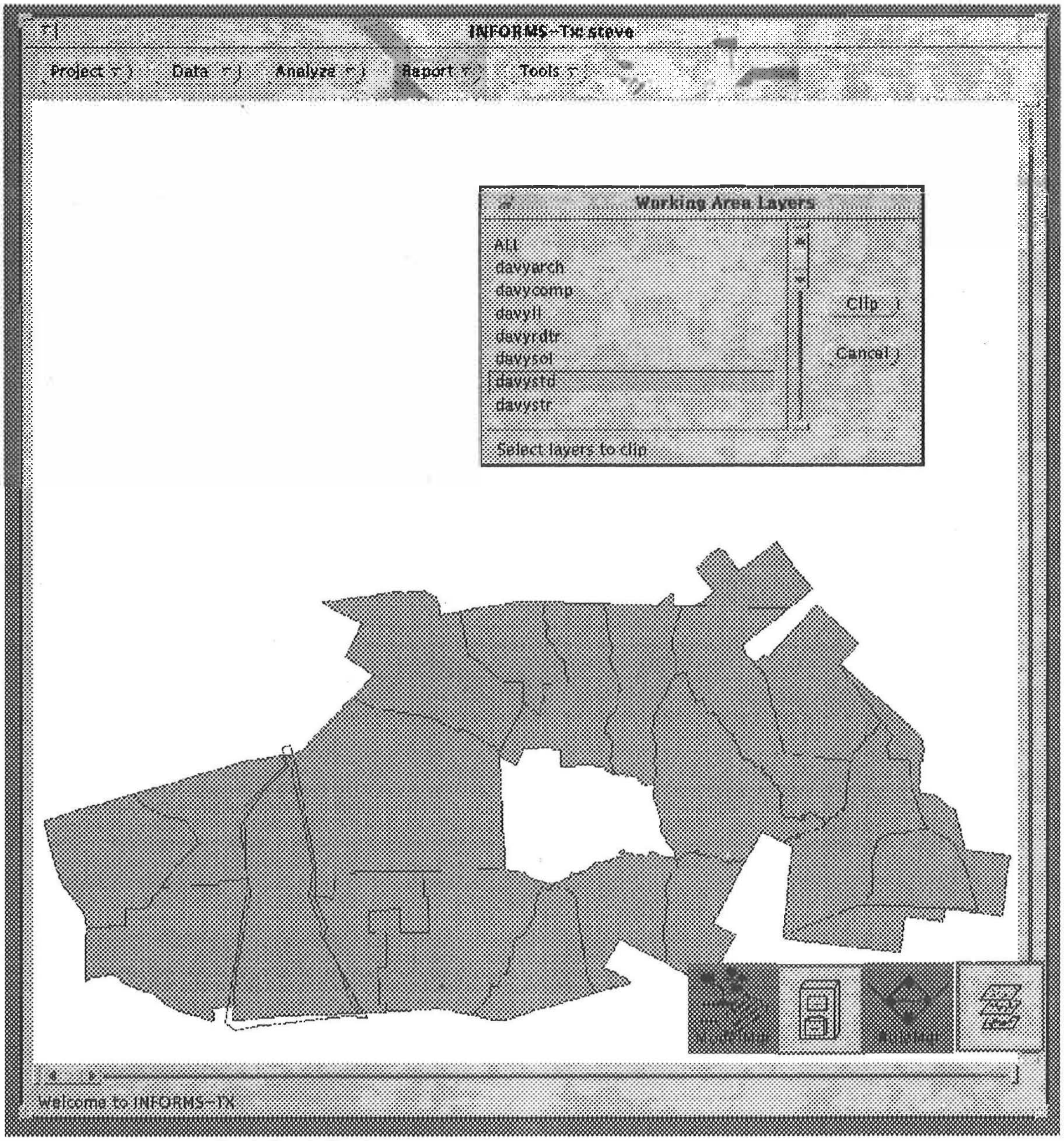
INFORMS-TX is designed to facilitate project-level planning on National Forests. INFORMS-TX should simplify three important steps in this planning process. These include: developing management alternatives (e.g., thinning, prescribed burning, etc.), assessing the impact of management alternatives, and comparing the potential outcomes for a forested area in order to assist managers in selecting a preferred alternative.

INFORMS-TX was developed around the planning process used in the Neches Ranger District. The typical land unit under scrutiny in the planning process is a forest stand within a compartment of a ranger district. INFORMS-TX software provides the resource manager with an array of tools to isolate the planning area from a larger database, review descriptive spatial and non-spatial data for that area, and apply various models and rulebases to the area to evaluate and select management alternatives.

The value of the INFORMS-TX product is that the user does not need to be a power user of the ORACLE RDBMS, the ARC/INFO GIS, or other significant software products in order to utilize the functionality of these products in project level planning. INFORMS-TX provides a relatively friendly graphical user interface. The complexity of a RDBMS or GIS is hidden behind the interface. Yet the user still has access to search and manipulate large volumes of spatial and non-spatial data, perform various GIS functions, process these data through various resource models, and evaluate site data against established rulebases to derive potential management alternatives. The OpenLook graphical interface provided by INFORMS-TX is consistent throughout these functions, thus providing the user with an easily learned shell for performing a broad range of tasks. The foundations of INFORMS-TX design and functional requirements have been refined throughout the term of this project and many others (Loh and Chen 1991, Loh and Saarenmaa 1992, Loh et al. 1991, Loh and Rykiel 1992, Loh and Power 1992).

Most resource managers will follow a similar path in using INFORMS-TX. Upon entering the system, the manager will typically display the GIS layer associated with their land management area. In the prototype developed at the Neches Ranger District, this area is the district itself. The layers most commonly accessed depict the forest compartments and stands for the district. Other layers available can include geographic features such as streams, soils, road and trail networks, etc. Layers available to the user will vary depending on the needs of the implementation site and availability of data. Actual use of the available layers will vary by project goals.

With a view of the whole management area on screen, the manager then focuses on only the area involved by the given project. Using a mouse, the study area is isolated by drawing a boundary around the area and then "clipping" this area from the total management area (see Figure 1). Through the clipping process, the system creates the necessary spatial and non-spatial data files to represent the study area in a special directory created for that manager. This feature allows the manager to freely manipulate aspects of this study area. The manager can view just this smaller land area (see Figure 2), run data associated with just this area through various rulebases and models, and create various management alternatives to help reach final management decisions. The clipping process creates a subset of smaller databases from larger corporate databases, thus protecting these larger databases and allowing the tasks associated with the study area to be accomplished more quickly and efficiently.

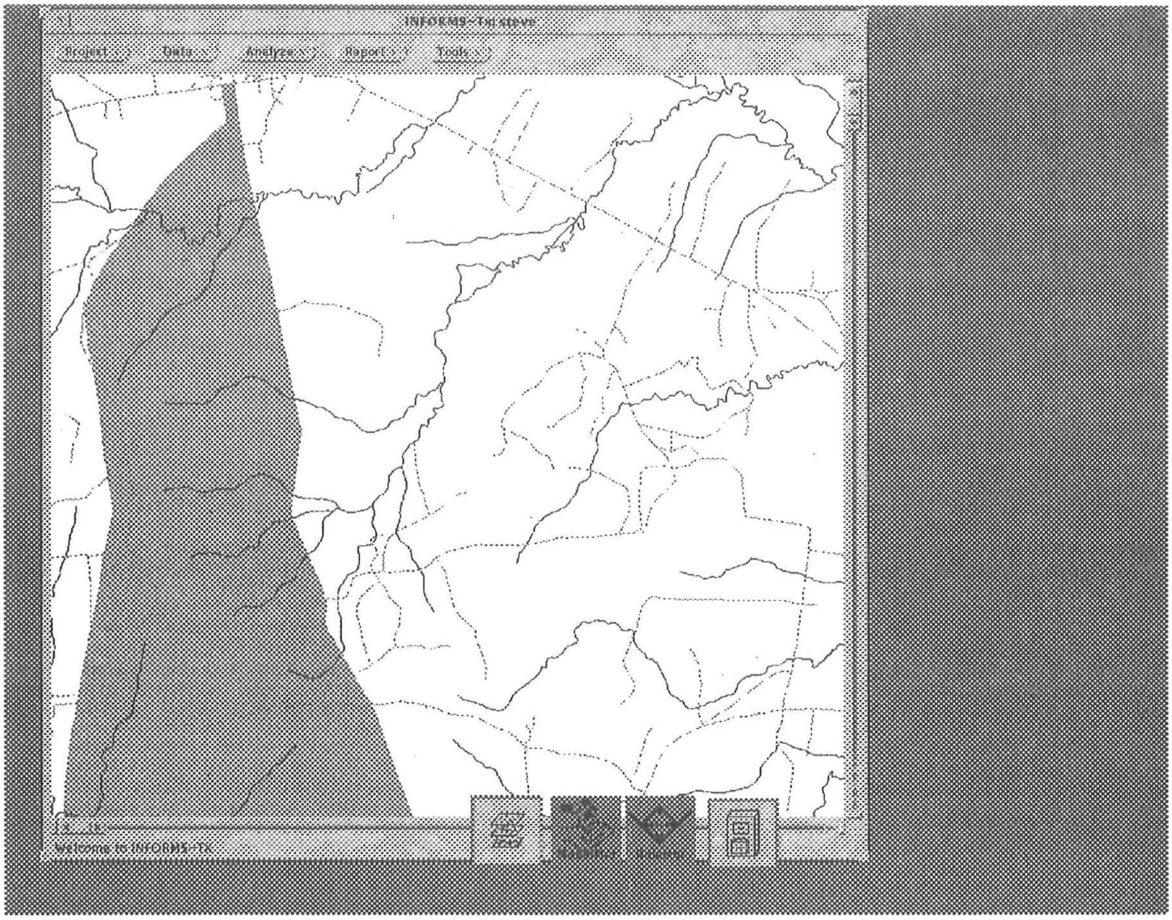


ALL
davyarch
davycomp
davyll
davyrdtr
davysol
davystd
davystr

Select layers to clip

Welcome to INFORMS-TX

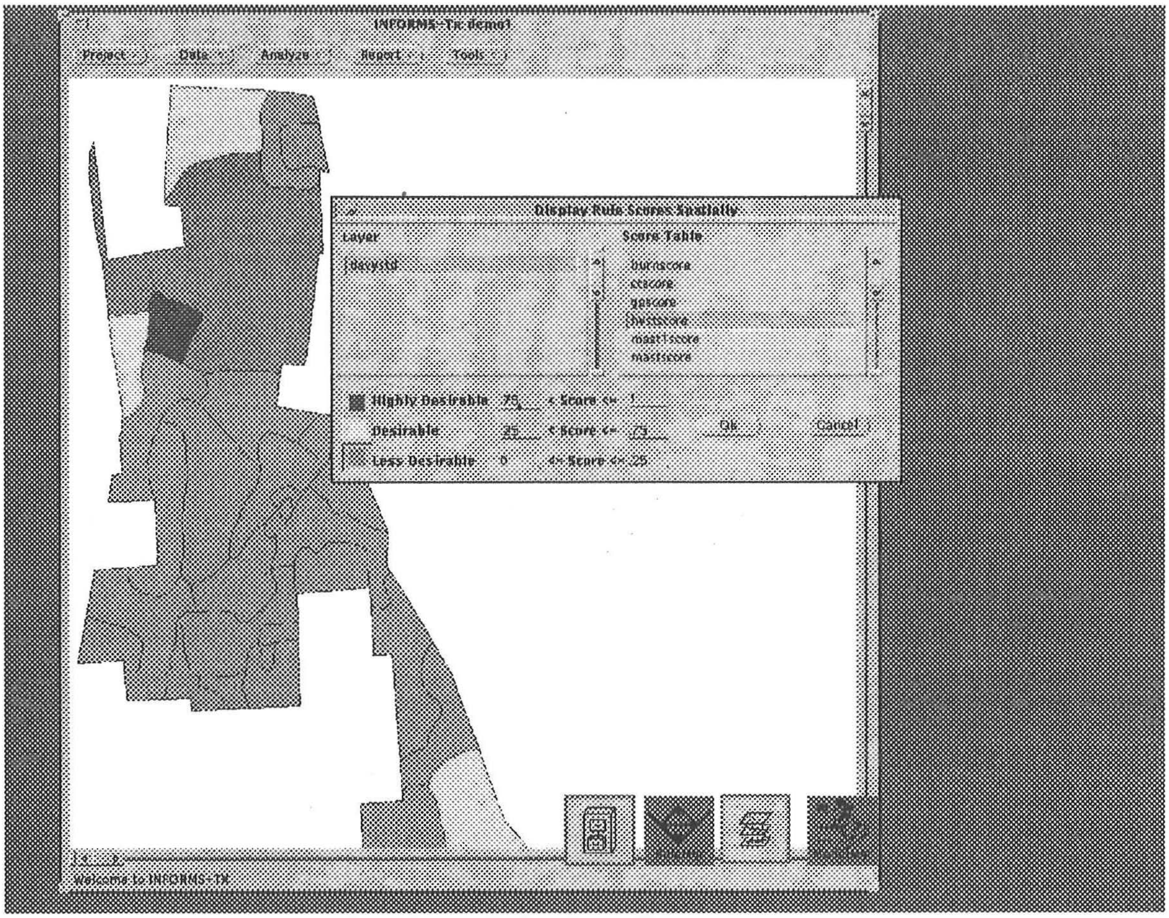
Fig. 1. A polygonally defined clipping area.



Welcome to INFORMS-TX

Figure 2. Display of the layers that were clipped.

Usually after clipping, the manager will then take advantage of the rulebases (i.e., knowledge bases) that are available through INFORMS-TX. The rulebases built into INFORMS-TX give an indication of the suitability of a particular prescription for stands in the clipped areaÑthe study area. Each stand can be evaluated against the rulebase to determine whether or not a particular prescription such as thinning is desirable. Stand data kept in the ORACLE database tables are accessed by the rulebase engine to determine suitability for treatment. The results of processing the stands of the study area through a given rulebase can be displayed graphically by GIS functions. Typically, three color codes are used to represent stands that are highly desirable, desirable, or undesirable candidates for a particular prescription (see Figure 3). These functions, as well as the ability to view the logic behind a given rulebase decision, are all readily and easily available from the INFORMS-TX graphical interface.



Layer: davystd

Score Table:
- burnscore
- ccscore
- gpscore
- hwstscore
- mast1score
- mastscore

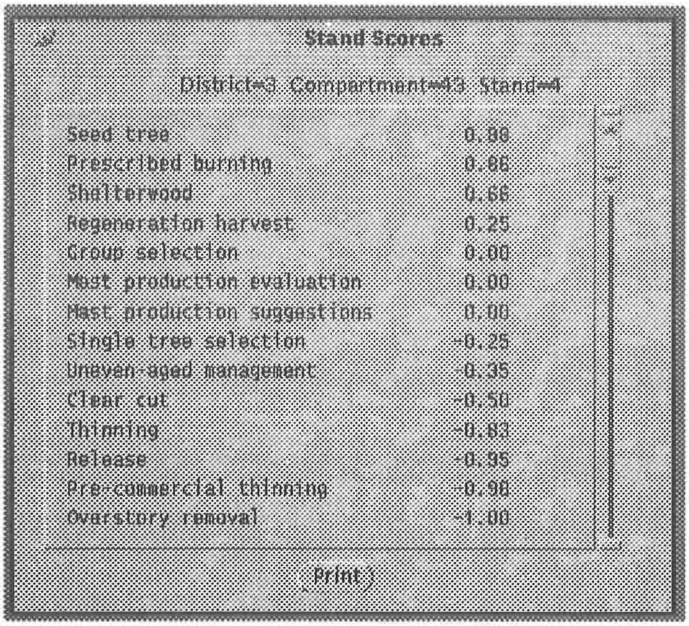
Highly Desirable 75 < Score <= 1

Desirable 25 < Score <= 75

Less Desirable 0 <= Score <= 25

Fig. 3. The results of the thinning rulebase displayed spatially.

With the project area defined and the rulebase information generated, the manager then proceeds to build management alternatives for each of the stands in the study area. Rulebase scores generated in the previous step are used as an aid in preparing these alternatives. In building management alternatives for the study or project area, the manager will typically review rulebase scores, review the line of reasoning used to derive selected scores, and compare his/her alternatives against these scores for reasonableness. Using the mouse, the manager can "click" on any stand to view data and scores associated with that stand (see Figure 4). Sets of alternatives generated by the manager for managing the project area are easily stored for later use and evaluation.

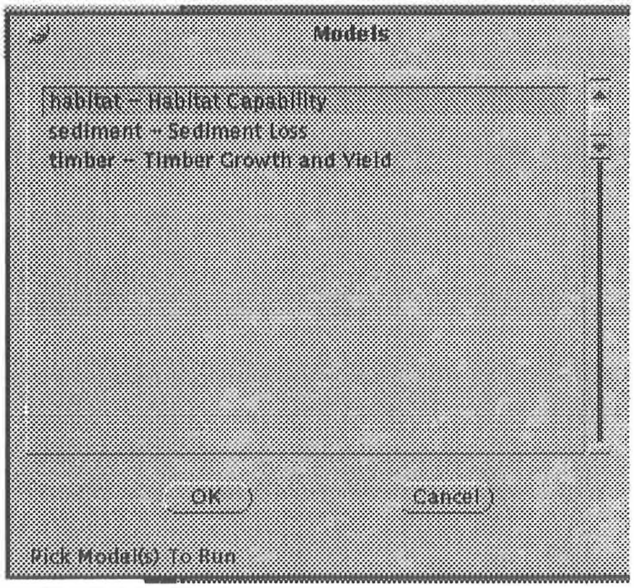


District=3 Compartment=43 Stand=4

```
Seed tree                        0.88
Prescribed burning               0.86
Shelterwood                      0.66
Regeneration harvest             0.25
Group selection                  0.00
Mast production evaluation       0.00
Mast production suggestions      0.00
Single tree selection           -0.25
Uneven-aged management          -0.35
Clear cut                       -0.50
Thinning                        -0.83
Release                         -0.95
Pre-commercial thinning         -0.98
Overstory removal               -1.00
```

Fig. 4. The rulebase scores for a chosen stand.

Most USFS ranger districts will utilize various natural resource models to evaluate the possible effects of their management decisions. INFORMS-TX can incorporate these models into the other tools mentioned (see Figure 5). Typical models include timber growth, wildlife habitat, and pest models, among others. After developing various alternatives for managing stands within a project area, the manager using INFORMS-TX can evaluate these alternatives by running these alternatives through the selected models. Models give an indication of the long-term effects on various issues, such as pest activity, as a result of a management action.



habitat -- Habitat Capability
sediment -- Sediment Loss
timber -- Timber Growth and Yield

Pick Model(s) To Run

Fig. 5. The Models dialog box.

All of the above steps represent important processes involved with determining appropriate management actions for a forest area. The INFORMS-TX tool facilitates these processes. The forest manager can at any time move back and forth between these steps to adjust various factors related to the project, and maintain a more organized and documented approach to planning.

INFORMS: SUMMARY AND FUTURE

INFORMS-TX captures only the GIS, DBMS, and other software functions necessary to support project-level planning. The intent is not to recreate a full featured GIS or DBMS, but to provide the user, through an easy-to-use interface, with the functions necessary to get the job done. The tool is meant to be simple yet useful.

At this juncture in time, INFORMS-TX has been built around the data and operations of the Neches Ranger District in Texas. To fine tune INFORMS-TX as it exists now, Region 8 Management Systems has committed to implement INFORMS-TX into as many as four other ranger districts within Region 8. Also, MAG expects to implement INFORMS-TX in a ranger district in Oregon in Region 6. These experiences are meant to test the flexibility of the system and to determine how easily models and GIS data can be integrated into INFORMS-TX. Ongoing with these activities is the effort to create thorough and professional user guides and installation manuals to facilitate the use of INFORMS-TX or a similar product.

INFORMS-TX is actually part of a larger concept called INFORMS, which will hopefully combine the best ideas and techniques from both INFORMS-TX, INFORMS-DG, and other similar decision-support systems. Several issues are yet to be resolved for INFORMS-TX and INFORMS in general. One issue involves the desire to tap more of the potential of a GIS as related to models. As now designed, models embedded within INFORMS-TX rely only on individual stand data to generate results. The effects of activities and conditions on adjacent or nearby stands on the stand in question are not evaluated by the models. There are potentially large benefits for management in capturing more of the spatial interactions at play in stand management. The sediment model used in INFORMS-DG does to some extent utilize a more complete set of spatial information. INFORMS-DG also includes a data visualization capability that relies on spatial data and the digital elevation model (DEM) to simulate a three-dimensional view of the forest. Future research efforts on INFORMS may well focus on expanding the power of models as related to spatial data and expanding the role of data visualization in project planning, while at the same time minimizing the amount of custom code by building a shell such as INFORMS-TX to utilize existing commercial software products.

LITERATURE CITED

Andersen Consulting. 1989a. Integrated Forest Resource Management System (INFORMS) Conceptual Design Workshop Report. Arthur Andersen & Co. April 1989.

Andersen Consulting. 1989b. Integrated Forest Resource Management System (INFORMS) System Design Workshop Report. Arthur Andersen & Co. October 1989.

Loh, D.K., Janiga, P.E., Tsai, C.M., Holtfrerich, D.R., Chu, Y.T. 1991. INFORMS demo: The Design Concept of Integrated Resource Management Systems. pages 137-140 *in*: Proceedings: International Conference on Decision Support Systems for Resource Management, College Station, Texas. April 15-18, 1991.

Loh, D.K., English, K.J., Choo, Y.K., Chu, Y.T. 1988. Integrated Natural Resource Management Automation--The Knowledge Shop.pages 158-167 *in:* Proceedings: Resource Technology 88, International Symposium on Advanced Technology in National Resource Management, College Station, Texas. April 15-18, 1991.

Loh, D.K., Saarenmaa, Hannu. 1992. The Design of Integrated Resource Management Systems. Texas A&M University, Department of Rangeland Ecology and Management, College Station, Texas and Finnish Forest Research Institute, Department of Mathematics, Silva, Finland.

Loh, D.K., Chen, Cy. 1991. Resource Management Systems Software Technologies for Research Management System Development. Energy, Resources and Environment Quarterly, Vol.4, No.1, 1991.

Loh, D.K., Rykiel, E.J. 1992. Integrated Resource Management Systems: Coupling Expert Systems with Geographic Information Systems and Database Management Systems. Journal of Environmental Management **16**: 167-177.

Loh, D.K., Power, J.M. 1992. Linking GIS/Remote Sensing with DSS. A book chapter in a UNESCO MAB book series on Decision Support Systems for Resource Management. J. Stuth and B.Lyons (eds.) 250 p.

McNamara, J., Davis, M. 1990. Integrated Forest Resource Management System (INFORMS). page 798 *in* Proceedings: Resource Technology 90, Second International Symposium on Advanced Technology in Natural Resource Management, Washington, D.C., American Society of Photogrammetry and Remote Sensing. November 12-15, 1990.

Oliveria, F., Swain, K. 1991. Progress Report for Implementation of INFORMS on the National Forests in Texas - Technology Development Project R8-90-13. Internal Report, Forest Pest Management Washington Office. October 1991. 6 p.

SPATIAL ANALYSIS AND INTEGRATED PEST MANAGEMENT IN A LANDSCAPE ECOLOGICAL CONTEXT

ROBERT N. COULSON AND JEFFREY W. FITZGERALD
Knowledge Engineering Laboratory, Department of Entomology,
Texas A&M University, College Station, TX 77843

MICHAEL C. SAUNDERS
Department of Entomology, Pennsylvania State University, University Park, PA 16802

FORREST L. OLIVERIA
USDA Forest Service, Forest Pest Management, 2500 Shreveport Hwy, Pineville LA 71370

Abstract. Integrated pest management (IPM), forest management, and environmental management are levels of focus in an increasingly complex spatial and temporal hierarchy of land use. Evaluating and projecting the consequences of actions and activities taken at each of these levels involves use of spatial analytical methodologies. In this paper we (i) describe the concept and practice of IPM in a landscape ecological framework and (ii) consider the utility and limitations of geographic information systems for spatial analysis at the landscape scale of ecological integration. The architects of IPM used a holistic approach in their initial definition of the concept and the ecosystem was identified to be the appropriate level for abstraction. However, the ecosystem concept is inherently vague about scale and boundary. We suggest that the landscape ecological concept of *ecotope* (which embraces ecosystem functionality within the context of a land unit that has discrete boundaries) is the appropriate unit of abstraction. The ecotope concept permits consideration of land units (chorology) as well as land attributes (topology) in structuring analyses to evaluate and project the consequence of management actions. Although the procedures for landscape analysis are in an evolutionary state, all require use of spatially referenced data. For this reason, the geographic information system (GIS) has proven to be a useful tool. The GIS provides a "tool box" of functions that are helpful in landscape analysis and interpretation: map generalization/simplification, map overlay, spatial query/browsing, spatial statistics, spatial relationships, spatial reasoning.

INTRODUCTION

Integrated pest management (IPM) has been a dominant theme in forestry for more than two decades. The social, economic, and ecological impacts of insects and diseases are no less significant today than in the past. However, IPM has taken on a new significance, since forest management practices are now linked directly to larger environmental issues (e.g., deforestation, sustainable production, loss of biological diversity, global warming, cultural heritage). IPM, forest management, and environmental management are levels of focus in an increasingly complex spatial and temporal hierarchy of land use. Evaluating and projecting the consequences of actions and activities taken at each of these levels involves use of spatial analytical methodologies, which are only just beginning to be developed. Conclusions from the analyses are interpreted within the context of principles of ecology and management science. In this paper our specific objectives are (i) to describe the concept and practice of IPM in a landscape ecological framework and (ii) to consider the utility and limitations of geographic information systems for spatial analysis at the landscape scale of ecological integration.

Pages 93-99 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

FOREST PEST MANAGEMENT IN A LANDSCAPE ECOLOGICAL CONTEXT

Integrated pest management

The formal beginning of IPM can be traced to the symposium proceedings *Concepts of Pest Management* (Rabb & Guthrie 1972). Since then, fundamental principles of IPM, and the forestry perspective on the subject (forest pest management - FPM), have evolved (Coulson 1981, USFS Anon. 1988). We are concerned here with both the concept and practice of IPM. Initially, IPM was a research and development activity. Emphasis was placed on issues of concept. Several specialized definitions were formulated. An example follows:

> ...the maintenance of destructive agents, including insects, at tolerable levels by the planned use of a variety of preventive, suppressive, or regulatory tactics and strategies that are biologically and economically efficient. It is implicit that the actions taken must be fully integrated into the total resource management process in both planning and operation. This means that pest management must be geared to the life span of the tree crop as a minimum and to a longer span where the resource planning horizon so requires...(Coulson & Witter 1984).

Implementation of this concept into forest management practice has proven to be a challenging task. Although the definition includes cryptic reference to a time frame, missing is any direct consideration of spatial scale or boundary. Pest management activities associated with suppression and prevention have quite different time and space constraints. The difficulty associated with merging concept and practice begins to be evident when we recognize that FPM is a site-specific activity, i.e., actions are directed to discrete land units of varying size. Furthermore, projecting the probable consequences of FPM practices involves interpretation based on ecological principles from several levels of integration, i.e., populations to landscapes. Simply stated, FPM practice embraces a hierarchy of land units and ecological levels of abstraction.

Landscape ecology and integrated pest management

Landscape ecology is the academic discipline that provides a scientific base for problem-solving and decision making in land-use management. Basic principles of landscape ecology are described in Forman & Godron (1986), Kolasa & Pickett (1991), Naveh & Lieberman (1984), Pickett & White (1985), Turner (1987), Turner & Gardner (1991), and Zonneveld & Forman (1990). This science deals with the study of landscape structure (components of the landscape and their linkages and configurations), function (quantities of flows of energy, materials, and species within and among landscape elements), and change (alteration in the structure and function of the ecological mosaic over time). Also included within the realm of landscape ecology are the actions and activities of humans relative to their environment.

From the onset, the developers of the IPM concept recognized the importance of a holistic approach and, therefore, identified the ecosystem (the biotic community together with the abiotic environment) as the appropriate level of focus (see Watt 1968 and Van Dyne 1969). The approach was appealing in that researchers could examine functionally how insect populations and communities influenced, or perhaps regulated, ecosystem level processes such as primary production, consumption, decomposition, or abiotic storage.

The fundamental problem with this approach is that the ecosystem concept is inherently vague about scale and boundary. In fact, ecosystems are often described simply as environments around special organisms of interest, e.g., the forest ecosystem, the cotton ecosystem, the apple orchard ecosystem. The term *ecotope* is used in landscape ecology to address ecosystem functionality within the context of a land unit that has discrete boundaries. Therefore, a landscape consists of a mosaic of ecotopes, i.e., tangible ecosystems (Figure 1).

With the ecotope serving as the basis for abstraction, landscapes can be viewed to have both horizontal and vertical dimensions. Horizontal (chorological) dimension refers to land units, which can be aggregated at different scales. For example, the convention used by the US Forest Service on national forests consists of a hierarchy beginning with the forest stand (the ecotope). Stands are combined to make compartments. Compartments are further clustered into a district. Districts form national forests (Figure 2). Vertical (topological) dimension refers to land attributes, e. g., flora, fauna, soil, landform, etc. One function of landscape ecological research is to integrate information on land units and land attributes (Zonneveld 1990).

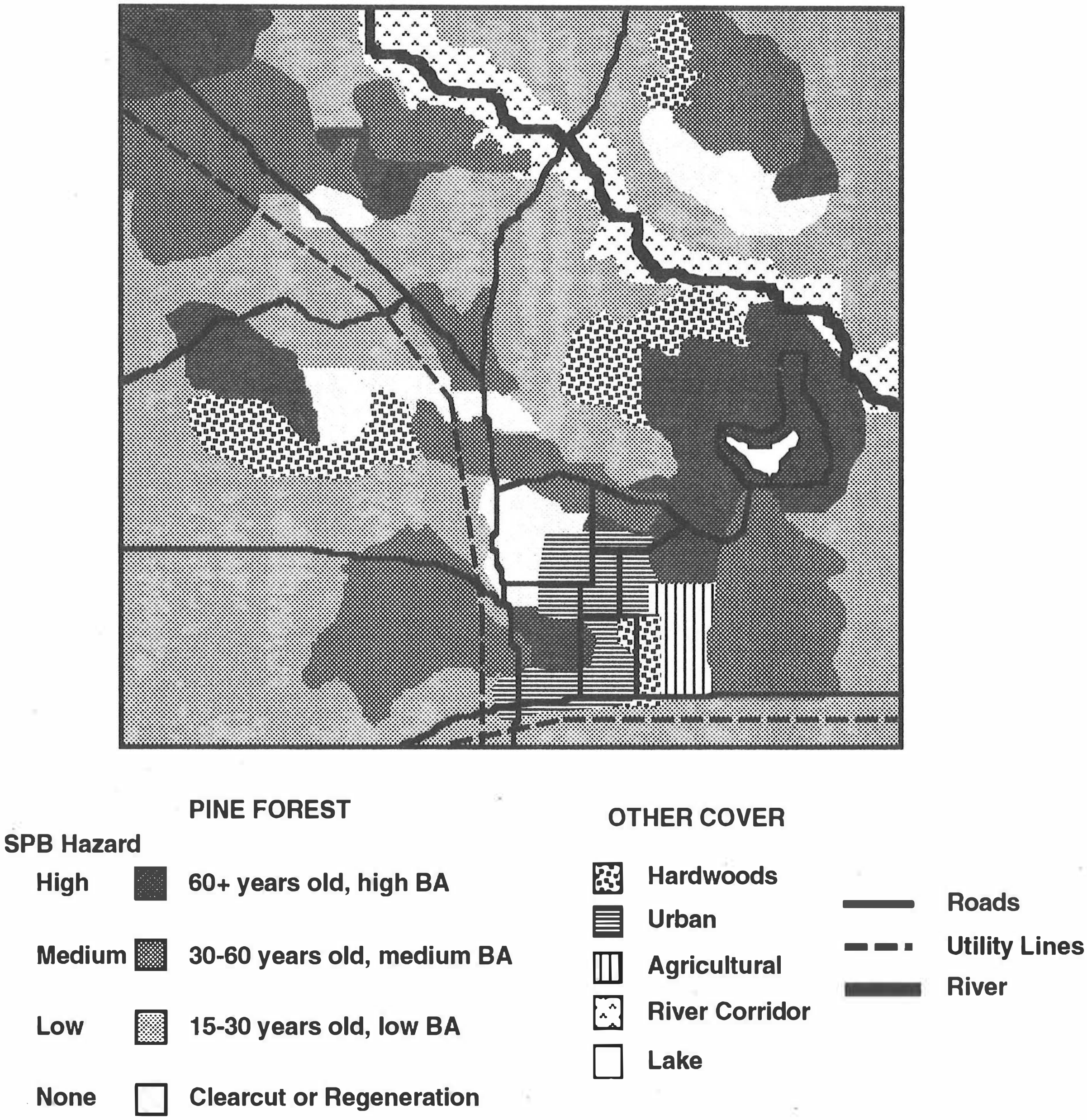


FIG. 1. forested landscape consisting of a mosaic of constituent ecotopes. The ecotope is the fundamental unit for IPM. One important function of landscape ecological research centers on integrating chorological (land unit) and topological (land attribute) information.

LANDSCAPE ANALYSIS, IPM, AND GIS

Geographic information systems and landscape ecology

One of the fundamental topics of study in landscape ecology centers on understanding how and why organisms are distributed across complex mosaics of ecotopes. Of course, this subject is of paramount importance to IPM as well. Changes in the distribution and abundance of a pest species can be assessed when studies of large-scale patterns and processes are interpreted within an ordered framework. The hierarchy of land unit classification, with the ecotope serving as the base, is a useful way to organize landscape level analyses. Examination of the distribution and abundance of a pest insect species (or guild) requires analytical techniques that include the interaction of the horizontal and vertical dimensions of a landscape in the context of a specific landscape characteristic. For example we may be interested in how herbivory by bark beetles in mature pine forests (the landscape characteristic) is influenced by land unit configuration and specific land attributes such as tree species composition, other age classes of trees, soil type, hydrography, etc. Although the procedures for landscape analysis are in an evolutionary state, all require use of spatially referenced data. For this reason, the geographic information system (GIS) has proven to be a useful tool.

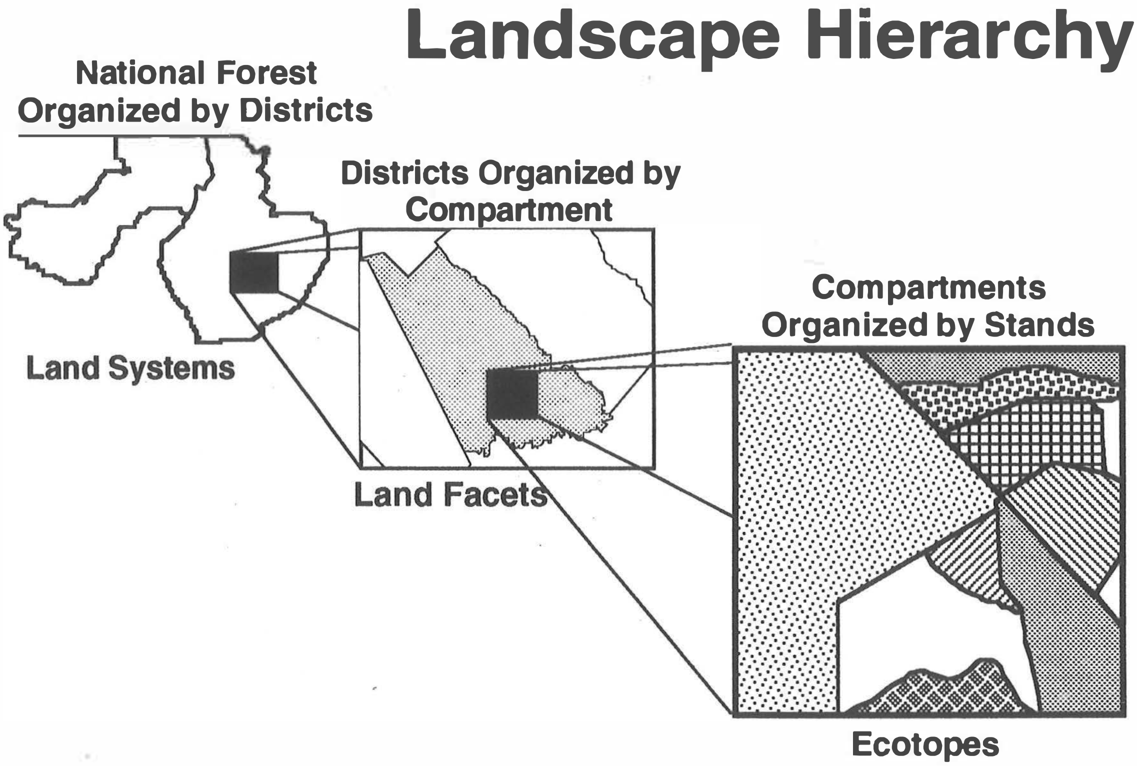


FIG. 2. With the ecotope serving as the basic level of abstraction, landscapes can be viewed at different scales. The convention used by the USDA Forest Service for national forests consists of a hierarchy beginning with the forest stand. Stands are combined to make compartments. Compartments are further clustered into a district. Districts form national forests.

Contemporary developments in GIS and the companion technologies of remote sensing and image processing are treated in Aronoff (1989), Buhyoff (1988 & 1990), Burrough (1988), Davis (1986), Laurini and Thompson (1992), Maguire, et al. (1991), Peuquet & Marble (1990), Star & Estes (1990), and Tomlin (1990). The appeal of GIS software is that it provides access to and display of geographically referenced databases. Interest in cartography provided the motivation for early GIS development. Potential practitioners looked beyond cartographic uses of GIS. Their expectation was that GIS could be used as a tool to address problems of spatial analysis and landscape modeling. However, the initial GISs had modest utility in this regard, with analytical functionality limited to Boolean operations, polygon overlay, buffer zones, and some statistical computation (Coppock 1989, Davis et al. 1988). This circumstance is beginning to change, as there is considerable research activity currently being directed to development of methods for spatial statistical analysis and landscape modeling (Turner & Gardner 1991).

Functionality of geographic information systems

GIS software and hardware usually consist of five subsystems (Burrough 1986). They are the: (1) data input subsystem, (2) data storage and management subsystem, (3) data visualization and output subsystem, (4) data manipulation and analysis subsystem, (5) user interface subsystem. Capabilities of the data manipulation and analysis subsystem determine how the GIS can be used to characterize landscapes.

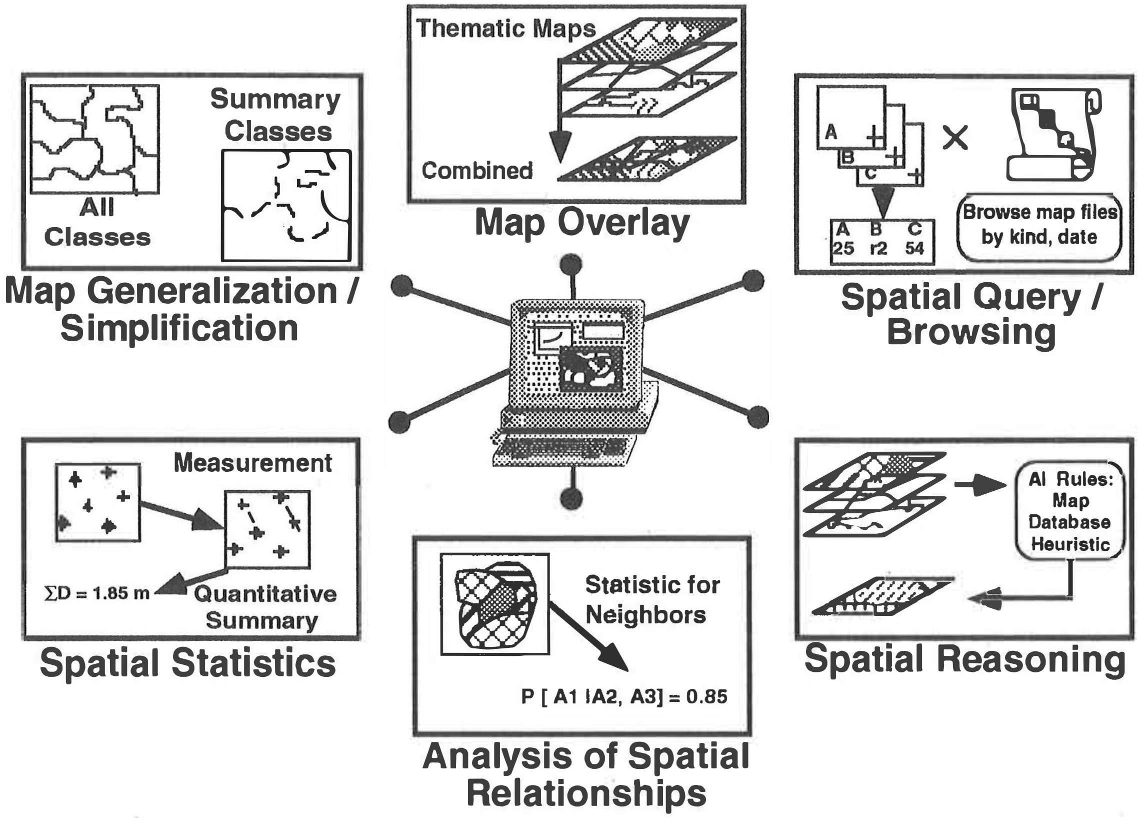


FIG. 3. The analytical functionality for most GISs includes utilities for map generalization/simplification, map overlay, spatial query/browsing, spatial statistics, analysis of spatial relationships, and spatial reasoning.

The data manipulation and analysis subsystem provides a "toolbox" of functions used to transform thematic map data. Manipulation and analysis either add value to the spatial database or solve spatial problems. The added value may come from creation of new thematic maps or visualizing spatial distributions. Spatial problems are solved using measurements of objects in space, by determining spatial relationships, and by creating predictive spatial models. Typical spatial analysis functions provided by GIS are (Burrough, 1986 and Laurini and Thompson, 1992) (Figure 3):

(1) *Map generalization and simplification*: These functions permit re-classification of spatial objects. The procedures allow the user to isolate the specific variables needed for analysis.

(2) *Map overlay*: Map overlay techniques can be used to combine thematic maps. These procedures allow for the synthesis of maps consisting of novel data themes.

(3) *Query and browse*: Query functions facilitate extraction of information from a spatial database. Browse functions permit exploring the contents of a spatial database.

(4) *Spatial statistics*: Usually, a GIS can provide descriptive statistics and histograms for attributes of spatial objects. Also, GIS usually provide for correlation analysis to compare spatial relationships that exist between and within thematic maps.

(5) *Analysis of spatial relationships*: A GIS can measure spatial arrangement of objects on a map. Spatial relationship measurements include proximity, distance, and trend.

(6) *Spatial reasoning*: Some systems provide tools for decision-making, incorporating both spatial information and heuristic knowledge. Human deductive reasoning can be imitated using expert systems techniques. The simplest systems use rule based reasoning to interpret within and among landscape data themes.

The GIS technology has improved dramatically in recent years. The suite of analytical tools has been broadened considerably. However, further development in statistics for spatial analysis and modeling is needed.

ACKNOWLEDGMENTS

We acknowledge and thank A. M. Bunting for technical assistance in preparation of the manuscript. This work was supported in part by the USDA Forest Service, Forest Pest Management, Special Projects Program (TEX6817) and the Texas Agricultural Experiment Station (TEX8082). This paper is Texas Agricultural Experiment Station TA No. 30903.

LITERATURE CITED

Aronoff, S. 1989. *Geographic Information Systems: A Management Perspective.* WDL Publications, Ottawa.

Anonymous. 1988. *Forest Health Through Silviculture and Integrated Pest Management: A Strategic Plan.* USDA Forest Service. US Gov.. Printing Office 576-488. 26 pp.

Buhyoff, G. J. (Ed.). 1988. Proc. Resource Tech. 88. *American Soc. Photogram. and Remote Sensing.* Falls Church, VA.

Buhyoff, G. J. (Ed.). 1990. Proc. Resource Tech. 90. *American Soc. Photogram. and Remote Sensing.* Falls Church, VA.

Burrough, P. A. 1988. *Principles of Geographical Information Systems for Land Resources Assessment.* Monographs on Soil and Resources Survey No. 12. Oxford Science Publications. Clarendon Press, Oxford.

Coppock, T. 1989. Editorial. *International Jour. Geog. Info. Systems.* 3: 99-101.

Coulson, R. N. 1981. Evolution of concepts of integrated pest management. *J. Ga. Entomol. Soc.* 16: 301-16.

Coulson, R. N., and J. A. Witter. 1984. *Forest Entomology: Ecology and Management.* John Wiley and Sons, NY. 669 pp.

Davis, E. 1986. *Representing and Acquiring Geographic Knowledge. Research Notes in Artificial Intelligence.* Morgan Kaufmann Publishers, Inc. Los Altos, CA.

Davis, J. R., I. W. Grant, and P. A. Whigham. 1988. Representing and applying knowledge about spatial process in environmental management. *AI Applications* 2 (4): 17-25.

Forman, R. T. T. and M. Godron. 1986. *Landscape Ecology.* John Wiley & Sons, NY.

Kolasa, J. and S. T. A. Pickett (Eds.). 1991. *Ecological Heterogeneity.* Ecological Studies 86, Springer-Verlag, NY.

Laurini, R. and D. Thompson. 1992. *Fundamentals of Spatial Information Systems.* The A. P.I. C. Series, No. 37. Academic Press Inc., NY.

Maguire, D. J., M. F. Goodchild, and D. W. Rhind (Eds.). 1991. *Geographic Information Systems.* Vol. 1 & 2. John Wiley & Sons. NY.

Naveh, Z. and A. S. Lieberman. 1984. *Landscape Ecology: Theory and Application.* Springer-Verlag, NY. 356 pp.

Peuquet, D. J. and D. F. Marble (Eds.). 1990. *Introductory Readings in Geographic Information Systems.* Taylor & Francis, NY.

Pickett, S. T. A. and P. S. White (Eds.). 1985. *The Ecology of Natural Disturbance and Patch Dynamics.* Academic Press, Inc. NY.

Rabb, R. L. and F. E. Guthrie (Eds.). 1972. *Concepts of Pest Management.* North Carolina State Univ., Raleigh, N. C. 242 pp.

Star, J. and J. Estes. 1990. *Geographic Information Systems, An Introduction.* Prentice Hall, Englewood Cliffs, NJ.

Tomlin, C. D. 1990. *Cartographic Modeling and Geographic Information Systems.* Prentice-Hall Inc., Englewood Cliffs, NJ.

Turner, M. G. (Ed.). 1987. *Landscape Heterogeneity and Disturbance.* Springer-Verlag, NY.

Turner, M. G. and R. H. Gardner (Eds.). 1991. *Quantitative Methods in Landscape Ecology.* Springer-Verlag, NY.

Van Dyne, G. M. 1969. *The Ecosystem Concept in Natural Resource Management.* Academic Press, NY.

Watt, K. M. 1968. *Ecology and Resource Management: A Quantitative Approach.* McGraw-Hill Book Co. NY.

Zonneveld, I. S. 1990. Scope and concepts of landscape ecology as an emerging science. In Zonneveld, I. S. and R. T. T. Forman (Eds.). 1990. *Changing Landscapes: An Ecological Perspective.* Springer-Verlag, New York.

Zonneveld, I. S. and R. T. T. Forman (Eds.). 1990. *Changing Landscapes: An Ecological Perspective.* Springer-Verlag, New York.

A MECHANISTIC APPROACH TO UNDERSTANDING AND PREDICTING SOUTHERN PINE BEETLE DYNAMICS

JOHN D. REEVE AND PETER TURCHIN
Southern Forest Experiment Station, USDA Forest Service, P.O. Box 5500, 2500 Shreveport Highway,
Pineville, LA 71360

Abstract. Despite extensive research on the behavior and ecology of the southern pine beetle (SPB) and its natural enemies, our understanding of its populations dynamics remains incomplete. In particular, it is unknown what role natural enemies play in the regional outbreaks seen in the SPB, nor what effect they have on the growth of local SPB infestations. In this article, we discuss how recent ecological theory can be adapted to address these questions in the SPB system. Our approach is based on a conceptual model which divides the system into two components, the first involving the movement of the SPB and its natural enemies between trees, and the second the interaction of the SPB and enemies once they arrive on a tree under mass-attack. We discuss what sort of experiments are necessary to investigate each component of this conceptual model, and review our results to date. We then show how the two components can be combined to generate predictive mathematical models of the system, and describe how the models can be empirically tested.

INTRODUCTION

The cyclic population outbreaks of the southern pine beetle (SPB), *Dendroctonus frontalis*, cause significant economic damage to pine forests in the South. During the outbreak year of 1985, for example, losses in the region due to the SPB exceeded $120 million (USDA 1987). Despite extensive research on the behavior and ecology of the SPB and its associates, however, our understanding of its population dynamics remains incomplete. On a regional scale, for example, it is unknown what mechanism causes SPB populations to regularly cycle between outbreak and endemic phases. Although there is circumstantial evidence that natural enemies may contribute to this cycling (Billings 1988; Stephen *et al.* 1989; Turchin *et al.* 1991), this hypothesis has not been critically examined. Much also remains to be learned about SPB dynamics on a local scale, at the level of individual SPB infestations, or "spots". It is unclear why some spots naturally cease growth, while others grow unchecked until control measures are applied. Another critical but unanswered question is the extent to which SPB dispersal connects different spots, and contributes to their early growth, before local reproduction has occurred.

What sort of information would be necessary in order to understand SPB dynamics, on both a regional and local scale? Recent ecological theory suggests that several different types of information are required to understand the dynamics of insect populations, and in particular predator-prey systems, like SPB and its natural enemies (Hassell 1978; Chesson and Murdoch 1986; Kareiva and Odell 1987; Murdoch and Stewart-Oaten 1989; Taylor 1988; Hassell *et al.* 1991; Ives 1992). First, information is needed on the movement of the organisms involved across a range of spatial scales, ranging from local to regional, and with respect to local concentrations of prey or predators (e.g. movement of the predators toward their prey). Second, we also need to know how the predator and prey interact once they reach the same location or patch. This will be determined by the attack rate and functional response of the predator, and by competition among the prey, as well as the predators. Finally, it is critical to know the duration of the life history stages of both predator and prey, especially those prey stages which are invulnerable to attack, since this can strongly influence the dynamics of the system (Murdoch *et al.* 1987; Godfray and Hassell 1989). Given these different types of information, one can construct mathematical models of a system which predict its behavior in some detail.

Pages 100-110 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

In this article, we outline how the above approach can be applied to investigate the dynamics of the SPB and its natural enemies, with the eventual goal of developing a predictive model of the system. To do this, we divide the system conceptually into two components. The first component involves all movement of the SPB and its natural enemies between trees, beginning when the SPB brood and natural enemies emerge from their natal tree, and ending when they arrive on new trees under mass attack by SPB. The second component involves the interaction of the SPB and its natural enemies once they arrive on the tree, which we call the "within-tree" interaction. For example, an arriving SPB will compete with other individuals for space within the phloem, and its progeny will be consumed by predators and parasitoids. After these interactions occur, SPB and natural enemy progeny are produced and emerge from the tree, entering the movement component of the system and completing the circle.

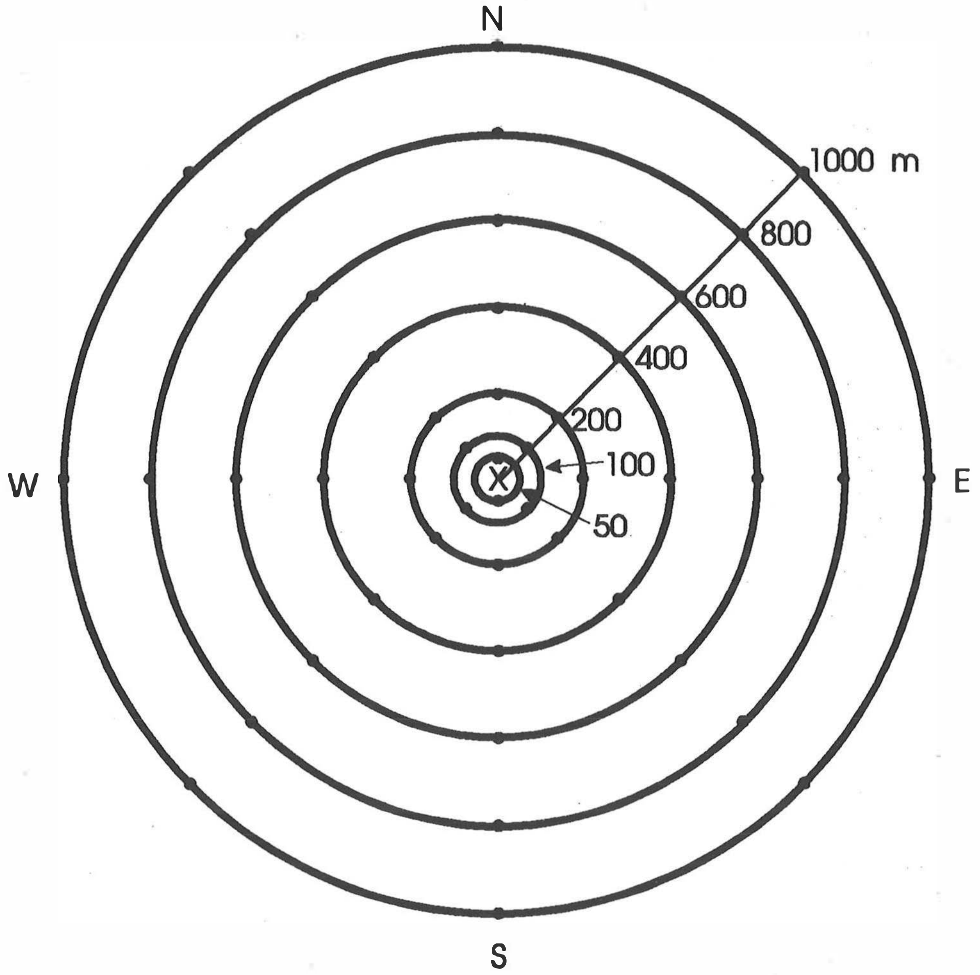


FIG. 1. Recapture grid. Each solid circle indicates the position of a trap. X indicates the point of release.

THE MOVEMENT COMPONENT

Although a number of different methodologies have been used to investigate and model the movements of insect populations, we have chosen the framework of diffusion equations to describe the movement of SPB and its enemies, an approach used with significant success in many other systems (Okubo 1980; Kareiva 1983; Kareiva and Odell 1987; Turchin 1989). For the SPB and its natural enemies, movement seems to occur essentially in a two-dimensional plane within the forest, because the insects are usually found flying in a narrow range of heights above the forest floor. Given that the insects move in only two dimensions, an appropriate general diffusion equation for the SPB is

$$\frac{\partial S}{\partial t} = -\frac{\partial}{\partial x}(\beta S) - \frac{\partial}{\partial y}(\beta S) + \frac{\partial^2}{\partial x^2}(DS) + \frac{\partial^2}{\partial y^2}(DS) - \delta S \tag{1}$$

Here S(x,y,t) is the density of flying SPB at a particular location in space and time, δ is their mortality rate, and ß and D are the drift and diffusion coefficients of the diffusion process. The drift coefficient ß controls the tendency of the beetles to move in particular direction (if it is zero there is no tendency). For example, if beetles are biasing the direction of their movement towards a tree producing attractive volatiles, then there will be a non-zero population drift towards the attractive tree. D encapsulates the undirected component of beetle movement. To complete this model of SPB movement it is necessary to specify the form of ß and D, which in general could be functions of the position of the beetles in space (their x,y coordinates) and other variables in the system. Given ß and D, the above equation can be solved to give the density of flying SPB at any point in space and time, given an initial distribution of beetles, and appropriate boundary conditions. Similar equations can be defined to describe the movement of the natural enemies in the system.

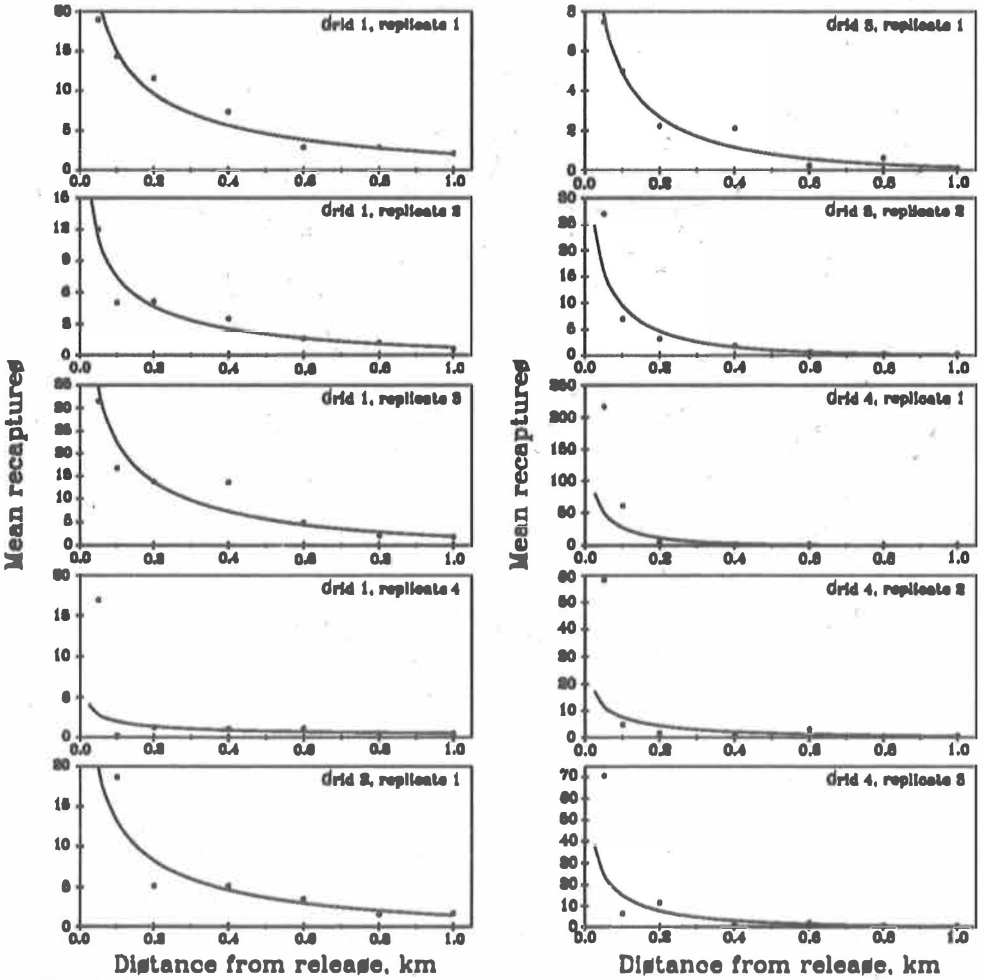


FIG. 2. Recaptures-with-distance curves for each replicate release, at four different locations (grids). The data points are the cumulative recaptures averaged over all traps at a given distance from the release point. The solid lines are the fitted diffusion model.

The next step in using the diffusion framework is to experimentally determine ß and D for SPB and its natural enemies. With SPB, this problem is complicated by the fact their movement seems to involve two distinct phases; the dispersal of brood beetles from the tree in which they developed, followed by their congregation on trees undergoing mass attack, in response to the release of the attractive pheromone, frontalin (Gara and Vité 1962, Vité *et al.* 1964). Different experiments and methods of analysis are necessary to measure beetle movement in each phase. To examine movement purely in the dispersal phase, a series of mark-recapture experiments were conducted in areas of the forest cleared of all trees attacked by SPB, thus eliminating any potential foci for beetle congregation (Turchin and Thoeny, in press). In these experiments, bolts containing SPB brood were transported to a central point and then coated with a fluorescent powder, which marked the beetles as they emerged. The marked beetles were then recaptured using an array of pheromone-baited funnel traps (Lindgren 1983) located at different distances and directions from the center (Fig. 1). Analysis of the resulting information indicated that a simple diffusion model incorporating in-flight mortality provided a good fit to the data (Fig. 2), and yielded estimates of the quantity D/δ, the ratio of the diffusion coefficient and the mortality rate.

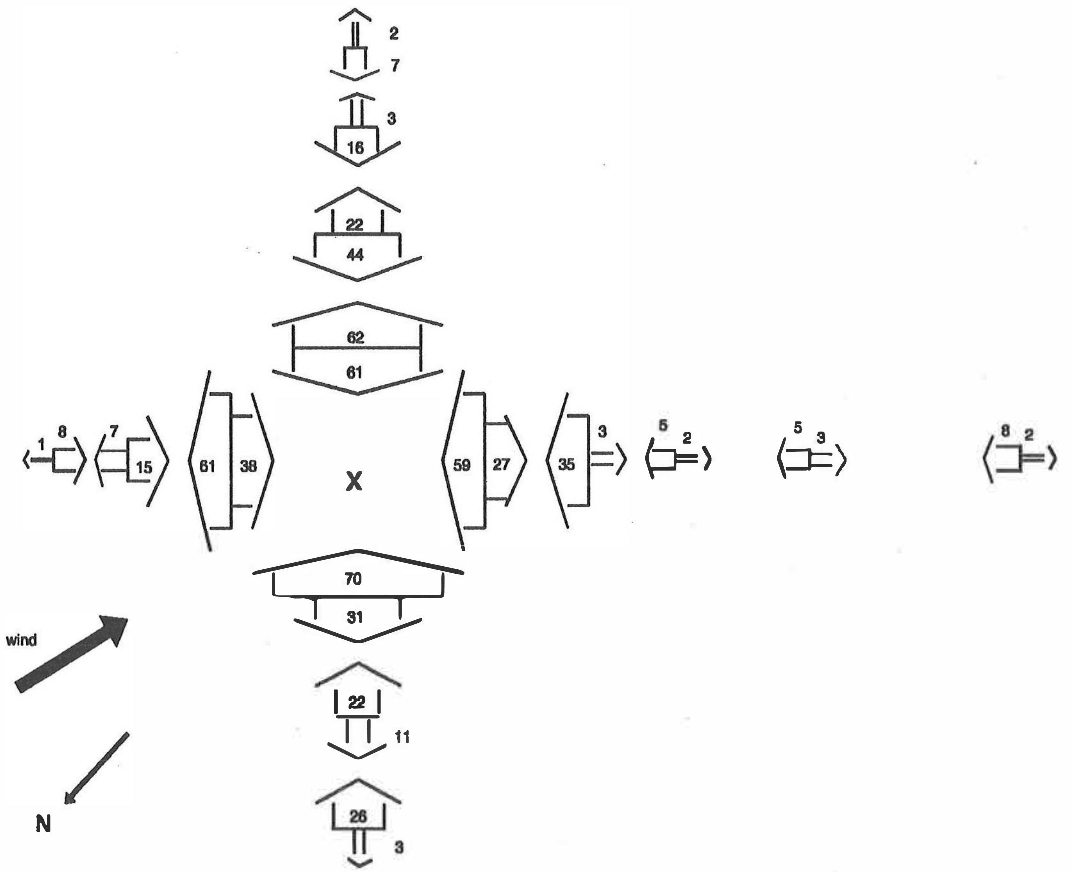


FIG. 3. The spatial structure of a beetle swarm around a focal tree. **X** indicates the focus of congregation (the mass-attacked pine tree). Arrows pointing towards (away from) the focus show how many beetles hit the 1 m^2 sticky screen going towards (away from) the tree. The width of the arrow and the number inside it indicate the actual number of beetles captured. Summing the numbers of beetles hitting both sides of the screen, we obtain an estimate of the swarming density at the spatial position of each screen. Taking the difference we obtain an estimate of net flux with respect to the congregation focus.

A second study, using different experimental methods, was necessary to examine SPB behavior during the congregation phase of movement. The basic premise of the study was that beetles flying in the vicinity of a mass-attacked tree use chemical (pheromones and host volatiles) and visual (the vertical shape of the tree, see Gara, Vité and Cramer 1965) cues to bias their movements towards the tree. This bias results in congregation and mass attack. The attractive bias is assumed to be a function of the distance and direction from the tree to the flying beetle. In addition, the bias is modified by the total number of beetles boring into the tree. At the beginning of mass-attack, the strength of the bias should increase with the number of attacking beetles, since more beetles are congregating on the tree, releasing frontalin. As the tree begins to fill with attacking beetles, however, the bias should decrease in strength, possibly even becoming negative, due to the release of the repellent pheromone verbenone (Payne 1980).

The approach of the second study was to quantify attractive bias by measuring the flux of flying SPB at various spatial points, around a single tree under mass-attack by SPB. Flux in relation to the mass-attacked tree is defined as the number of SPB crossing a unit of surface area (1 m^2) per unit of time (1 day) toward the tree, minus the number crossing the surface away from the tree. To begin the experiment, a single loblolly pine (*Pinus taeda*) was baited with frontalin and turpentine, to initiate SPB attack. As soon as mass attack was underway, these artificial volatiles were removed, allowing the attack to proceed naturally. To measure the flux of flying SPB toward the tree, 1 m^2 sticky screens were erected at different distances and directions from the tree. The course of the mass attack was monitored by counting the number of entrance holes of boring beetles on 16 smoothed areas of bark (1 dm^2 in area) on the focal tree. Analysis of the resulting data has shown that the flux of beetles toward the tree is a function both of the number of beetles attacking, and the distance from, the focal tree (Fig. 3).

Given information on the fluxes of SPB, our eventual goal is to determine the form of β, D, and δ for this phase of SPB movement, and so fully define equation (1). Combined with the results of the dispersal phase experiment, the resulting diffusion model will provide a complete description of beetle movement (see Fig. 4 for a conceptualization of how this model of beetle movement would work). The same experimental techniques will eventually need to be applied to key natural enemies in the system. Once diffusion equations for the SPB and natural enemies are defined, they can then be solved to determine the total number of SPB and natural enemies which arrive on the surface of the tree during attack. These inputs to the tree are the inputs to the second half of our conceptual model of the SPB system, involving the interaction of the SPB and its natural enemies once they arrive on the tree.

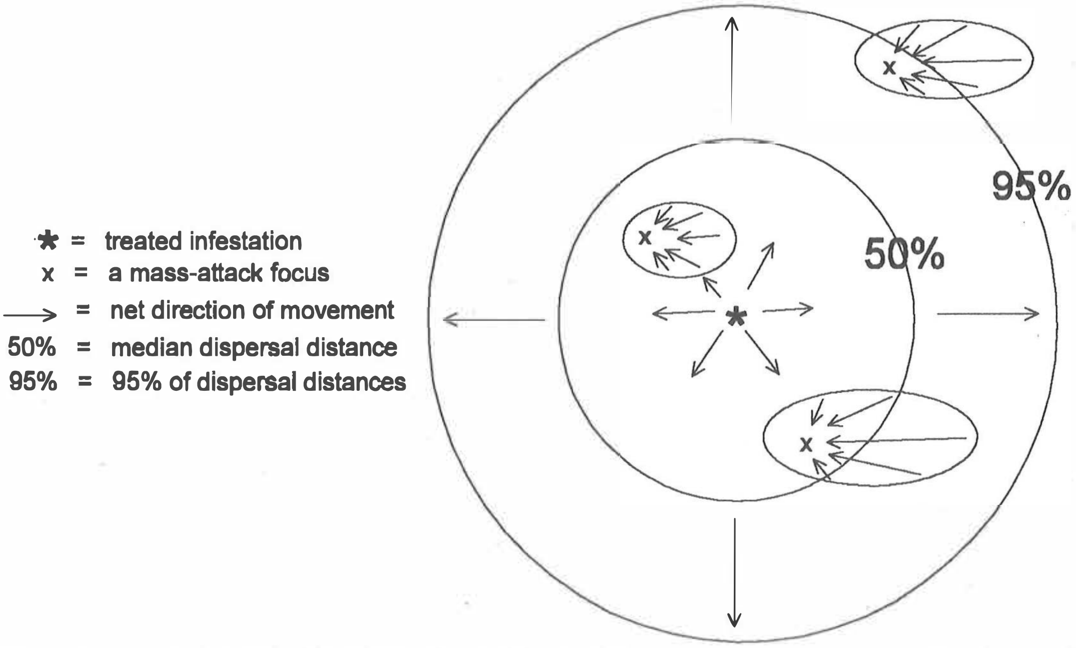


FIG. 4. A conceptual model of intraforest dispersal in the SPB. Arrows indicate net population fluxes. Thus, individual beetles may be moving in randomly chosen directions, but the average population flow will occur in the direction indicated by arrows. Solid concentric circles indicate the spatial scale of disperal, enclosing 50% and 95% of all dispersers, respectively. Ovals delineate attractive areas of mass-attack, or congregation, foci. These foci, which could be either single trees or spots, are indicated by **X**.

THE WITHIN-TREE INTERACTION

To complete our model of SPB dynamics, we now focus on the interaction of the SPB and its natural enemies once they have arrived on a tree under mass-attack. Many different aspects of the biology and behavior of the SPB and its enemies could, in theory, influence this interaction. These include the attack rates and functional responses of the different enemy species, and any interference or competition between them. Unfortunately, there is almost no information of this kind for the enemies of SPB, especially under natural conditions. In petri dishes, adults of the SPB predator ***Thanasimus dubius*** (Coleoptera: Cleridae) have been shown to have a Type II functional response on SPB adults (Turnbow *et al.* 1978; Mizell 1980; Nebeker and Mizell 1980), but no information exists on the behavior of clerid larvae, which are thought to consume large numbers of SPB brood underneath the bark (Thatcher and Pickard 1966). Dix and Franklin (1974, 1981, 1983) have observed aggressive encounters among SPB parasitoids, an indication that interference is occurring among them. While this could potentially affect the dynamical behavior of the system, no measurements of the degree of interference were made. In general, although the basic ecology and life histories of many SPB natural enemies are known, we lack the quantitative information necessary to understand their effects on SPB dynamics.

Perhaps the main reason why we lack quantitative information on natural enemies is that much of the interaction takes place beneath the bark surface, making direct observation of natural enemy and SPB behavior difficult. Because we cannot easily use observational methods, we have adopted a more practical, if indirect, approach by quantifying the interaction between the SPB and its natural enemies at the level of the tree. At this level, one has an initial set of inputs to the tree, consisting of the number of SPBs and natural enemies arriving on the tree. Once there the organisms interact (the "within-tree" interaction), generating a set of outputs, which are the number of SPB and enemies eventually emerging from the tree (the progeny of the arriving individuals). This idea can be written mathematically as

$$\begin{aligned} S' &= S \cdot f_s(S, X_1, X_2, \ldots) \\ X_1' &= X_1 \cdot f_1(S, X_1, X_2, \ldots) \\ X_2' &= X_2 \cdot f_2(S, X_1, X_2, \ldots) \\ &\text{etc.} \end{aligned} \tag{2}$$

where S is the number of SPB attacking the tree, and X_1, X_2, ... are the number of natural enemy species 1, species 2, etc., arriving on the tree. S', X_1', X_2', ... are the number of SPB and natural enemy progeny later emerging from the tree. The within-tree interaction is described by the functions f_S, f_1, f_2, etc., which are essentially per capita growth rates. The particular shape of each function would be determined by the details of the behavior and biology of each enemy, and the SPB. For example, if enemy 1 (say *Thanasimus*) possessed a Type II functional response, then one would expect f_S to increase as arriving SPB density (S) increases, because the clerids would become saturated at high prey densities (assuming all other densities (X_1, X_2, ...) remain the same). If there were also significant competition for food among clerids, in addition, then one would expect f_1 to decrease as clerid density increases on the tree.

We are currently using two different but complementary approaches to determine the within-tree interaction. The first, a field study of trees within SPB infestations, employs naturally-occurring variation in enemy and SPB numbers to determine the within-tree interaction (i.e., the form of f_S, f_1, etc.), with all the enemy species present. The study involves measuring the number of natural enemies and SPBs arriving on the tree, using sticky-traps. Bark samples are then taken to estimate the density of successful SPB attacks, and then emergence traps attached to catch both the emerging SPB brood and natural enemies.

Response surface methodology (RSM) will then be used to estimate the within-tree interaction functions. The RSM approach is similar to polynomial fitting of the data, but also permits nonlinear transformation of the variables to be fitted (Box and Cox 1964), and thus provides greater flexibility. In essence, RSM is a phenomenological, and hence model-independent, approach to fitting a function to ecological data (Turchin and Taylor 1992). Because of the typical residual structure in ecological data, we will not fit Equation (2) directly to the data, but instead will use the statistical model

$$\log S'/S = g(S, X_1, X_2, \ldots) + \varepsilon \qquad (3)$$

where ε is the error term, and g is the response surface to be fitted using Box and Draper (1987) methods. Stepwise regression of log S'/S on the numbers of natural enemies visiting the tree (i.e. X_1, X_2, ...) will be used to determine which natural enemy species have a significant effect on the SPB, and so should be included in the response surface model. It should also be possible to fit analogous response surfaces for each of the natural enemy species, which would describe how the number of emerging individuals of each species is related to the number arriving on the tree, and SPB density.

The second natural enemy study, a field experiment using tree cages, manipulates the density of *Thanasimus* and SPB within enclosures which exclude all other natural enemies, to examine the contribution of *Thanasimus* to the total within-tree interaction. This experiment will allow us to examine the pairwise interaction between the SPB and one natural enemy species, in contrast with the field study, which involves the interactions among all the species. *Thanasimus* is an abundant natural enemy of the SPB, making it a logical first choice for this type of experiment. The same methods could, however, be used to study the effects of many of the other natural enemy species.

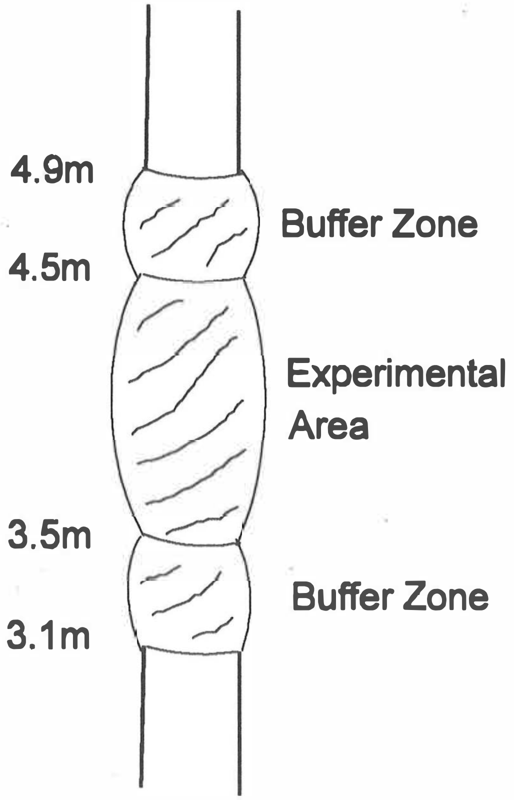


FIG. 5. Tree cage used to manipulate the densities of *Thanasimus* and SPB, while excluding other natural enemies.

The experiment has eight different treatments, four clerid densities crossed with two SPB densities. The first step in the experiment is to choose loblolly pines in an area where SPB are prevalent, and then install the cages (see Fig. 5). These are 1.8 m long cylindrical enclosures, made from fine-meshed saran screen, divided into a 1 m experimental area in the center (to which the SPB and clerids are added), and buffer zones above and below the experimental areas (no insects added). The buffer zones act as barriers to the within-bark movement of SPB and natural enemies from outside the cages. The trees are then baited with frontalin and turpentine, to induce SPB attack on the tree outside of the cage. As the tree succumbs to attack, the required number of SPB and clerids may then be added to the cage. Bark samples are then taken after several weeks to estimate the attack density of SPB. Just before SPB emergence, the tree is felled and the caged area removed and held within a rearing can, to measure the number of SPBs and clerids emerging. Response surface methodology will again be used to analyze the outcome of the experiment. Because only one natural enemy species is involved, however, the model simplifies to

$$\log S'/S = g(S,X) + \varepsilon \qquad (4)$$

Here S and X are the inputs of SPBs and clerids to the cage, while S' is the number of SPB emerging.

SYNTHESIS

Once the movement and within-tree interaction components of the SPB system are known, it should possible to construct and test quantitative mathematical models of the system. We plan to construct a hierarchy of models, beginning with one of a single tree under mass attack. Starting with an initial distribution of SPB and natural enemies in space, the model would first predict the number and temporal pattern of insects arriving on the focal tree, and then using the within-tree interaction component, predict the number of SPB and natural enemy progeny later emerging from the tree. The next step in modeling the system would be to construct a spot dynamics model. Again, the model would take an initial distribution of organisms in space and predict the number arriving on one or more focal trees. The progeny emerging from these trees would then be fed back into the movement part of the model, after an appropriate developmental delay, where they could potentially attack new trees or disperse away from the spot. To test these two models, one would need an estimate of the density of flying SPB and natural enemies in the vicinity of the focal tree or spot, since this provides the initial condition of the model. The predictions of the model could then be compared with the growth of actual spots, under different initial conditions. The final model in the sequence would be a regional one, which would predict where spots would occur within a large geographic area, and would also predict how densities of the SPB and it natural enemies fluctuate through time. An important test of this model would be its ability to predict the amplitude and period of SPB oscillations seen in nature.

CONCLUSION

A number of different hypotheses have been advanced to explain the occurrence of SPB outbreaks. These include the influences of climate (King 1972), systematic shifts in individual quality between endemic and epidemic populations (Hayes and Robertson, in press), an interaction between hosts (possibly involving cyclic changes in host quality) and SPB populations (Berryman 1976), and a cycle driven by natural enemies. We have focused on the predator-prey aspect of SPB population dynamics, because we believe this is currently the most fruitful direction, given the indirect evidence supporting this hypothesis. Our goal is to either refute or provide support for the enemies hypothesis. However, other hypotheses could be included within the general modeling framework we have advanced in this paper. For example, if there are in fact cyclic changes in the quality of SPB populations (perhaps in their fecundity), we could incorporate this in the model, and then see if it predicted oscillations in SPB density similar to those seen in the field. By proceding in this way, our modeling approach should allow us to test each of the above hypotheses.

A key feature of our approach is its explicit consideration of the spatial dimension of SPB dynamics. Until recently, very little quantitative information was available about the spatial scale and factors affecting SPB dispersal (Turchin and Thoeny, in press). Without such information, we would never be able to explain such puzzling spatial features of SPB dynamics as the apparent synchronization of outbreaks over large spatial scales (e.g. at the level of states). Are regional SPB outbreaks synchronized by SPB and/or natural enemy movement? Or are they synchronized by correlated weather patterns?

It is clear that both data and models are required to answer questions of the sort raised above. However, the dynamics of SPB outbreaks have traditionally been studied either purely empirically, or with phenomenological models (e.g., Gold *et al.* 1980). There has been little, if any, interaction between the models and data. Theory is needed to indicate what sorts of data must be collected. For example, by writing down the diffusion model of SPB movement, we have identified the key parameters that need to be measured in field experiments. On the other hand, models unrestrained by data are not helpful in eliminating competing hypotheses that purport to explain SPB outbreaks. We believe that a mechanistic framework combining modeling and empirical work, such as the one proposed here, is necessary for sorting out various hypotheses explaining SPB outbreaks.

CONCLUSION

We thank G. Barnett, D. Rhodes, G. Woodley, and J. Fryar for providing field assistance. J. Hayes read and commented on the manuscript. P. Turchin was partially supported by USDA Competitive Grant #92-37302-7606.

LITERATURE CITED

Berryman, A. A. 1976. Theoretical explanation of mountain pine beetle dynamics in lodgepole pine forests. Environmental Entomology **5**: 1225-1233.

Billings, R. F. 1988. Forecasting southern pine beetle infestation trends with pheromone traps. *In* T. L. Payne and H. Saarenmaa, editors, Integrated Control of Scolytid Bark Beetles. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Box, G. E. P., and D. R. Cox. 1964. An analysis of transformations. Journal of the Royal Statistical Society B **26**: 211-243.

Box, G. E. P., and N. R. Draper. 1987. Empirical Model-Building and Response Surfaces. John Wiley and Sons, New York, USA.

Chesson, P. L, and W. W. Murdoch. 1986. Aggregation of risk: relationships among host-parasitoid models. American Naturalist **127**: 696-715.

Dix, M. E., and R. T. Franklin. 1974. Inter- and intraspecific encounters of the southern pine beetle parasites under field conditions. Environmental Entomology **33**: 131-134.

Dix, M. E., and R. T. Franklin. 1981. Observations on the behavior of the southern pine beetle parasite *Roptrocerus eccoptogastri* Ratz. (Hymenoptera: Torymidae). Journal of the Georgia Entomological Society **16**: 239-248.

Dix, M. E., and R. T. Franklin. 1983. Behavior of four braconid parasites and one pteromalid parasite of the southern pine beetle. Journal of the Georgia Entomological Society **18**: 125-138.

Gara, R. I., J. P. Vité, and H. H. Cramer. 1965. Manipulation of *Dendroctonus frontalis* by use of a population aggregating pheromone. Contribution of the Boyce Thompson Institute **23**: 55-66.

Godfray, H. C. J. and M. P. Hassell. 1989. Discrete and continuous insect populations in tropical enviroments. Journal of Animal Ecology 58: 153-174.

Gold, H. J., W. D. Mawby, and F. P. Hain. 1980. A framework for modeling endemic-epidemic transitions in southern pine beetle. *in* F. P. Hain, editor, Population Dynamics of Forest Insects at Low Levels. North Carolina Agricultural Research Service, Raleigh, NC.

Hassell, M. P. 1978. The Dynamics of Arthropod Predator-Prey Systems. Princeton University Press, Princeton, New Jersey, USA.

Hassell, M. P., R. M. May, S. W. Pacala, and P. L. Chesson. 1991. The persistence of host-parasitoid associations in patchy environments. I. A general criterion. American Naturalist **138**: 568-583.

Hayes, J. L., and J. L. Robertson. 1992. Current status of bark beetle genetics and some thoughts about future needs. *in* J. L. Hayes and J. L. Robertson, editors, Bark Beetle Genetics: Status of Research. U.S. Department of Agriculture, Forest Service, General Technical Report, in press.

Ives, A. 1992. Continuous-time models of host-parasitoid interactions. American Naturalist **140**: 1-29.

Kareiva, P. 1983. Local movements in herbivorous insects: applying a passive diffusion model to mark-recapture field experiments. Oecologia **57**: 322-327.

Kareiva, P., and G. Odell. 1987. Swarms of predators exhibit "preytaxis" if individual predators use area-restricted search. American Naturalist 130: 233-270.

King, E. W. 1972. Rainfall and epidemics of the southern pine beetle. Environmental Entomology 1: 279-285.

Lindgren, B. S. 1983. A multiple funnel trap for scolytid beetles (Coleoptera). Canadian Entomologist 115: 299-302.

Mizell, R. F., III. 1980. *Thanasimus dubius* (F.): Some Behavioral Factors Affecting Its Predatory Role. Thesis. Mississippi State University, USA.

Murdoch, W. W., R. M. Nisbet, S. P. Blythe, W. S. C. Gurney, and J. D. Reeve. 1987. An invulnerable age class and stability in delay-differential parasitoid-host models. American Naturalist 129: 263-282.

Murdoch, W. W., and A. Stewart-Oaten. 1989. Aggregation by parasitoids and predators: effect on equilibrium and stability. American Naturalist **134**: 288-310.

Nebeker, T. E., and R. F. Mizell III. 1980. Behavioral considerations in quantifying the impact of *Thanasimus dubius* (F.) adults on bark beetle populations. *in* F. M. Stephen, J. L. Searcy and G. D. Hertel, editors, Modeling Southern Pine Beetle Populations. U.S. Department of Agriculture, Technical Bulletin 1630.

Okubo, A. 1980. Diffusion and ecological problems: mathematical models. Spring-Verlag, Heidelberg-Berlin-New York.

Payne, T. L. 1980. Life history and habits. *in* R. C. Thatcher, J. L. Searcy, J. E. Coster, and G. D. Hertel, editors, The Southern Pine Beetle. U.S. Department of Agriculture, Forest Service, Technical Bulletin 1631.

Stephen, F. M., M. P. Lih, and G. W. Wallis. 1989. Impact of arthropod natural enemies on *Dendroctonus frontalis* (Coleoptera: Scolytidae) mortality and their potential role in infestation growth. In D. L. Kuhlhavy and M. C. Miller, editor(s), Potential for Biological Control of Dendroctonus and Ips Bark Beetles. Center for Applied Studies, School of Forestry, Stephen F. Austin State University, Nacodoches, TX.

Taylor, A. 1988. Large-scale sptial structure and population dynamics in arthropod predator-prey systems. Annales Zoologici Fennici **25**: 63-74.

Thatcher, R. C., and L. S. Pickard. 1966. The clerid beetle, *Thanasimus dubius*, as a predator of the southern pine beetle. Journal of Economic Entomology **59**: 955-957.

Turchin, P. 1989. Population consequences of aggregative movement. Journal of Animal Ecology **58**: 75-100.

Turchin, P., and A. D. Taylor. 1992. Complex dynamics in ecological time-series. Ecology **73**: 289-305.

Turchin, P., and W. Thoeny. 1992. Quantifying intraforest dispersal of southern pine beetles with mark-recapture experiments and a diffusion model. Ecological Applications, in press.

Turchin, P., P. L. Lorio, Jr., A. D. Taylor, and R. F. Billings. 1991. Why do populations of southern pine beetles (Coleoptera: Scolytidae) fluctuate? Environmental Entomology **20**: 401-409.

Turnbow, R. H., R. T. Franklin, and W. P. Nagel. 1978. Prey consumption and longevity of adult *Thanasimus dubius*. Environmental Entomology **7**: 695-697.

USDA. 1987. Final environmental impact statement for the suppression of the southern pine beetle. U. S. Department of Agriculture, Southern Region, Management Bulletin R8-MB-2.

REGIONAL DYNAMICS OF SOUTHERN PINE BEETLE POPULATIONS

JOHN M. PYE
Southeastern Forest Experiment Station, USDA Forest Service, Research Triangle Park, NC 27709

Abstract. Critical analysis of a dataset on southern pine beetle activity assembled by 11 states and spanning 31 years reveals broad scale patterns and variability of beetle outbreaks and resulting tree mortality. Spatial and temporal patterns are explored at both regional and state scales, and decadal and annual time steps. These analyses indicate that outbreaks can be initiated simultaneously at multiple sites and across multiple states. Outbreaks also appear to cycle through an initial, intensive phase of damage and then to spread into a more extensive phase where damage is less concentrated. However, because the data are assembled from operational records, critical appraisal of data quality is essential to proper interpretation of results. For this reason, methodological artifacts may be contributing in some degree to the observed patterns. Two analyses are illustrated where inconsistencies in data definitions currently prevent credible analysis (merchantability shifts during outbreaks, and the contribution of National Forests to surrounding outbreaks). By clarifying broad scale variability and processes, spatial and temporal analyses at these regional scales can be a crucial complement to finer scaled analyses of pest dynamics. Because beetle dynamics are extremely variable over time, work on initiating collection of more methodologically defensible data cannot begin too soon.

The principal objective of this paper is to explore broad scale southern pine beetle (SPB) dynamics for processes which might be responsible for initiating outbreaks, based on a recently published 31 year dataset of regional scope (Price and others 1992). Initiating factors are focussed on because 1) factors initiating outbreaks may differ from those which terminate them, and 2) suppression efforts at this early phase of outbreak may be more effective than efforts during outbreak peaks.

This paper has a secondary objective. While an earlier compilation of southern pine beetle outbreaks (Price and Doggett 1982) was used in numerous investigations (Mawby and Gold 1984; Mawby and Hain 1985; Mawby and Gold 1984; Mawby and others 1989; Michaels and others 1986), little attention was given to the origins and limitations of the underlying data. Because these data were originally collected by various State forest pest specialists for operational rather than scientific purposes, data comparability is an important concern. Explicitly addressing such issues is the best means to minimize its misinterpretation.

The paper will thus describe first how the data were derived. This will be followed with discussion of the patterns implied by the data, and the implications of data quality on proper interpretation of these patterns.

DATA DERIVATION AND METHODS

The data on southern pine beetle used here are annual measures of outbreak status and timber volume damage. The data from 1960 to 1980 were solicited from State forest pest specialists near the end of this period and first published as Price and Doggett (1982). Data extending the series through 1990 were collected in 1989 and 1991 and the full series published as Price et al. (1992) along with some discussion of how the data were derived. Two types of data are discussed below, both at an annual time step: outbreak status and damage (mortality) estimates. The dataset also contains separately derived estimates of salvage amounts, but these are not addressed here.

Pages 111-124 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

Outbreak Status

The severity of SPB infestations is usually characterized for some area as a ratio of the number infestations ("spots") over the amount of potential host. The former is based on detection flights and ground checks. The latter is obtained by summing Forest Inventory and Analysis estimates of acres in loblolly/shortleaf and oak/pine forest types. When the ratio equals or exceeds 1.0 the region is termed "in outbreak." Data on outbreak status are available South-wide by county for 1960 through 1990.

Damage Estimates

States estimate annual volumes of pulpwood and sawtimber mortality caused by SPB from spot data using a variety of extrapolation methods. The pulpwood estimates are reported in cords and sawtimber in MBF. However, these separate estimates have been combined and reported here as total damage in cubic feet. These estimates are available at the State rather than county level. For some States the estimates extend from 1990 all the way back to 1960, but South-wide coverage has only been available since 1972.

Because the data on outbreak status report infestation frequency adjusted for amount of available host, this measure helps inform forest owners on the historical infestation risk experienced by susceptible forests in their area. Damage estimates on the other hand provide a rough indication of the impact of beetle populations on the State's economy. Additionally, because successful reproduction by the beetle requires killing the host tree, volume of timber killed also provides our best region-wide proxy for SPB population levels by reflecting variations in both spot numbers and spot size.

Difficulties with these two types of data can arise in four areas: aerial survey and ground checking intensity, determinations of susceptible acres, extrapolation from spot counts to volume estimates, and assignment of damage to merchantability class.

Aerial Survey and Ground Checks

Two details are relevant to spot detection. First, not all patches of dead or dying pine trees are infested by southern pine beetle. Patches located on aerial sketch maps must be checked on the ground to confirm SPB as the cause of mortality. Second, because small spots are far more likely than large spots to cease expanding on their own (Hedden and Billings 1979), States disregard spots smaller than 5 or 10 trees.

Flights to detect beetle spots suffer understandable technical limitations. Observers may miss seeing a spot for a variety of reasons: proximity to the flight line, poor weather, or lack of development of crown discoloration on infestation. Spot locations may be inaccurately sketched on maps, preventing ground truthing and allowing double counting of the spot the next flight. The ability of observers to control these problems will likely differ within and across states. Technologic improvements in navigation have likely reduced some sources of error over time (Dull 1980) but may have introduced a temporal bias.

Aerial detection flights are conducted for pragmatic reasons to help landowners protect their forests from damage. Such motivations are in practice constrained by budgets, budgets which vary by state and from year to year. Concentrating limited efforts where they will do the most good, agencies tend to fly less intensively when beetle activity is judged low, and not fly in those areas where beetles are not thought a problem. Judgments on where and when to fly can be based on pheromone sampling (Billings 1992), previous population levels (Mawby and others 1989), and reports from ground personnel, aerial fire control operations, and concerned landowners. More bothersome is how varying budgets can affect flight intensity and therefore thoroughness of spot detection. Additional concerns about varying coverage of detection flights include those surrounding interpretation of missing data (Mickler and Dwire 1992), and the impact of varying survey intensity on our ability to support spot suppression during critical endemic-epidemic transitions (Mawby and others 1989).

Budgets also can affect the thoroughness of ground checking, despite evidence of their importance in correcting aerial estimates (Mayyasi and others 1975). Data on the intensity and consistency of ground checks are not available across the scope of this dataset. However, lack of ground checks in South Carolina in 1989 and 1990 resulted in limiting all infested counties to the lowest outbreak category (.1 to less than 1 spot per thousand).

Susceptible Acres

Acreage estimates used as the denominator in spots per thousand are also subject to uncertainties, principally arising from the temporal and spatial resolutions of the data. The only regionally compatible data source available for estimating acreages of susceptible host material is collected by the Forest Inventory and Analysis (FIA) units of the US Forest Service's Southeastern and Southern Stations. Although FIA samples approximately forty five thousand locations region wide, county-level estimates of acres by forest type strain the spatial resolution of the sampling design, and intervals between surveys mean estimates can be up to nine years out of date (Ray Sheffield and Joanne Faulkner, Southeastern and Southern FIA respectively, personal communication 1992). The temporal and spatial limitations of the data mean that host acreage estimates must be viewed as only approximate indicators of actual amounts of host material available in any given county and year.

Because SPB estimates are reported on an annual basis, a method is needed to interpolate county-level host acreages between FIA survey years, and two were employed with these data: step and linear. In step interpolation, acres from a given survey are assumed to continue unchanged until replaced by data from the next survey. Because this approach is simple to use and can produce ratings each year as new spot counts become available, it was the most common method used in the dataset.

Linear interpolation assumes that host acres change gradually between surveys. Linear interpolation was employed between 1972 and 1990 and only for Georgia. FIA surveys were conducted three times in Georgia during this period (1971-1972, 1981-1983, and 1988-1989). For each year and county between these survey dates host acreages were estimated by linearly interpolating between adjacent survey years. If for a given county a year lay outside the survey dates, the acreage figure from the nearest survey year was used.

Of course, actual host acreage dynamics are more complex than either interpolation method. However, comparing how interpolation methods affect assignment to outbreak intensity classes sheds some light on the sensitivity of this measure to host acre change. Outbreak classes were recalculated for all counties in Georgia for 1973 to 1988 based on step interpolated acres and compared with the ratings calculated using linearly interpolated acres.

TABLE 1. Comparison of outbreak class ratings determined using two methods for interpolationg host acres between survey years (see text). The comparison here is for 159 Georgia counties for the years 1973 through 1988.

	No.	Ratings Using Step Interpolation				
	observations	0	1	2	3	**Total**
Ratings	0	1790	2	0	0	**1792**
Using	1	7	464	2	0	**473**
Linear	2	0	15	147	1	**163**
Interpolation	3	0	0	8	108	**116**
	Total	**1797**	**481**	**157**	**109**	**2544**

Table 1 shows the two approaches produced identical ratings in 2509 of the 2,544 possible comparisons (159 counties times 16 years). The 35 differences involved adjacent ratings, but with a bias. Linear interpolation rated 30 more severely, presumably due to a reduction in host acres occurring during the period (data not shown). The 98.6% agreement in ratings between the two approaches is comforting, but the more important error associated with year to year acreage fluctuations remains unknown.

Another inconsistency concerns how states have handled National Forest lands. Because the USDA Forest Service has responsibility for controlling spots in National Forests, many states do not bother flying detection flights over them, and do not count spots there. For these States, adding State and National Forest spots is difficult because National Forest tallies are not broken out by county. Compounding the difficulty, standard FIA reports of susceptible acres by county do not distinguish Federal from other ownerships. Thus several states exclude Federal spots but include Federal acres when calculating outbreak intensities and classes, tending to understate the true severity of outbreaks. Table 2 shows how eight of the states treated National Forest spots and/or National Forest susceptible acres in their calculations of county level outbreak status.

TABLE 2. How different States handled inclusion of National Forest acres and spots in calculating outbreak status.

		spots	
		yes	no
acres	yes	AL, GA, MS	NC, SC, TN, TX
	no	none	LA

Damage Estimates:

Little information is available on the methods employed by states to estimate pulpwood and sawlog volume damages. Ideally each spot would be visited by ground crews and estimates made of the sawtimber and pulpwood volumes killed by the beetle. Volumes by the two product classes could then be summed to the state level. However, measuring volumes of all killed trees is expensive. Some states count trees killed and apply state average tree volumes to these counts to obtain statewide pulpwood and sawtimber volume damages. Estimates of amounts salvaged (not reported here) are typically obtained by a separate survey of mills or other log purchasers.

Overview of Potential for Error

The methods and concerns discussed above suggest that errors in the data are particularly likely at certain spatial and temporal scales. Because methods are most likely to differ between rather than within states, comparisons between counties within a state are more robust than comparisons across state borders. Similarly, to the extent that changes in personnel and methods occur only sporadically over time, year to year changes are probably safer than comparisons between decades. Rankings and relative shifts are probably on safer ground than determinations of absolute amounts.

PATTERNS AND RESULTS

This paper takes a graphical, exploratory approach to data analysis rather than applying statistical tests of hypotheses. Statistical approaches were avoided for three reasons: 1) the data describe full spatial coverage of the population of interest, not a random subsample, 2) the data appear both spatially and temporally autocorrelated, and 3) statistically rigorous formulations for most of the comparisons are elusive. The purpose is thus not to statistically test the importance of specific causal factors but to suggest hypotheses for more specific tests. The analyses below progress from broad to narrower scales, and progress from spatial to temporal comparisons and then to a combination of the two.

SPB range and host availability

Figure 1 shows how frequently counties have been in outbreak status during the period 1960-1990. Southern pine beetle outbreaks have been reported to occur at one time or another across most of the South. A total of 559 counties from east Texas to North Carolina and from Tennessee to the Gulf coast have reported SPB outbreaks during this period. Areas suffering particularly chronic outbreaks include east Texas, southwest Mississippi, and the South Carolina uplands. Indeed, twenty-one counties South-wide were reported to be in outbreak more years than not.

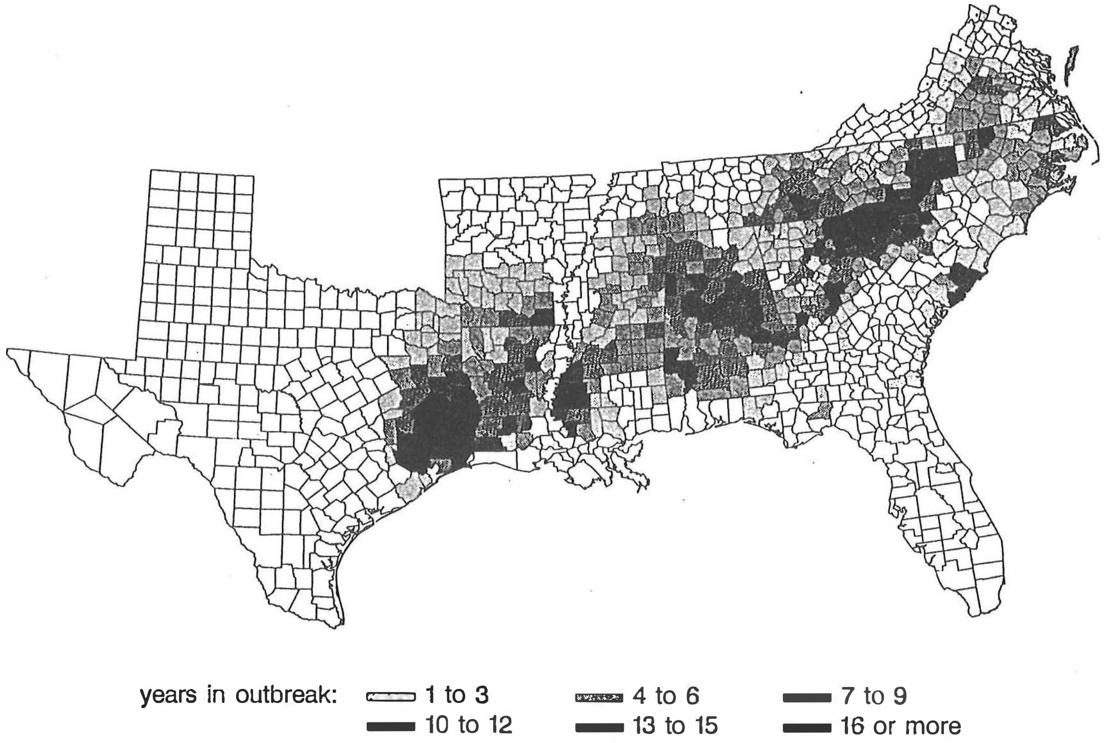


FIG. 1. Total years in SPB outbreak status during the period 1960-1990 as reported by State forest pest specialists. Outbreak is defined as one or more SPB spots per thousand acres of susceptible host type.

Other distinguishing spatial features include gaps in outbreak incidence along the Mississippi River and Gulf Coast, and an isolated area with outbreaks in the Florida panhandle. Also visible is a trough in outbreaks along the upper Atlantic coastal plain. That is, outbreaks are rare in the upper coastal plain but occur in counties nearer the coast.

The spatial distribution of SPB outbreak frequency closely follows the distribution of its major hosts. Figure 2 shows the combined timber volumes of loblolly, shortleaf and Virginia pines, expressed as cubic feet of wood per land acre (per Census Bureau figures). The timber volumes were collected by Southern and Southeastern Forest Inventory and Analysis Units (Eastwide Database) and describe conditions in the last decade, although it is very similar to that of loblolly and shortleaf from the 1960's (Pye 1992).

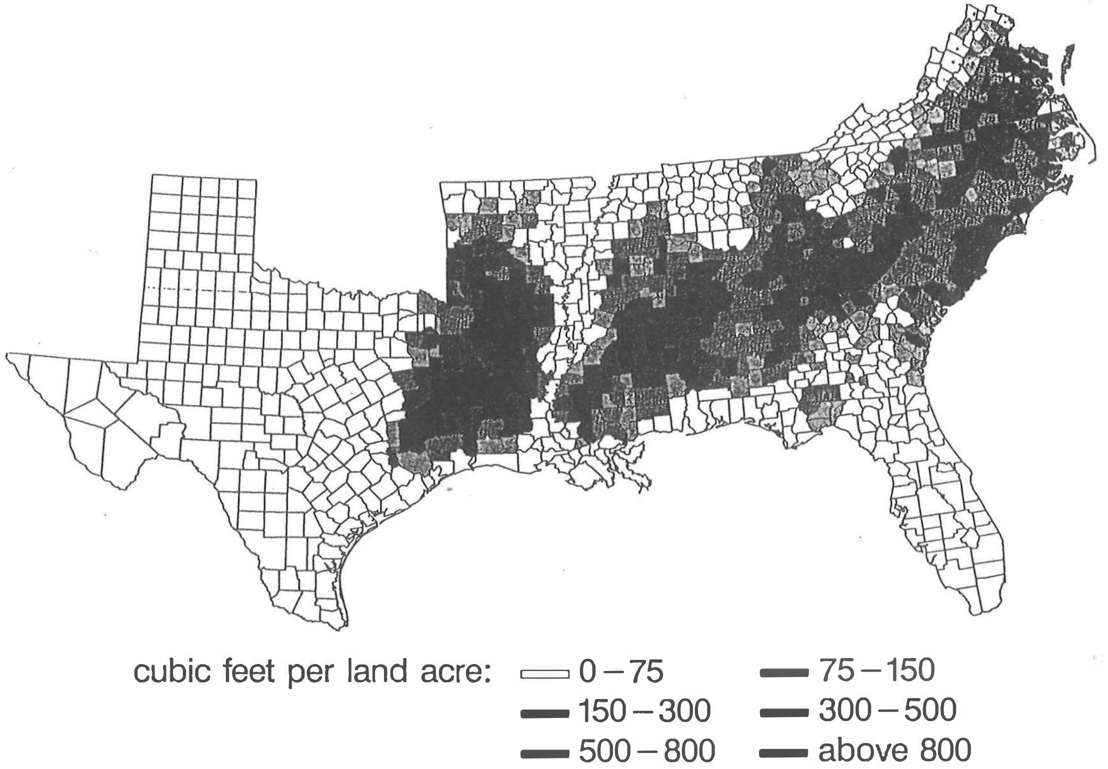


FIG. 2. Combined volumes of three SPB host species: loblolly, shortleaf and Virginia pines, expressed as cubic feet per acre of land. Data were collected by the Forest Inventory and Analysis units of the Southern and Southeastern Forest Experiment Stations and assembled as part of their Eastwide Database. These data were graciously forwarded by the Asheville office of Forest Pest Management. The data describe conditions from FIA's most recent survey cycle for each state and thus report conditions in the late 1980's to about 1991.

The two distributions suggest that, in the long run, southern pine beetle is able to take advantage of susceptible species throughout their range. The absence of outbreaks along the Gulf Coast, the Mississippi River, and upper Atlantic Coastal Plain all agree with reduced availability of these three host species. Areas with large concentrations of host (east TX, southwest MS, and piedmonts of GA and SC) show greater frequency of outbreak, even when adjusted for host acres. Patterns along the northern range of the distribution show lesser agreement. Both Virginia and northern Louisiana/southern Arkansas show disproportionately fewer outbreaks than their host material might indicate, suggesting that climatic factors may be responsible for reduced populations at the beetle's northeastern and northwestern ranges. In contrast, outbreaks in the southern Appalachians appear higher than the three host species might suggest, and may be due to pitch pine, whose southern distribution extends into this region (Burns and Honkala 1990).

These conclusions must be checked against alternative, methodological explanations. Two considerations are particularly relevant: State differences in detection intensity, and omission of areas which do not have these host species.

Abrupt changes in outbreak frequency along State lines are not uncommon. The bulk of the range limits occur within and not along state borders, and most changes in outbreak frequency do coincide with change in host availability. However, two cases are apparent where outbreak frequencies change along state borders in ways not readily explainable by simple changes in host volume: northwest South Carolina, and the borders of Alabama with Mississippi and Georgia. Such differences do not affect the overall interpretation of beetle range but might need to be considered in other evaluations.

Areas with particularly older, stressed pines might be particularly at risk to SPB. Because National Forests manage stands on longer rotations than most private land owners, pine stands in National Forests are often thought particularly vulnerable to attack by southern pine beetle (Carter and others 1990). Indeed, the three areas of most chronic outbreak shown in Figure 1 all include National Forests: east Texas (Sabine, Angelina, Sam Houston and Davey Crockett National Forests), southwest Mississippi (Homochitto NF), and northeast Georgia-western South Carolina (Chattahoochee and Sumter NF's). It would be tempting to use these data for explicit testing of the influence of National Forest holdings on frequency of outbreak, but the different handling of Federal lands across the region dictates particular care in interpreting the outbreak classification of any county which contains National Forest lands.

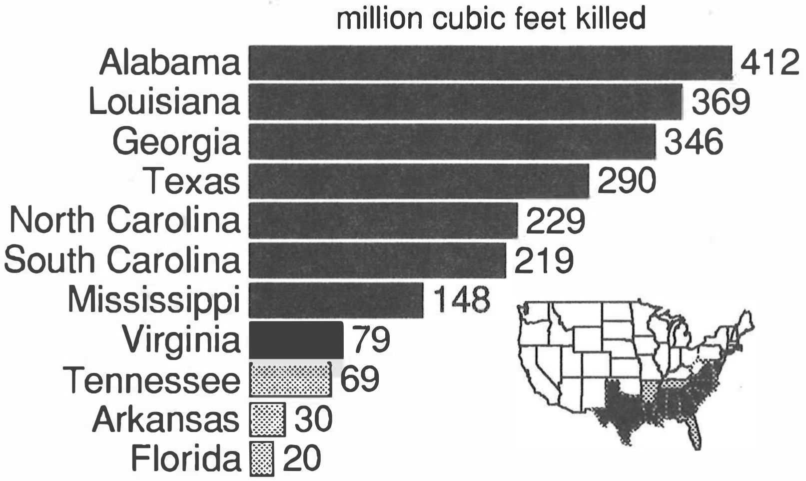


FIG. 3. Reported volumes of timber killed by SPB during the period 1972 through 1990, by state. The three States shown in gray reported the least amounts of damage. The remaining eight states thus conveniently represent a curving transect from southwest (Texas) to northeast (Virginia), made use of in Figures 4 and 5.

Damage estimates provide another view of how long term impacts of SPB may differ spatially across the region. Figure 3 shows total reported damages by state for the period 1972 and 1990. Not surprisingly, states with greater amounts of host species (and therefor near the heart of the outbreak range) report greater amounts of damage than states near the northern, southern and eastern peripheries.

As noted above, comparisons between states are particularly risky with this dataset. The rankings between states are much safer than absolute estimates of damage, but conclusions are safest when bolstered by other data, as are those in the above paragraph. For example, it would be imprudent to conclude that Alabama in truth has suffered greater damage than, say, Texas, but it does appear safe to conclude that Georgia has suffered more than Virginia. Although no quantitative estimates of error are available, a reasonable course might be to assume a factor of two error on the estimates for purposes of ranking between states, and perhaps a larger factor for determining absolute damages.

Relative shifts between years should be more reliable than absolute measures of damage. Figure 4 shows how damage estimates have varied by year, both by state and across the region. During this 19 year period there were three large outbreaks and 2-3 lesser ones. A regular cycle of 6-7 years apparent at this regional scale is not reflected in damages by state. Different sets of states are responsible for different regional outbreaks. The first regional outbreak occurred across virtually the entire South, but the outbreaks in 1979-80 and again in 1988 were strictly mid-South events, and the extreme outbreak of 1985-86 was limited to Louisiana and Texas. The smaller outbreak in 1982 was only apparent in Virginia.

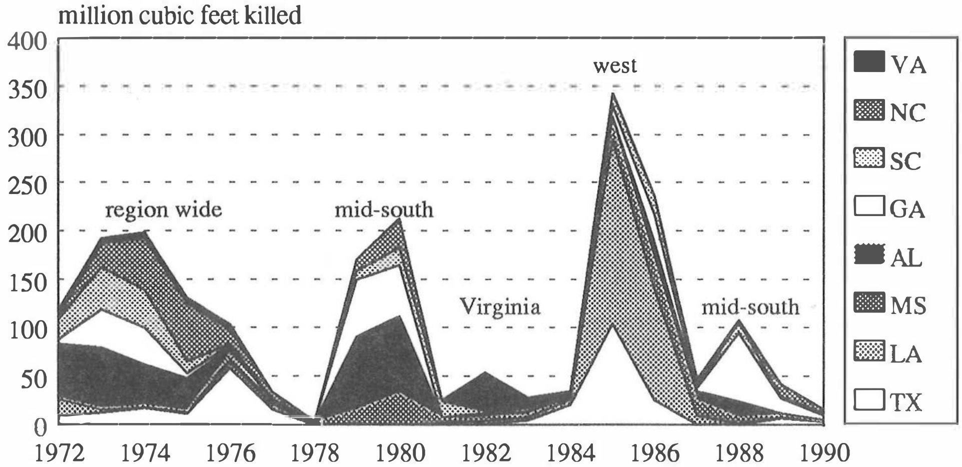


FIG. 4. Area graph of reported volumes of timber killed by SPB as reported by the eight highest reporting states (see Figure 3). Labels above peaks indicate subregions where damage occurred.

At least for the period spanned here, most outbreaks appear to occur simultaneously in adjoining states, suggesting that outbreaks can operate across distances of 500 to 1500 km. Comparisons of timing between different states is complicated however by differences in absolute damage between states. One way to account for these differences is to normalize the damages of each state to vary between that state's own maximum and minimum during this period. That way the relative variations for each state can be compared for characteristics such as timing of outbreak initiation and recession.

Figure 5 shows these relative variations in SPB damage for each of the eight states suffering the largest total damages. The temporal pattern for each state is stacked one above the other, and ordered to reflect their spatial distribution from southwest to northeast. In this arrangement, the synchrony of outbreaks in adjoining states can be seen as parallel deflections in adjoining lines. The single state outbreaks of Texas (1976) and Virginia (1982) appear as isolated blips, but the remaining three major outbreaks clearly span multiple adjoining states. Such outbreaks may peak in different years in different states, but for the major outbreaks beginning during this time period, each outbreak is initiated in the same year. That is, outbreaks during the seventies and eighties apparently started simultaneously across large parts of the region, rather than beginning in one state in one year and subsequently spreading to the next state.

This spatial temporal pattern of simultaneous initiation argues against beetle dispersal or host maturation as factors triggering outbreaks at these broad scales. Rather it suggests a large scale process such as weather is responsible for synchronizing populations across large portions of the region. Of course, methodological explanations should be considered as well. By sharing information among themselves, forest pest specialists in adjoining states might become mutually concerned an outbreak was underway, and in response intensify their monitoring and find more spots. In theory, synchronizing shifts in sampling intensity (or volume extrapolation parameters) could make the resulting state observations appear more synchronous than the underlying populations. This would suggest the unlikely situation that State forest pest specialists respond strongly to information derived from outside their borders and less strongly to information available from within.

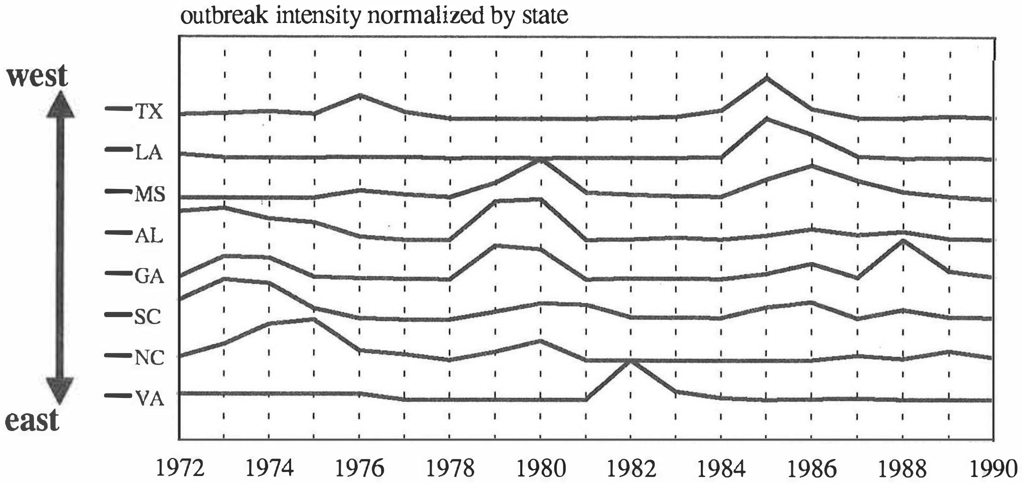


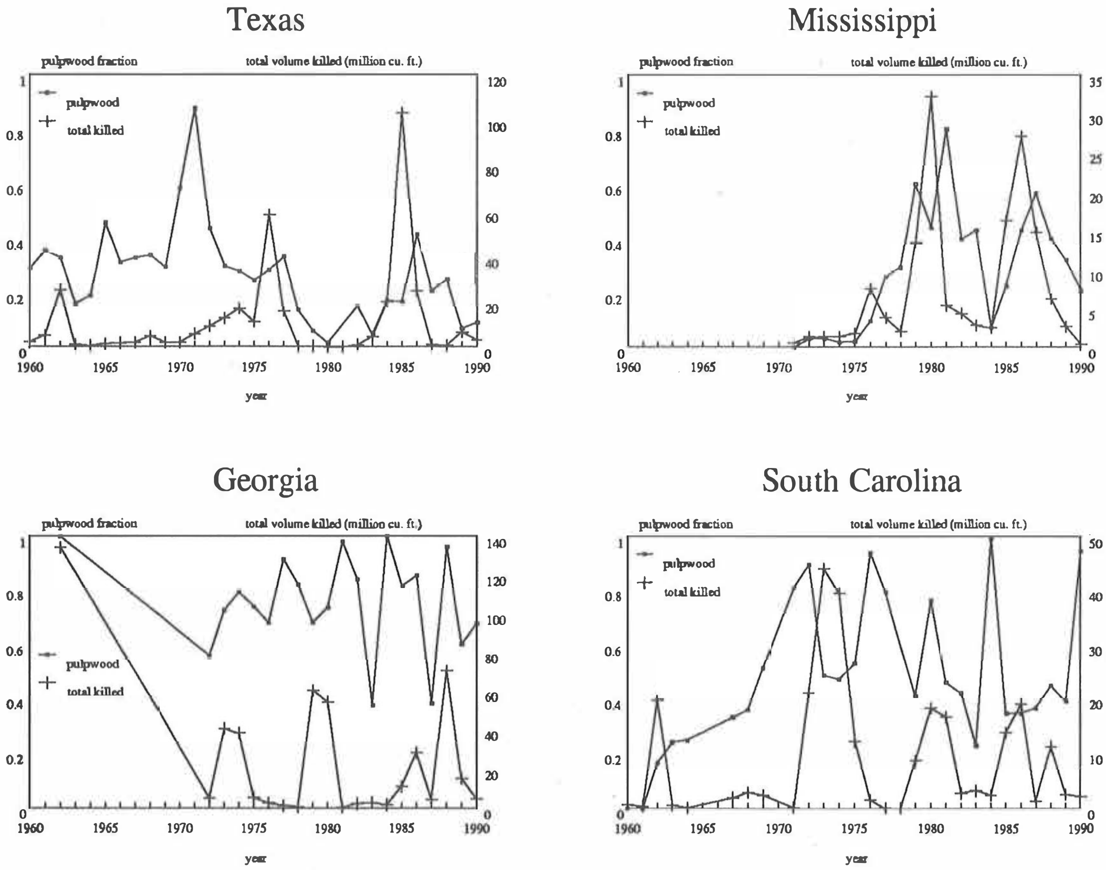
FIG. 5. Relative temporal dynamics of reported state level SPB damage between 1972 and 1990. Chart was constructed by normalizing each state's annual damage to vary between 0 and 1, based on that state's maxima and minima during the period. The resulting series for the states were stacked one above the other, with their order reflecting each state's relative spatial arrangement from southwest to northeast. Parallel deflections graphically indicate a broad scale spatial autocorrelation in timing of outbreak.

Another potentially useful analysis involves how damage is distributed between the two different product classes, pulpwood and sawtimber. Estimates of economic damage should be quite sensitive to merchantability assumptions, and biologic concerns are involved as well. During low outbreak years spots are believed to be primarily restricted to the highest risk, older stands, but during severe outbreaks spots develop more equally in stands of different age classes (Mason and others 1981). Such shifts in host size classes killed might therefor appear as shifts between the two product classes, so long as assignment of damage to the two merchantability classes were based on consistent criteria such as stem size.

Indeed, as illustrated in Figure 6, some states do show large swings in merchantability class with outbreak cycle. The southcentral states of Texas, Louisiana, Mississippi and Alabama showed pulpwood share expanding dramatically during outbreaks, often with a modest lag. The southeastern states of Georgia, North Carolina, and South Carolina however showed little relationship between outbreak intensity and pulpwood share.

Unfortunately, such patterns cannot be so clearly interpreted. Checks on data definitions and extrapolation methods used by the different States reveal that many States evaluate merchantability based on salability of the spot as salvage rather than its potential value had the infestation not occurred. Thus product degrade, market depression and small sale volume confound biologic shifts toward smaller stems which might have occurred. Additional extrapolation difficulties further complicate interpretation. South Carolina for example does not update its estimate of average tree size during an outbreak, missing shifts in size class which might occur from year to year. In Georgia all non-Federal damages are converted to cords to reflect the prevalence of weight-based purchasing practices.

Much of this problem arises from conflicting objectives. Those wishing to characterize potential benefits of beetle suppression need data which reflects the uses to which the trees would have been put had they not been damaged. Those wishing to emphasize mitigation opportunities for the landowner want data showing salvage opportunities given that damage has already occurred. The result is that assignments to product class are virtually useless for regional appraisals.


Texas

Mississippi

Georgia

South Carolina

FIG. 6. Annual SPB-caused mortality (pulpwood plus sawtimber) and the fraction of this total reported as pulpwood for four states. Although for Texas and Mississippi the two measures appear correlated, merchantability definitions make its interpretation obscure. See text.

The analyses above began with outbreak status at regional scales, then examined damage estimates at regional then state scales. This last analysis involves relationships between the two types of data, and explores the relationship between the extent of an outbreak, indicated by outbreak status information, and the intensity of the outbreak, as indicated by damage estimates. Quantitatively relating the two types of data might shed light on state-level dynamics of the outbreak process, and could also provide a means for estimating damage levels prior to 1972 for those states where damage estimates are only available for more recent years.

A potential difficulty relating the two types of data is that outbreak counties may have differing amounts of susceptible forest, and their contribution to statewide damage should reflect this. For this analysis, the estimates of susceptible volumes in Figure 2 were used to weight each county's status. As these volume estimates were collected in the recent FIA survey cycle, weights were only applied to outbreak data from 1981-90. The susceptible volumes in outbreak counties in a given year and state were summed and compared to that state's total susceptible acres. Figure 7 shows the resulting annual "percent of susceptible volume in outbreak counties" plotted against damages for several representative states.

Two patterns are apparent. First, there is a rough correspondence between the extent of an outbreak across the resource and the intensity of that outbreak in terms of volume mortality. Thus when total SPB damages are high, much of a state's susceptible pines are in outbreak areas. Conversely, very little damage is reported in those years with few reported outbreak counties. This should not be surprising, although many states show a large scatter to this relationship.

Second, there is a regular progression during an outbreak from an initial intensive phase of growth to a more extensive phase. That is, in the first part of an outbreak damage increases rapidly with little increase in extent. Growth in total damage then slows but continues to expand across the resource. Finally the outbreak collapses and recedes toward the origin. On the plots this cycle appears as a counterclockwise progression, and was found in the outbreak cycles of 7 of the 10 states reporting outbreaks in the 1980's. Such a pattern is consistent with spatial expansion of outbreaks from epicenters, but the contagious spatio-temporal pattern this also implies has not yet been confirmed.

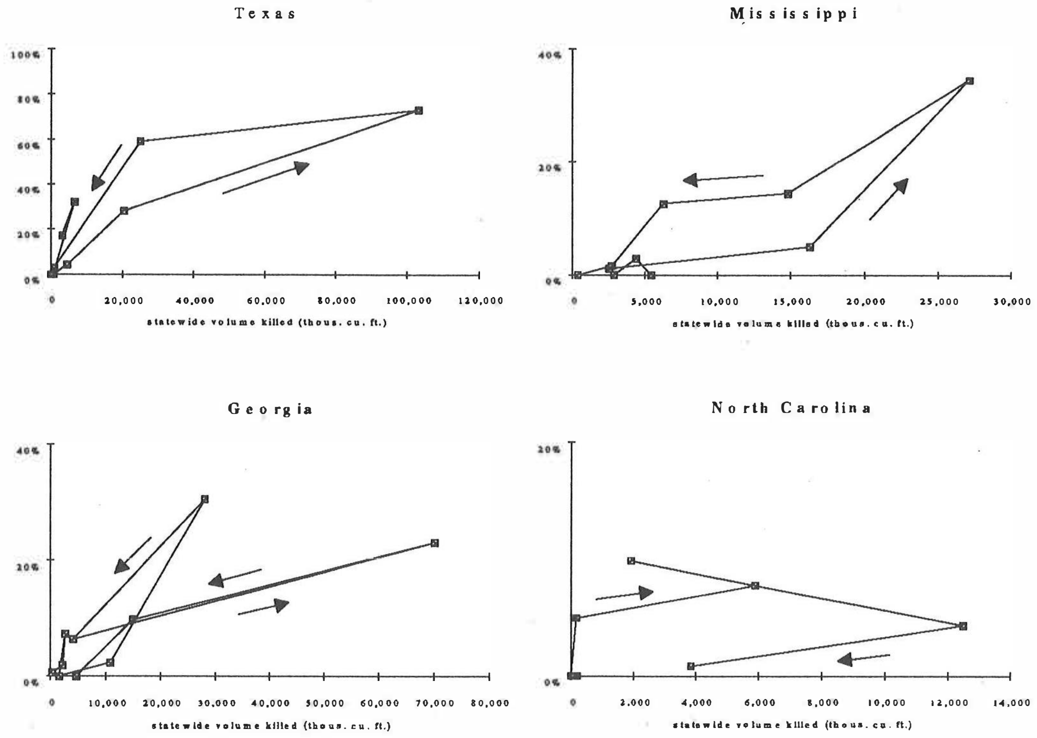


FIG. 7. The percent of each state's combined volumes of loblolly, shortleaf, and Virginia pine located in counties in outbreak status (y axis), plotted against the reported state-wide volume damages for that year (x axis). Lines connect successive years with arrows indicating direction from earlier to later. Of the four states shown, only North Carolina fails to show a counterclockwise pattern.

Examination of methods suggests a potential complementary explanation. Detection efforts during the initial phase of an outbreak might be focussed on those counties containing stands at greatest risk. Damage per acre in high risk, high volume stands could indeed be quite high, accounting for the "intense" damage observed. In following years, states might expand their detection efforts to include counties with stands of lower risk, also finding them to be in outbreak. With smaller spots and lesser basal areas, damage in these less susceptible stands might be lower and would constitute the "extensive" phase. In each case true outbreaks are found. The potential problem with this shift in detection would be that the outbreak may have begun simultaneously in both the high and low risk areas but simply was unreported in the lower risk areas until later in the outbreak, giving the appearance of expansion when none was there. Resolving the degree to which methodology amplifies true outbreak shifts requires distinguishing between when a status of "no outbreak" arises from actual detection versus when a county was not checked.

A common thread to the analyses above has been critical regard to its derivation and data quality limitations and focus on the spatial and temporal scales of methodological shifts. Thus, of the analyses shown here, estimates of statewide damage are the most uncertain, because the spatial unit of investigation most closely matches the most probable scales of methodological change:state wide and multi-year. Similar comparisons of long term change in outbreak severity would also be questionable. Fortunately, many methods available for quantitative analysis of spatial and temporal trends remove the more suspect gradual or broad scale shifts and focus on the more credible relative, fine scale shifts.

Note that two analyses have been illustrated which are particularly in need of improved data. These are: evaluation of stem size shifts during across phases of outbreak, and tests of the role of National Forests as outbreak epicenters. Such analyses would best be conducted with data from individual states after careful appraisals for data consistency.

CONCLUSIONS

There are two, complementary explanations to the patterns illustrated above. The first explanation runs as follows:

- host characteristics appear to define long term risk of SPB outbreak.
- outbreaks occur across multiple, adjoining states
- outbreaks are initiated simultaneously at multiple locations in adjoining states
- outbreaks expand from multiple epicenter(s) located in multiple states

There is, however, a complementary set of explanations, one who's contribution to the patterns observed cannot fully be resolved, and which is based on a more cynical appraisal of the methods involved.

- State pest specialists in a region convince each other an outbreak is underway
- looking first in highest risk locations, they find high rates of damage
- looking later in lower risk areas, smaller trees and lower damage rates are found

Two points are relevant to appraising the relative importance of these two sets of explanations. The first involves the importance of ad hoc information sources in focussing detection efforts appropriately. The contributions of extension agents and landowners are hard to quantify, but should serve to keep efforts focussed where damages are most severe. Secondly, even an order of magnitude precision in sampling may be sufficient when populations fluctuate over several orders of magnitude (A.Berryman in (Volney 1992)). This would particularly be the case with most quantitative temporal or spatial analyses, which often focus on fine scale changes.

Although I've attempted to demonstrate those areas where useful insight can be gained, it is equally important to recognize that only through greater standardization of methods, definitions, and survey intensities can these analyses be confidently defended against methodological artifacts. Such improvements will be increasingly important for many pressing broad scale problems, such as effects of global warming on pest impacts to forests.

Although this paper has focussed on characterizing potential errors internal to this dataset, there is another potential error implicit to broad scale investigation of southern pine beetle dynamics. Hierarchy theory tells us that because controlling processes frequently change across scales, conclusions regarding broad scale processes should be based on observations collected at these scales, rather than on extrapolation from observations collected at other scales (Meentemeyer 1989; Urban and others 1987). This dataset represents, along with its closely allied FPM variant, the only compatible records for comparing the dynamics of SPB over multiple states and across multiple outbreaks. This broad perspective is crucial for understanding the context or representativeness of more rigorous, finer scale studies.

Broad scale analyses should also be useful for assessing the scaleability of stand level risk factors. Stand level risk factors such as slope, pine basal area, and disturbance history may continue in importance at larger scales, or be replaced by other predictive measures, such as physiographic region, volume of susceptible hosts, or frequency of severe storms. Only by comparing data from a range of scales can we determine where shifts in controlling processes may occur. Factors which might particularly benefit from broad scale data include landscape structure, weather, and beetle/predator dynamics (Rykiel and others 1988; Lovelady and others 1991; Turchin and others 1991).

On a more pragmatic note, timber markets and government control policies are typically defined at the broad scales explored here. Evaluations of policy options for minimizing welfare damage of SPB will need to reflect the dynamics of southern pine beetle at compatible scales.

In sum, reliable, long term data on forest pests is critical to identifying ecosystem responses to changing climate, estimating long term risks to forest landowners, and determining area-wide effectiveness of control policies. The data described here provides a tantalizing view of the potential utility of rigorously collected broad scale datasets. Hopefully it will further stimulate Federal and State efforts to ensure such data will be available in the decades to come.

LITERATURE CITED

Billings, R.F. 1992. Forecasting infestation trends of the southern pine beetle. page 171 in Allen, D.C. and Abrahamson, L.P., editors. Proceedings: North American forest insect work conference. March 25-28, 1991. Denver, CO. Gen. Tech. Rep. PNW-294.

Burns, R.M. and B.H. Honkala. 1990. Silvics of North America. Agriculture Handbook 654. Washington, DC: USDA, Forest Service.

Carter,D.R., J. O'Laughlin, and C. McKinney. 1991. Southern pine beetle impacts and control policy in the 1982-1986 Texas epidemic. Southern Journal of Applied Forestry **15**:145-153.

Dull, C.W. 1980. Loran-C radio navigation systems as an aid to southern pine beetle surveys. Pineville, LA: USDA Agriculture Handbook No. 567.

Hedden, R.L. and R.F. Billings. 1979. Southern pine beetle: factors influencing the growth and decline of summer infestations in east Texas. Forest Science **25**:547-556.

Lovelady, C.N., P.E. Pulley, R.N. Coulson, R.N., and R.O. Flamm. 1991. Relation of lightning to herbivory by the southern pine bark beetle guild (Coleoptera: Scolytidae). Environmental Entomology **20**:1279-1284.

Mason, G.N., R.R. Hicks.,Jr, C.M.V. Bryant, M.L. Matthews, D.L. Kulhavy, D.L. and J.E. Howard. 1981. Rating southern pine beetle hazard by aerial photography. pages 109-114 *in* Hedden, R.L.; Barras, S.J., and Coster, J.E., eds. Hazard-Rating Systems in Forest Insect Pest Management: Symposium Proceedings. Washington, DC: US Forest Service Gen. Tech. Rpt. WO-27..

Mawby, W.D. and H.J. Gold. 1984. A reference curve and space-time series analysis of the regional population dynamics of the southern pine beetle. Researches of Population Ecology **26**:261-274.

Mawby, W.D. and H.J. Gold. 1984. A stochastic simulation model for large-scale southern pine beetle (*Dendroctonus frontalis* Zimmerman) infestation dynamics in the southeastern United States. Researches on Population Ecology **26**:275-283.

Mawby, W.D. and F.P. Hain. 1985. The large-scale prediction of southern pine beetle populations. New Orleans:USDA Forest Service. General Technical Report SO-56:53-55.

Mawby, W.D., F.P. Hain, and C.A. Doggett. 1989. Endemic and epidemic populations of southern pine beetle: implications of the two-phase model for forest managers. Forest Science **35**:1075-1087.

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. Journal of Economic Entomology **68**: 336-338.

Meentemeyer, V. 1989. Geographical perspectives of space, time, and scale. Landscape Ecology **3**:163-173.

Michaels, P.J., P.J. Stenger, and D.E. Sappington. 1986. Modelling changes in the epidemic range of southern pine beetle using temperature and objective moisture indicators. Theoretical and Applied Climatology **37**:39-50.

Mickler, R.A. and K. Dwire. 1992. Quality assurance principles: an effective tool for managers and researchers assessing regional pest management concerns. Pages 38-40 *in* Allen, D.C. and Abrahamson, L.P., editors, Proceedings: North American forest insect work conference, March 25-28, 1991, Denver, CO. Gen. Tech. Rep. PNW-294.

Price, T.S. and C.A. Doggett. 1982. A history of southern pine beetle outbreaks in the southeastern United States. Macon, GA: The Georgia Forestry Commission. 35 pp.

Price, T.S., C.A. Doggett, J.M. Pye, and T.P. Holmes. 1992. A history of southern pine beetle outbreaks in the southeastern United States. Macon, GA: Georgia Forestry Commission. 67 pp.

Pye, J.M. 1992. Broad scale patterns of outbreak risk and damages from southern pine beetle. Southern Journal of Applied Forestry (submitted).

Rykiel, E.J.Jr., R.N. Coulson, P.J.H. Sharpe, T.F.H. Allen, and R.O. Flamm. 1988. Disturbance propagation by bark beetles as an episodic landscape phenomenon. Landscape Ecology **1**:129-139.

Turchin, P., P.L. Lorio, Jr., A.D. Taylor, and R.F. Billings. 1991. Why do populations of southern pine beetles (Coleoptera: Scolytidae) fluctuate? Environmental Entomology **20**: 401-409.

Urban, D.L., R.V. O'Neill, and H.H. Shugart,Jr. 1987. Landscape ecology. BioScience **37**: 119-127.

Volney, W.J.A. 1992. Is there a need for long-term data sets? Pages 141-144 *in* Allen, D.C. and Abrahamson, L.P., editors, Proceedings: North American Forest Insect Work Conference. March 25-28, 1991. Gen. Tech. Rep. PNW-294.

THE SPATIAL DYNAMICS OF INVASIONS BY EXOTIC FOREST PESTS

ANDREW LIEBHOLD, EUGENE LUZADER, JOEL HALVERSON
USDA Forest Service, Northeastern Forest Experiment Station, 180 Canfield St., Morgantown, WV 26505

GREGORY ELMES
Dept. of Geology and Geography, West Viginia University, Morgantown, WV 26506

Abstract. Biological invasion occurs when a species becomes established in an area disjunct from its usual range of distribution. Over the last century biological invasions have greatly increased in North America and many of these new species are damaging forest pests. The invasion phenomenon consists of three processes: 1. establishment, whereby a founding population is transported to the new environment, 2. establishment, during which the founder population either becomes established as a permanent, reproducing population or goes extinct; 3. spread, where the founder population expands its range into adjoining areas of suitable habitat. Consideration of spatial processes is important during each of these three phases. Further, any attempts to reduce the impacts of invading forest pests should be directed in an appropriate manner toward each of the three invasion phases .

Over the last century, technological advances have greatly facilitated intercontinental travel by humans and their goods. An undesirable by-product of this technology has been the dramatic increase in biological invasions caused by a breakdown of natural biogeographic barriers that once limited the interchange of the world's biota. Figure 1 demonstrates that around 1860, there was a dramatic increase in the rate of establishment of exotic species in this country. Presumably this change reflects the great increase in intercontinental mobility that occurred between 1850 and 1900.

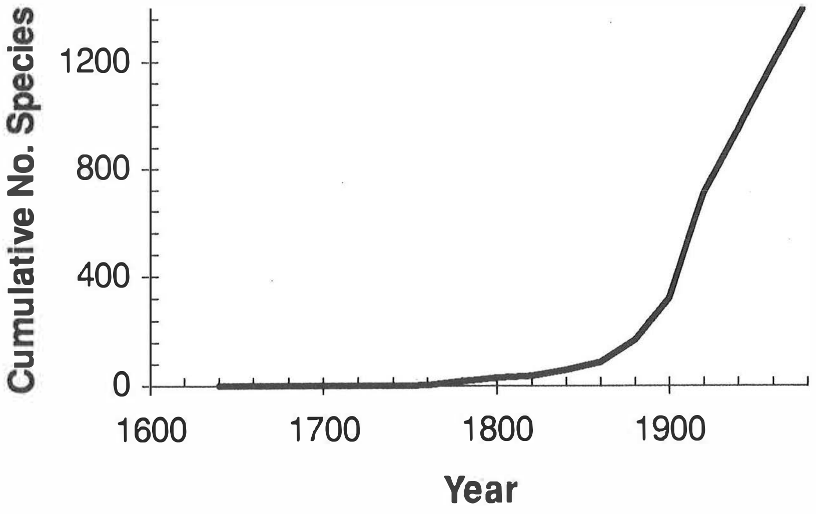


FIG. 1. Cumulative number of exotic species of insects and mites introduced to the United States (from Sailer, 1978)

Pages 125-132 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

This increase in the number of exotic organisms generally has resulted in a substantially greater number of forest pests. For a variety of reasons, introduced species are more likely to be pests than are native species (Simberloff 1986, di Castri, 1989). Pimentel (1986) estimated that of the 70 major insect pests of U.S. forests, 19 were introduced species. This proportion (27%) is much higher than the proportion of pests seen in native species (less than 1%). This increasing load of pest species is likely to result in spectacular and long term impacts on forest ecosystems. Introductions of major forest pests to North America, such as the gypsy moth, dutch elm disease and chestnut blight, are examples of introductions that have caused catastrophic tree mortality, and in some cases caused the virtual elimination of previously dominant tree species. Thus, the accumulation of biological invasions is a problem comparable in some respects to some of the more well-known contemporary environmental problems such as atmospheric warming and acidic deposition.

Consideration of biological invasions from a landscape ecology perspective is useful since movement through space is an inherent feature of these invasions. As a landscape process, a biological invasion can be divided into three processes: arrival, establishment, and spread (Elton, 1958; Dobson and May, 1986). Because of their economic importance and accelerating frequency, all three stages of biological invasions recently have been the object of increased scrutiny (Mooney & Drake 1986, Groves & Burdon, 1986, Drake et al. 1989, Hengeveld 1989).

ARRIVAL

Biological invasions have been occurring without human intervention for millions of years. Chance dispersal events as well as natural modifications of habitats such as glaciation and climate change have contributed to the natural dynamics of change in species ranges over geologic time. The field of biogeography has developed as a dicipline that focuses on this natural movement of species distributions (MacAurthur and Wilson 1967). Humans have greatly accelertated this natural intercontinental ebb and flow of species in two ways. First, we augmented the natural movement of organsims both by accidental transportation of species (e.g. in the ballasts of ships) and by intentional introductions (e.g. introduced natural enemies). Simberloff (1986) noted that the patterns of species introductions parallels the ongoing intercontinental commerce patterns (e.g. most introductions to North America have come from Europe). The second way in which we have accelerated the natural rate of biological invasions is by disturbance of habitats. These disturbances do not alter the arrival process but, instead, seem to enhance the establishment of certain species.

The gravity of the problems created by biological invasions was not fully realized until the early 1900's. Before this time, most governments had a rather *laisez faire* attitude about introductions. For example, many people went to great lengths to introduce and establish bird species such as the European starling, *Sturnus bulgaris*, in North America around 1890 apparently with no concern about potential ecological damages (Hengeveld 1989). In 1912 Congress enacted the Domestic Plant Quarantine Act, which gave authority to the U.S. Department of Agriculture (USDA) to regulate the movement of plant and animal material into and within the country (Weber, 1930); these regulations have been modified substantially since then. The quarantine measures were designed to decrease invasions by directly limiting the arrival process and thus represent a first line of defense against invasions.

ESTABLISHMENT

Every seed that falls to the ground does not develop successfully into a reproducing plant. Similarly, many invaders may arrive successfully in a new habitat but few become established. Here we define establishment as the process that results in a population that persists for many generations. Founding populations typically are very small and consequently at great risk to extinction. Generally, the smaller the founder population, the less likely is establishment. Though many scientists have referred to a "minimum viable population", there rarely is a distinct threshold. Instead, it is more realistic to consider the *probability* of establishment as being a continuous function of the initial population. This function reflects many characteristics of the species, such as its intrinsic rate of reproduction, mate location abilities, and genetic diversity (Mooney & Drake 1986).

The dynamics of all animal and plant populations are highly stochastic and typically affected strongly by variations, such as weather, in the environment. When viewed over very small areas, even well established populations may become extinct locally as a result of this stochastic variation. When the population is established over large areas, zones of local extinction are reinfested quickly from adjoining areas. The invading population also may follow the same pattern and become extinct locally, but because its initial distribution is completely isolated, the result is total extinction (Figure 2). It is for this reason that most arrivals usually do not result in establishment.

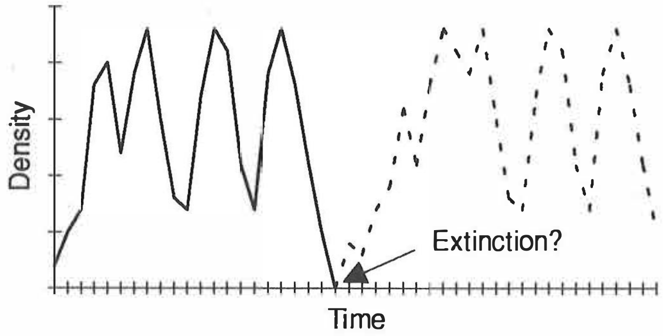


FIG. 2. Dynamic patterns in a hypothetical invading population that fails to establish (solid line) and a hypothetical established population that is re-infested from adjoining populations.

Understanding this process has important implications for management. The activity we call "eradication" is aimed at reversing the process of establishment; eradication is forced extinction. But we can see from the above description that eradication is likely to succeed only in situations where the target population is both low in density and highly restricted in its spatial distribution.

SPREAD

Once a population is established, its density typically will increase and it will expand its distribution into adjoining areas of suitable habitat. For most biological invasions this is the only process that we can observe directly since the arrival and establishment phases typically occur without notice by humans.

The spread process is driven by two behaviors of the species: population growth and dispersal. Most models of population spread have concentrated on these two behaviors. The simplest and probably the most widely applied population spread model was developed by Skellam (1951). Skellam's model combined Fick's law of diffusion with an exponential model of population growth.

Fick's law states that the concentration, C, of particles is normally distributed across any dimension, x, and thus the concentration at any point in time after release at point $x = 0$ is described by:

$$C_{x,t} = \frac{M\,e^{-x^2/4Dt}}{2\sqrt{pDt}} \qquad (1)$$

where t is the time since the initial release of M particles at point $x = 0$ and D is the "diffusivity" or diffusion coefficient" (Okubo, 1980). The diffusion coefficient is constant for any class of particles and environmental conditions (e.g. temperature); C is distributed normally at time, t, with a variance of Dt. Fick's law assumes that particles move randomly.

The exponential population growth model mathematically describes the concept of unlimited population growth:

$$N_t = N_0 e^{rt} \tag{2}$$

where N_t is the number of individuals at time t and r is the "intrinsic rate of natural increase" (birth rate - death rate under optimal condition; i.e. no crowding).

Skellam combined Fick's law of diffusion with the exponential growth model to obtain a generalized model of the spread of an invading organism:

$$N_{x,t} = \frac{N_{0\ 0}\ e^{rt-x^2/4Dt}}{4pDt} \tag{3}$$

where $N_{x,t}$ is the density of organisms distance, x, from the point of release and time, t, from the time of release of $N_{0,0}$ organisms at time 0. The assumption of random movement in this model implies that the population will spread radially, at an equal rate in all directions. Skellam (1951) showed that for any detection threshold, T, such that the infested area at any time t is restricted to points where $N_{x,t} > T$, the expansion velocity of the infested front, V, is constant and can be described:

$$V = 2\sqrt{rD} \tag{4}$$

The above model assumes that both r and D are constant through both time and space during the period of range expansion of the invading organism, an assumption that does not intuitively seem likely in many cases (i.e. spatial variation in the habitat may profoundly affect birth/death functions, as well as dispersal rates). Nevertheless, there has generally been a good congruence between predictions of this model and observed rates of spread of most exotic organisms (Levin, 1989). For example, Long (1979) found that the larch casebearer *Coleophora laricella* has been spreading in the northern Rocky Mtns. at a constant radial rate, as predicted by Skellam's (1951) model.

CASE HISTORY: THE GYPSY MOTH IN NORTH AMERICA

The gypsy moth, *Lymantria dispar* L. is one of the most destructive exotic organisms in North America. It is a major forest pest through-out much of the northern hemisphere; the species is associated primarily with *Quercus* species though, it is polyphagous in its feeding habits. In many areas, epidemics are common and resultant defoliation can cause substantial ecological and economic impacts.

The gypsy moth was introduced accidentally from France to Medford, Massachusetts, in either 1868 or 1869 by an amateur entomologist (Liebhold, Mastro & Schaeffer, 1989). It is an example that illustrates how long it can take from the time of arrival until damaging levels are reached. It wasn't until 1889, 20 years after arrival, that the first outbreak occurred. Eradication was attempted several times but ultimately failed, and the range of the gypsy moth has since spread through-out most of northeastern North America. The current distribution of the species includes a large area composed of the north Atlantic states of the US and parts of bordering Canadian provinces (Fig. 3). A second, discrete population exists in Michigan that is due to a secondary introduction and failed eradication efforts. The primary and secondary infested regions continue to spread; there are no current programs underway to stop this spread (though some state and federal programs are aimed at slowing the spread). In contrast, numerous isolated infestations arise sporadically (e.g. recent infestations in California, Oregon and British Columbia); considerable resources are allocated by state and federal agencies to eradicate these populations. These efforts largely have been successful.

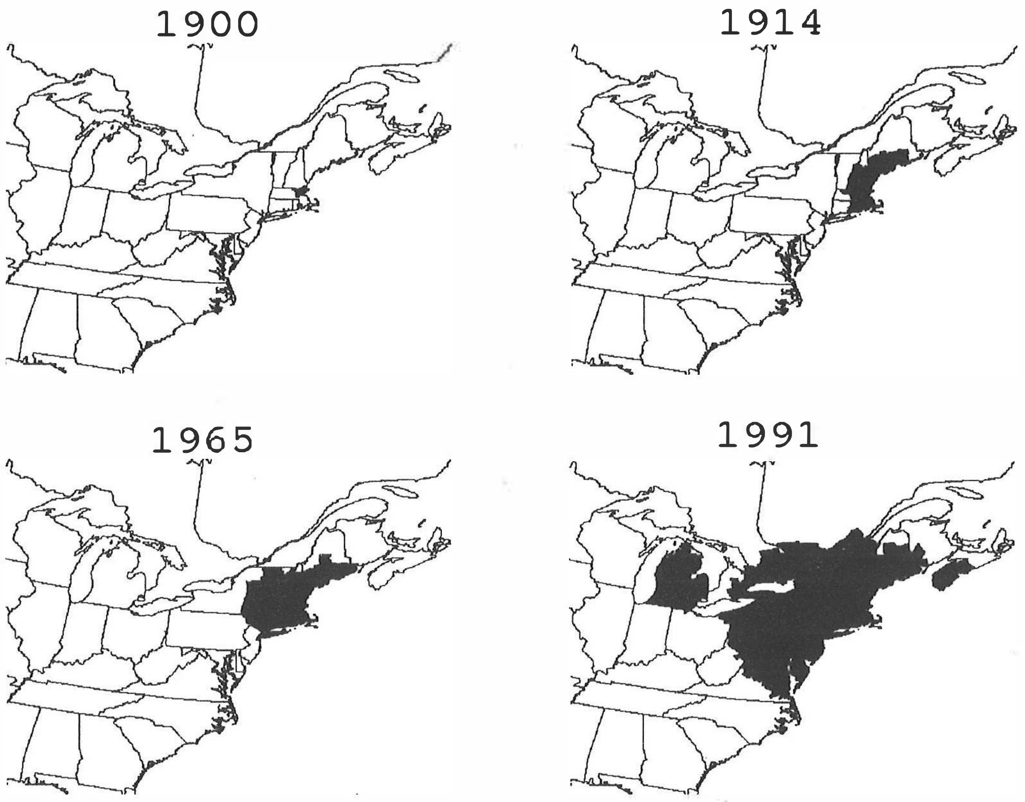


FIG. 3. Historical spread of the gypsy moth through North America (black areas indicate the generally infested area).

The relatively slow rate of spread of the gypsy moth (historically, compared with that of other organisms) is related to its biology. Females in North American populations are unable to fly, thus the primary mechanism for gypsy moth dispersal is thought to be wind-borne passive movement of first instars (Mason & McManus, 1981). The expansion of the generally infested area and the founding of isolated populations also may occur when egg masses or other life stages are transported accidentally on human-made objects (Talerico 1981).

Because the gypsy moth feeds on a wide variety of tree species, it is likely that gypsy moth populations ultimately will invade most of the US and Canada. However, the rate of spread is so slow (relative to the historical spread of other exotic organisms) that it may be many years before the full range of the potential habitat becomes infested. Figure 4 illustrates the historical rate of spread of the gypsy moth. These data indicated that three distinct periods occurred during which spread rates differed: a high rate (9.45 km/year) from 1900 to 1915, a low rate (2.82 km/year) from 1916 to 1965, and a very high rate (20.78 km/year) from 1966 to 1990. Furthermore, expansion was slower (7.61 km/year) during the period of 1966-1990 in counties where the mean minimum temperature was less than 7° C. These data are more fully analyzed in Liebhold et al. (1993). The slow rate of spread from 1916 to 1965 could be due to a variety of possible reasons. We believe the most likely reason for this slow rate of spread was that during that period, federal and state agencies were attempting to stop the spread of the generally infested area by intensive monitoring and population suppression along the leading front of the gypsy moth range. Those attempts ultimately failed to achieve the desired goal of stopping the spread, but they probably did contribute to slowing the rate of spread.

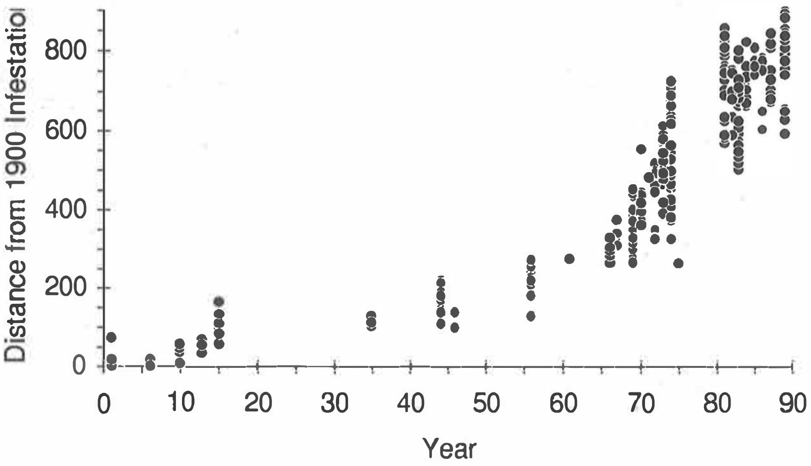


FIG. 4. Historical spread of the gypsy moth in North America. Each circle represents a U.S. county or a Canadian census district.

Liebhold et al (1993) also attempted to calculate the radial rate of spread independently from population parameters. Equation (4) was used to estimate this rate from estimates of *r*, the intrinsic rate of increase, and *D*, the diffusion coefficient (dispersal magnitude). They obtained approximate estimates of r from observations of maximum population growth in the field. Estimates of D were derived from a field experiment of natural dispersal of wind-born first instars (Mason & McManus 1981). The resulting estimate, 2.5 km/yr, was substantially less than the current empirically derived expansion rate of 21 km/yr. The higher observed rates of expansion may be due to human-caused movement of gypsy moth life stages which was not incorporated in estimates of *D* made here.

SUMMARY

Considering the acceleration of international commerce and travel, biological invasions will increase and result in new, more damaging forest pest problems. Attempts to minimize these impacts should be directed at the three phases of the biological invasion process: arrival, establishment, and spread. For these actions to be effective, attention should focus on applying a management strategy appropriate to the condition of the current phase of the invasion process. During the arrival phase, damages can be mitigated largely through quarantine procedures. Eradication is an appropriate management strategy only during the establishment phase. During the spread phase, procedures designed to slow the spread are the only remaining mitigation procedures that may be feasible.

ACKNOWLEDGMENTS

We thank S. DeLost and B. Kelley for reviewing this manuscript. This research was funded by the U.S. Dept. of Agriculture (USDA) Competitive Grants Program (Nos. 89-37250-4533 and 91-37302-6278) and the USDA Forest Service Gypsy Moth Research and Development Program.

LITERATURE CITED

Di Castri, F. 1989. History of biological Invasions with special emphasis on the old world. Pages 1-30 *in* J.A. Drake, H.A. Mooney, F.di Castri, R.H. Groves, F.J. Kruger, M. Rejmanek, and M. Williamson, editors. Biological Invasions: a Global Perspective. SCOPE 37. Wiley, Chichester.

Dobson, A.P and R.M. May. 1986. Patterns of invasions by pathogens and parasites. Pages 58-76 *in* H.A. Mooney and J.A. Drake, editors. Ecology of Biological Invasions of North America and Hawaii. Ecological Studies 58. Springer-Verlag, New York, NY.

J.A. Drake, H.A. Mooney, F.di Castri, R.H. Groves, F.J. Kruger, M. Rejmanek, and M. Williamson, editors. 1989. Biological Invasions: a Global Perspective. SCOPE 37. Wiley, Chichester.

Elton, C.S. 1958. The Ecology of Invasions by Animals and Plants. Methuen, London.

Groves, R.H, and J.J. Burdon, eds. 1986. Ecology of Biological Invasions. Cambridge Univ, Press., Cambridge.

Hengeveld, R. 1989. Dynamics of Biological Invasions. Chapman & Hall, London.

Levin, S.A. 1989. Analysis of risk for invasions and control programs. Pages 425-435 *in* J.A. Drake, H.A. Mooney, F.di Castri, R.H. Groves, F.J. Kruger, M. Rejmanek, and M. Williamson, editors. Biological Invasions: a Global Perspective. SCOPE 37. Wiley, Chichester.

Liebhold, A, V. Mastro, and P.W. Schaefer. 1989. Learning from the legacy of Leopold Trouvelot. Bulletin of the Entomological Society of America **35**: 20-21.

Liebhold, A.M, J.A. Halverson, and G.A. Elmes. 1993. Gypsy moth invasion in North America: a quantitative analysis. Journal of Biogeography (in press)

Long, G.E. 1979. Dispersal theory and its applications. Pages 244-250 *in* A.A. Berryman and L. Safranyik, editors. Dispersal of Forest Insects: Evaluation, Theory and Managmenent Implications. Washington State Univ. Press, Pullman, WA.

MacArthur, R.H and E.O. Wilson. 1967. The Theory of Island Biogeography. Princeton University Press, Princeton, NJ.

Mason, C.J. and M.L. McManus. 1981. Larval dispersal of the gypsy moth. Pages 161-202 *in* C.C. Doane and M.L. McManus, editors. The Gypsy Moth: Research Toward Integrated Pest Management. USDA For. Serv. Tech. Bull. 1584.

Mooney, H.A and J.A. Drake, editors. 1986. Ecology of Biological Invasions of North America and Hawaii. Ecological Studies 58. Springer-Verlag, New York, NY.

Okubo, A. 1980. Diffusion and ecological problems: Mathematical Models. Biomathematics 10. Springer-Verlag, Berlin.

Pimentel, D. 1986. Biological invasions of plants and animals in agriculture and forestry. Pages 149-162 *in* H.A. Mooney and J.A. Drake, editors. Ecology of Biological Invasions of North America and Hawaii. Ecological Studies 58. Springer-Verlag, New York, NY.

Sailer, R.I. 1978. Our immigrant insect fauna. Bulletin of the Entomological Society of America **24**: 3-11.

Simberloff, D. 1986. Introduced Insects: A biogeographic and systematic perspective. Pages 3-26 *in* H.A. Mooney and J.A. Drake, editors. Ecology of Biological Invasions of North America and Hawaii. Ecological Studies 58. Springer-Verlag, New York, NY.

Skellam, J.G. 1951. Random dispersal in theoretical populations. Biometrika **38**: 196-218.

Talerico, R.L. 1981. Methods of gypsy moth detection and evaluation. Pages 31-63 *in* C.C. Doane and M.L. McManus, editors. The Gypsy Moth: Research Toward Integrated Pest Management. USDA For. Serv. Tech. Bull. 1584.

Weber, G.A. 1930. The plant Quarantine and Control Administration: Its History, Activities and Organization. Brookings Inst. (Washington, DC), Inst. for Gov. Res. Serv. Mon. of the U.S. Gov. No. 59.

FOREST HEALTH MONITORING WITH AIRBORNE VIDEOGRAPHY

H. ROSS PYWELL
USDA Forest Service, Forest Pest Management, Methods Application Group, 3825 East Mulberry Street, Fort Collins, Colorado 80524

Abstract. Airborne videography is emerging as another remote sensing tool available to forest resource managers. The U.S. Forest Service has been developing and evaluating video image capture and analysis technology for use in monitoring forest health. Combining a high-quality Super-VHS video camera system with Global Positioning System (GPS) navigation, and image processing and geographic information systems (GIS), forest health specialists are able to detect and monitor forest pest activity over large areas. Videography offers many advantages over more traditional methods of pest detection and monitoring, including lower cost than ground methods, higher accuracy than conventional aircraft-based sketch mapping, and faster turnaround time than conventional remote sensing methods. Video data can quickly be converted to a digital form for analysis and integration into a GIS environment. This paper presents an evaluation of videography for detecting and monitoring forest insect and disease conditions. Integration of video with other technologies and its application to resource inventories are discussed.

INTRODUCTION

To discuss the importance and utility of airborne videography for forest health monitoring applications, it is essential to understand the scope of insect and disease problems and the land manager's information needs. It is also important to understand the role videography can play in the forest health monitoring arena and its relationship to existing aerial survey technologies.

Insect and disease damage is one of the most serious causes of tree mortality and growth loss in North American forests. Insects and diseases as a group damage commercial forests, reducing both the amount of timber harvested and the quality of the products. Approximately 2.4 billion cubic feet of timber is killed by insects and diseases each year in the United States. This is 24 times the amount of forest fire-caused mortality (Ciesla, 1983). Outbreaks of insects and diseases can occur in destructive proportions at any time on forested lands. The frequency of occurrence, intensity and duration are difficult to predict. Surveys of forested lands are essential to determining insect and disease presence, population trends, and the need for control measures.

The USDA Forest Service, Forest Pest Management (FPM) is responsible for the detection, evaluation, and control of insect and disease impacts upon the Nation's forest resources. Only through prompt discovery of damaging forest pests, can timely, effective action be taken to prevent or suppress damage, or salvage timber. Resource managers require estimates of the location and intensity of pest damage to plan and conduct suppression or salvage programs. Often, these estimates are obtained from aerial detection surveys conducted to discover pest outbreaks when they first appear and to monitor changes.

Pages 133-141 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

TRADITIONAL AERIAL MONITORING METHODS

Insect and disease surveys are usually flown as part of an ongoing systematic monitoring plan. The methods and procedures used for aerial detection surveys have been developed in considerable detail but may vary from one region of the country to another. Historically, aerial detection surveys have been of two types: 1) visual sketchmapping surveys, and 2) aerial photographic surveys.

Sketch mapping surveys

Visual sketchmapping is the technique of delineating the area of pest-caused damage onto maps based on observations by an entomologist or pathologist flying in a small aircraft. Aerial sketchmapping has been the most efficient and economical method of detecting and appraising recognizable pest damage over large remote forest areas. Sketchmapping is highly subjective, however; the resulting data can be no more accurate than the competence of the sketchmapper and the conditions under which the data were obtained. No two sketchmappers will or can be expected to record the same pest outbreak in exactly the same way. For this reason, sketchmapping should be regarded more as an art than as an exact science (Klein et al., 1983).

When an outbreak is detected its causal agent and host are identified, and its location is marked on the survey map. Large outbreaks are drawn as polygons while very small infestations, usually less than 10 trees in a group, are designated as a dot. Sketchmap surveys are used to record current year defoliation and mortality, locate new infestation areas, detect new and potential pest problems for ground evaluation, stratify damage intensity for aerial photographic surveys, and provide historical records of insect and disease outbreaks and their rate of spread. Most of this work is done when insect activity and the resultant damage is at the peak of visible symptoms, usually judged by vegetation color change. Although annual sketchmap surveys supply resource managers with current and useful information about the status of pests, more reliable remote sensing techniques could provide improved data on the location and extent of the pest damage.

Aerial photographic surveys

Aerial photography is another available survey tool for forest health monitoring. Color and color-infrared (CIR) photography are valuable tools for assessing insect and disease activity on forest lands. Photography has been used to estimate current and/or total levels of damage and mortality from pests. Photos provide a historical record of pest activity and have been used to monitor the rate of spread and trends of a pest over time. Chemical, biological, and cultural treatment methods can be evaluated with the use of aerial photography to determine the vegetation damage prevented.

Most aerial photography applications in pest management can be divided into two broad classes - mapping photography and sampling photography. Mapping photography can be defined as a block of continuous photo coverage that, when assembled into a photo mosaic, could be termed a photo map. Mapping photography is generally used for mapping the total extent of a pest problem (delineating polygons of damage), or mapping a pest's vegetation type. This type of photography usually covers a large ground area and therefore enables the photointerpreter to observe various patterns, or trends, and distribution of the pest activity. Sampling photography can be defined as photo coverage of a small area that is representative of a larger unit or type. Sampling photography is generally used with some type of survey sampling design. This type of photography is used when it is not operationally feasible or cost effective to evaluate 100 percent of the area of concern. A sampling design utilizing aerial photos can be used to obtain an estimate of pest activity and the photo estimate can be strengthened by ground sampling. Since most sampling photography is acquired at larger photo scales, the interpreter can obtain more reliable data, such as tree counts, identifiable pest symptoms and tree species, etc. (Myhre, 1988).

The use of aerial photography as a detection method has certain advantages and is very useful, but it has some disadvantages and limitations. The primary advantages of photography are that a permanent image record is preserved for a point-in-time and that photography provides a source of detailed information. Through the use of photointerpretation techniques and equipment, aerial photos can provide more accurate information than sketchmapping methods. One of the main disadvantages of using photography over sketchmapping is the high cost and the amount of time required in processing film and prints, interpreting photos, and transferring information from photos to a map. This delay can severely impact suppression and control decisions.

DEVELOPMENT OF AIRBORNE VIDEOGRAPHY

Airborne videography is emerging as a remote sensing tool available to resource managers. Recent changes in this technology have made video a viable sensor for the acquisition of timely information for resource management applications. Video technology has been evaluated by FPM for forest health monitoring applications. As a result of these evaluations, the Methods Applications Group (MAG) of FPM has developed an airborne video system to support a variety of aerial survey needs. The overall system consists of two major components - an airborne video image acquisition component and a video image processing component.

Background

Television or video (Latin word meaning "I see") has existed for many years. It was not until recent years that this technology moved into the remote sensing arena. In the early 1980s, a variety of research and development efforts began to evaluate videography as a potential remote sensing tool for natural resource management. During this time, a variety of airborne cameras emerged; a few were commercially available and the rest were still in the research and development stage.

Because of improvements made in the mid-1980s in image quality, affordability, and portability, video equipment became increasingly viable as a remote sensing tool. A joint project with the Forest Service (FPM/MAG) and the University of Minnesota/Remote Sensing Laboratory began in 1986 to assess the operational feasibility of a color-infrared (CIR) video camera for forest health monitoring. The camera used in this test was a prototype CIR camera developed by the University of Minnesota, and is now marketed under the trade name Biovision. The camera was a three-tube color camera which had been modified to simulate the spectral response of color-infrared film. The objective of this assessment was to determine if CIR video imagery obtained with an airborne video camera was capable of detecting aerially visible tree defoliation and mortality caused by forest insects. The assessment tests were conducted over areas containing mountain pine beetle, *Dendroctonus ponderosae* Hopkins, mortality in Wyoming and forest tent caterpillar, *Malacosoma disstria* Hubner, defoliation in Minnesota (Munson et al., 1988). Two general conclusions were apparent from the examination of the video imagery, sketch map data, and aerial photography. First, the degree of detail possible in mapping classes of defoliation from video is superior to that obtainable via the sketch mapping technique. Second, the positional accuracy of polygons (map locations) of insect damage appeared to be greater when using video imagery thatn when than when using sketch mapping. The discouraging part of the tests was the poor resolution of the color-infrared tube camera. However, the assessment provided enough positive results to justify the continued evaluation and development of this technology.

Airborne videography should not be viewed as a replacement for aerial photography, but can be substituted for photography where the needs do not demand the quality and cost of photography. There are many resource activities where remote sensing and aerial photography data are not being used, primarily due to cost. These gaps could be filled by using airborne videography techniques (Myhre et al, 1990b). Listed below are attributes of videography that offer advantages over conventional aerial photographic film and camera systems.

1. Imagery is available immediately, making video particularly useful in applications requiring rapid turnaround time such as pest surveys and disaster assessment (i.e., fires, flooding, etc.).

2. The operator can view "live" imagery on a monitor in the aircraft concurrent with the acquisition, making the video acquisition process less subject to error than that of photography. The image display allows camera exposure settings to be adjusted interactively.

3. The audio track permits notation of pertinent information, which may be of use in future analysis, directly on the video tape while in flight.

4. A straightforward pathway is provided from the videotape to digital format for computerized image processing and incorporation into a geographic information system (GIS).

5. Video cameras and videotape are lower in cost relative to conventional aerial photography cameras and film.

6. Airborne video improves the success rate of acquiring the desired coverage at a given point in time. This is especially important when narrow biological windows are involved.

7. Video cameras have higher light sensitivity than film cameras allowing useable imagery to be acquirred under less than ideal weather conditions.

8. Video is useful in locations where aerial film and processing may be difficult to obtain.

In 1988, following the CIR video test previously discussed, MAG employees evaluated the status of commercially available video technology that could be adopted for airborne use. Our intent was to eventually deploy video systems to multiple field locations, so we restricted our evaluation to commercially available "off-the-shelf" technology. The evaluation produced the following information:

1. New solid-state cameras using charged couple device (CCD) sensors are superior to tube cameras. Solid-state cameras are less prone to damage from vibration making them more suitable for aircraft operation.

2. Shuttered video cameras are available that produce higher quality imagery by reducing blur from image motion and vibration that arise in airborne operations.

3. A new recording system called Super-VHS (S-VHS) is now available. S-VHS has several advantages over VHS, including increased resolution (700 lines of horizontal resolution for S-VHS vs 400 lines for VHS), improved color quality, and improved signal-to-noise ratio through an increased band width.

Based on the new advancements in video, FPM/MAG personnel developed an airborne video package suitable for addressing forest pest management applications. This package consists of an airborne video image acquisition module and a video image processing module (Myhre et al., 1990a.)

Video acquisition system

The airborne video acquisition system currently in use by FPM consists of the following components:

Video Camera - The camera system features S-VHS format, three CCD sensors (one each for red, green, and blue), high-speed shutter system for reducing image motion and blurring, remote-controlled 9.5 mm to 143 mm zoom lens that allows both zooming and image brightness to be controlled from within the aircraft.

Video Recorder - A portable S-VHS recorder used for recording both video imagery and audio notes during the flight mission.

Video Monitor - A 10-inch S-VHS color monitor used for observing both what is being recorded and the image quality so that necessary adjustments can be made in flight.

Caption Generator - This unit links the video camera, video recorder, and an aircraft navigation system (GPS or LORAN-C). Through this linkage, aircraft positional information (latitude, longitude, bearing) can be recorded on the video frames for future use in determining the location of video frames.

Electronic Navigation Unit - A Long Range Navigation (LORAN-C) or Global Positioning System (GPS) navigation system can provide positional data, as well as time, date, and aircraft heading, through an RS-232 interface to the caption generator.

Camera Mount - A mount suitable for holding the camera in a relatively stable, level, and vibration-free state over the aircraft camera hole.

Additional Equipment - This includes all cabling to link all components and the power converters and inverters needed to match equipment power demands to the aircraft's power supply.

Together these components provide a compact and versatile image acquisition system. They fit easily into almost any small, single engine aircraft having a 6-inch or larger camera hole. As the system provides instant feedback on image coverage and quality, users can quickly become proficient in its use.

Consolidated procurement package

To simplify the transfer and implementation of this technology, a consolidated procurement package was established for the video image acquisition system. The consolidated package ensures that the users of the video system have all the correct components, and that the system will function as it was designed and field-tested.

Prior to the establishment of the consolidated procurement package, four systems were purchased with technical assistance from MAG. The Forest Service groups which first obtained the systems include:

NE Area/FPM Field Office - St. Paul, MN
Region 8/National Forests in Texas - Lufkin, TX
Region 8/FPM Field Office - Alexandria, LA
Nationwide Forestry Applic. Program - Salt Lake City, UT

Under the procurement package established for fiscal year 1991, six systems were purchased and delivered to the following groups:

Region 2/FPM - Denver, CO
Region 3/Kaibab N.F. - Williams, AZ and Region 3/FPM
Region 4/FPM Field Office - Boise, ID
NE Area/FPM Field Office - Durham, NH
NE Area/FPM Field Office - Morgantown, WV
FPM/MAG - Fort Collins, CO

A second consolidated procurement package has been initiated for 1992. A call letter has gone out from the Washington Office (Director of Forest Pest Management) to Forest Service units requesting information from them and their State cooperators.

Video image processing system

Once video imagery has been successfully captured on tape, it can be used immediately in management applications. This use can be as simple as viewing the video tape on the monitor or using the imagery to do sketchmapping in the office. There are, however, more sophisticated tools for using video imagery. MAG has been using the Map and Image Processing System (MIPS), a product of MicroImages Inc. of Lincoln, Nebraska. MIPS runs in a DOS operating environment on any 80386 microcomputer with a math coprocessor. The software supports an array of peripheral devices including digitizers, plotters, color printers, scanners and optical disc drives.

MIPS offers the advantage of being able to capture video frames from tape and convert them to a digital form. In MAG's case, the frames are captured as TARGA files, but other formats are supported. Once the frames are stored as digital images, they can be geometrically corrected to a map base and mosaiced. The software permits the user to annotate polygons of insect activity using a cursor on the screen or do automated classification based on color composite pixel values (Myhre et al., 1990a). This digital data can be moved easily to a variety of geographic information systems for use and analysis with other data. There are a number of other image processing systems in the market place with similar capabilities.

APPLICATION OF AIRBOURNE VIDEOGRAPHY

FPM/MAG has acquired airborne video imagery of a variety of pest activities and host types and examined or evaluated this imagery to various degrees. The list of video coverage acquired to date includes the vegetation impacts of the following forest insects and diseases: gypsy moth, *Lymantria dispar* (L.), mountain pine beetle, *Dendroctonus ponderosae* Hopkins, southern pine beetle, *Dendroctonus frontalis* Zimmermann, spruce beetle, *Dendroctonus rufipennis* (Kirby), spruce budworm, *Choristoneura fumiferana* (Clemens), Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins, and oak wilt, a systemic, lethal disease caused by *Ceratocystic fagacearum* (Microascales, Ophiostomataceae).

The most vigorous test of videography as applied to forest health monitoring was conducted in July 1991 to compare the effectiveness and cost of airborne video to conventional sketchmapping and CIR aerial photography for classifying and mapping gypsy moth defoliation in Michigan (Buffington, 1991). For the purpose of this test, 1:11,000 scale 9 inch by 9 inch CIR aerial photography and 1 mile swath width color video were acquired over 35,000 acres in central Michigan. The area was almost completely forested in upland oak and pine forest types. To minimize the impact of ongoing insect activity and refoliation on the study results, the photographic and video imagery were taken within 24 hours of each other. Due to logistical and weather problems, sketchmapping was done 4 days later, but it is felt that this had little effect on the study results.

Procedures

Sketchmapping was done by a trained entomologist with 3 years experience in sketchmapping. Areas of defoliation were delineated on a 1:24,000 scale topographic map using a classification of heavy (100 percent to 75 percent defoliation), moderate (40 percent to 75 percent defoliation), and light/none (less than 40 percent defoliation). This work required 2 hours to complete.

Office sketchmapping was done using the video imagery. Sitting in front of the monitor, an analyst viewed the imagery and delineated the same defoliation classes described above on a 1:24,000 scale topographic map. The analyst was able to pause, rewind, and fast forward the video tape to help determine location and severity of defoliation. This work required 2.5 hours to complete.

The CIR aerial photography was used as the standard against which the first two methods were compared. The photography was interpreted in stereo using the same defoliation classes. The resulting defoliation polygons were then transferred to a 1:24,000 scale topographic map using a Bausch and Lombe Zoom Transferscope. The interpretation and transfer process took 40 hours to complete.

The three maps were then digitized and put into a GIS for comparison and analysis. All defoliation polygons smaller than 5 acres were determined to be not meaningful and were discarded prior to analysis.

Results

A visual inspection of the three map products showed them to be very different. Even with the polygons smaller than 5 acres removed, the map produced through interpretation of the CIR photography had very fine detail and many small polygons. The map produced through conventional aerial sketchmapping was very broadly drawn with large polygons. The video office sketchmap was more closely aligned with the map produced from CIR photography, but did not have the same level of detail. Locational accuracy relative to the map produced from aerial photography was better on the office sketchmap than the conventional sketchmap. The GIS was used to compute the number of defoliation polygons and the minimum, maximum and average size. These data ara presented in Table 1 for each of the three mapping processes. Table 2 presents the total acreage by defoliation class for each of the three mapping processes. It is believed that the differences between the CIR photography data and the office sketchmapping data are a result of the better spectral response of the CIR imagery. Defoliation was more easily detected in the CIR imagery, while on the true color video, bare ground, wetlands, and stands with low stocking densities were sometimes confused with defoliation.

TABLE 1. Number of polygons and average size of polygons based on five-acre minimum mapping unit (Buffington, 1991).

Map Type	Number of Polygons	Min. Size (acres)	Max. Size (acres)	Ave. Size (acres)
Aerial Sketch	43	20.7	1,454.8	266.4
Office Sketch	141	5.1	562.3	37.6
Aerial Photo	159	5.1	735.7	42.9

TABLE 2. Acres of each defoliation class by map type (Buffington, 1991).

	Defoliation Class in Acres		
Map Type	Heavy	Moderate	Light/None
Aerial Sketch	7,219	4,283	24,944
Office Sketch	2,587	2,619	31,298
Aerial Photo	3,912	2,949	29,642

Table 3 presents cost comparisons between the three remote sensing procedures. All costs are actual costs incurred in the process and presented in U.S. dollars. Depreciation of equipment is not included in the cost analysis. It should be pointed out that the aircraft used for video and photo acquisition was a twin engine aircraft with a higher operating cost than the aircraft used for aerial sketchmapping. This is a logistical artifact of this particular study. The smaller aircraft with the lower operating cost could be used for video acquisition, making the cost of office sketchmapping of this area almost identical to conventional aerial sketchmapping.

TABLE 3. Cost analysis of remote sensing techniques used to define and map gypsy moth defoliation. All monetary values in U.S. dollars (Buffington, 1991).

Technique	Time (hrs.)	Plane/Pilot	Mapper/Analyst	Film/Processing	Total
Aerial Sketch	2.0	$105/hr	$9.68/hr	0	$229.36
Video Acquisit.	1.5	$250/hr	$20.90/hr	$12.95	$419.30
Office Sketch	2.5	---	$10.00/hr	---	$25.00
					$444.30
Photo Acquisit.	2.0	$250/hr	$20.90/hr	$1100.00	$1641.80
Photo Interp.	40.0	---	$10.00/hr	---	$400.00
					$2041.80

CONCLUSIONS

Videography will not replace any existing remote sensing systems. We do feel however that enough evaluation has been done to document its usefulness as an additional tool for the resource manager. The technology is relatively inexpensive to acquire and use. Field-level personnel with little or no remote sensing background can be quickly trained to operate the equipment efficiently. In the last year, FPM has placed six video acquisition systems in the field. Almost as soon as these units became operational, field personnel began finding new applications for the systems. While the systems were initially purchased for forest health monitoring activities, they have also been used for post-fire mapping, site preparation planning, stand prescription maps, timber sale activities, watershed inventory, riparian habitat mapping, law enforcement and storm damage assessment. Videography is also being applied to a number of resource problems in other government agencies. U.S. Fish and Wildlife Service personnel have several years experience in using airborne videography to monitor wetland changes and conditions. They have integrated video data into a GIS environment and use the resulting data base to drive waterfowl production models (Cowardin et al., 1989, Sidle et al., 1990).

Videography has demonstrated the following advantages over conventional aerial survey techniques (sketch mapping) for monitoring forest health: 1) the system can be installed in most of the survey aircraft now used for conventional sketchmapping; 2) videotape provides a permanent record of conditions as they exist at the time of the survey; 3) eliminates the subjective evaluation of the observer while in flight; 4) provides improved positional accuracy of the data collected, and 5) provides more accurate estimates of the areal extent and severity of pest damage. The major advantages of videography over aerial photography are: 1) imagery is available to be viewed and analyzed the same day it is acquired; 2) video can be acquired under high overcast or broken cloud conditions where photography cannot be obtained; and 3) the cost of video imagery is far less than conventional frame photography.

Video technology is continuing to change rapidly as equipment vendors and resorce managers begin to realize its potential as a remote sensing tool. As it changes, MAG will continue to evaluate it's utility in forest health monitoring.

LITERATURE CITED

Buffington, K. 1991. Remote Sensing Techniques For Mapping Gypsy Moth Defoliation. Master's Thesis, Department of Forest Science, Colorado State University, Fort Collins, CO.

Ciesla,W.M. 1983. The Multi-Faceted Control of Pests that Damage our Forests. Pages 196-203 *in* 1983 Yearbook of Agriculture, USDA, Washington.

Cowardin, L.M., P.M. Arnold, T.L. Shaffer, H.R. Pywell, L.D. Miller. 1988. Duck numbers estimated from ground counts, MOSS map data, and aerial video. *in* J.D. Scurry, editor, Proceedings: Fifth national MOSS users workshop. Louisiana Sea Grant College Program, Baton Rouge, and U.S. Fish and Wildlife Service, Slidell, LA.

Klein, W.H., S. Tunnock, J.G.D. Ward, and J.A.E. Knof. 1983. Aerial Sketchmapping. *in* Forest Insect & Disease Survey Methods Manual, USDA Forest Service, Forest Pest Management/Methods Application Group, Fort Collins, CO.

Munson, A.S., R.J. Myhre, S.M. Dewhurst, and D.E. Meisner. 1988. Assessment of a Color-Infrared Aerial Video System for Forest Insect Detection and Evaluation. Pages 242-252 *in* Proceedings of Second Forest Service Remote Sensing Applications Conference, Slidell, LA, April 1988. .

Myhre, R.J. 1988 Aerial Photography for Forest Pest Management. Pages 153-162 *in* Proceedings of Second Forest Service Remote Sensing Applications Conference, Slidell, LA, April 1988.

Myhre, R.J., L.A. Graham, and C.W. Sumpter. 1990a. Airborne Video Technology. Pages 293-298 *in* Proceedings of Third Forest Service Remote Sensing Applications Conference, Tucson, AZ, April 1990 .

Myhre, R.J., C.W. Sumpter, and L.A. Graham. 1990b. Airborne Videography - A Potential Tool for Resource Managers. Pages 590-594 *in* Proceedings of Resource Technology 90 Symposium, Washington. D.C., November,1990.

Sidle, J.G. and J.W. Ziewitz. 1990. Use of aerial videography in wildlife studies. Wildlife Society Bulletin **18**:56-62.

REVIEW OF SPATIAL ANALYSIS TECHNIQUES

ROBIN M. REICH
Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523

BRIAN W. GEILS
USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO 80526

Abstract. This paper reviews some common techniques for analyzing spatial patterns. Topics include quadrat and distance sampling for describing point distribution patterns (uniform, random, and aggregated) and geostatistical techniques such as Moran's I statistic, spectral analysis, the Mantel test, and wavelet analysis for characterizing spatial structures of populations. The various methods described differ in both the kinds of data to which they may be appropriately used and in the information which they provide.

INTRODUCTION

The problem of assessing spatial patterns has assumed considerable importance within the past few decades (Moore 1954, Morisita 1959, Matern 1960). The first attempts to analyze spatial patterns used simple, visual description (Curtis and McIntosh 1950). These methods were adapted because of the spatial complexity encountered in various ecological studies and the need for relevant information over extensive areas (Curtis and McIntosh 1950). Direct, visual characterization of spatial pattern is influenced by subjective, personal interpretation and is now seldom used for quantitative or comparative studies. Although individuals in many natural plant communities are not randomly distributed (Ashby 1935), many early sampling methods were developed under the simplifying assumption that populations were randomly distributed (Clark and Evans 1954). If sample distributions departed significantly from random, resulting statistics and estimates of their reliability could be seriously flawed (Cole 1946). Several methods based on quadrats or distance measurements were developed to determine which statistical distributions best approximated observed spatial point patterns. Likewise, many inference tests require that observations be statistically independent. Whereas in fact, observations close to each other may be spatially correlated due to factors and processes such as soil fertility or propagule dispersal. In addition to displaying spatially related trends in the data, geostatistical methods enable investigators to detect complex patterns and to compare several data sets as transects or surfaces.

ANALYSIS OF SPATIAL POINT PATTERNS

The recognition of nonrandom patterns in biological populations has led to the development of numerous mathematical models based on assumptions essential in the formation of particular spatial patterns (Clark and Evans 1954). In general, departures from randomness have been tested by assessing the degree and direction that observed distributions deviate from various known statistical distributions. Agreement between theoretical and observed distributions, however, does not require that the observed spatial distribution was formed under the same assumptions as the theoretical distribution (Morisita 1959, Pielou 1959). Discrepancies among various models may be attributed to the sensitivity of the tests employed in detecting the various degrees of nonrandomness (Blacksmith 1958). Two of the most frequently applied methods of expressing nonrandomness in spatial distributions are described below.

Pages 142-149 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

Quadrat Sampling

The quadrat method is used primarily to study vegetative characteristics other than spatial patterns (Mawson 1968). Quadrats are used extensively in forestry and ecology to sample such vegetative characteristics such as frequency, density, abundance, and presence (Curtis and McIntosh 1950). Although quadrat methods can detect nonrandom patterns, results may vary significantly with quadrat size (Pielou 1957). This affect can be alleviated to some extent with the use of contiguous quadrats.

Several frequency distributions have been used to test the results obtained from the quadrat method. These are: the negative binomial, Neyman's type A, and Thomas' double Poisson distribution. Of the three distributions, the negative binomial distribution has the most desirable properties for modeling contagious distributions. It has two parameters which can be interpreted in a biological sense as a density parameter and a heterogeneity parameter. As the latter increases to infinity, the negative binomial distribution will converge to a two-dimensional Poisson distribution (Daniels 1978).

Distance Sampling

Distance sampling, the second method of determining nonrandomness, is used primarily to study the spatial relationships of biological populations (Mawson 1968, Pielou 1959, Holgate 1965, Clark and Evans 1954, Moore 1954). This method depends partly or wholly on distances from randomly selected points to the nearest tree, or from randomly selected trees to their nearest neighbor. The underlying assumption is that the observed distance distribution in a randomly distributed population conforms to a Poisson distribution with population entities randomly located within an infinitely large area (Cottam et al. 1953).

As with the quadrat method, several frequency distributions such as the normal, binomial, Poisson, negative binomial, and Neyman's type A distribution are used to test results obtained from distance sampling methods. Mawson (1968) compared the frequency distribution of point-to-tree and tree-to-tree distance measurements with the above mentioned theoretical distributions and concluded that the observed distributions differed significantly from the reference distribution. He found the normal distribution to be good for random spatial patterns and poor for uniform spatial patterns, and the binomial distribution good for uniform spatial patterns. Mawson (1978) showed, however, that point-to-tree and tree-to-tree distances may appear to be random, aggregated, or uniformly distributed. Therefore, it is essential that the distribution of distance measurements should not be the only method used to detect nonrandom spatial patterns in biological populations (Pielou 1959).

Five of the more promising distance sampling methods include Clark and Evans (1954) nearest neighbor index, Holgate's ratio and Holgate's correlation index (1965), Pielou's index of nonrandomness (1959) and Hopkins and Skellam's coefficient of aggregation (Pielou 1977, Payandeh 1970).

Clark and Evans (1954) developed an index for detecting nonrandom spatial patterns based on the average distance between randomly selected trees and their nearest neighbor. This index has been used to estimate the density of randomly distributed populations or to describe the spatial aggregation of populations of known density. Thompson (1956) modified Clark and Evans nearest neighbor index by comparing the mean distance to the n-th nearest neighbor, thus eliminating the need for an independent estimate of the population density. He concluded that this test is better suited to detect larger-scale heterogeneity than Clark and Evans' nearest neighbor index.

Holgate (1965) introduced two indices for detecting nonrandom patterns based on distances between randomly selected points to the s-th and t-th nearest neighbors. He examined these methods on three populations with known spatial distributions and concluded that both indices were valid for random spatial distributions. Holgate argued that the ratio index was more sensitive in detecting aggregated distributions and the correlation index was better in detecting uniform distributions.

Pielou (1959) devised an index of nonrandomness based on distances between randomly selected points and their nearest neighbor. This index has been used to evaluate departure of spatial distributions from completely random distributions (Mountford 1961).

Hopkins and Skellam developed a test for detecting nonrandom spatial patterns in plant populations based on the assumption that a population has a random spatial distribution if the distribution of distances from randomly selected points to their nearest neighbor were identical to the distribution of distances from randomly selected trees to their nearest neighbor (Pielou 1977, Payandeh 1970).

Indices derived from distance sampling have certain advantages over quadrat sampling when estimating the spatial patterns of a population. Cottam and Curtis (1956) pointed out that by eliminating the use of plots, distance sampling is more efficient in terms of time and equipment needed. The authors pointed out that the major disadvantage of distance sampling is an unfamiliarity with the methods, as well as the precision and limitations associated with their use.

SPATIAL ANALYSIS OF MAPPED DATA SETS

Because of the difficulty in randomly selecting individual trees within a given population researchers tend to map the location of individual trees and then apply distance sampling or quadrat sampling techniques in an attempt to analyze spatial patterns. Cliff and Ord (1981) point out that if one were to examine all possible distances between observations, they would not be independent thus violating the underlying assumption of independent observations under the null hypothesis (Ripley 1981). In such instances, exact tests should be used in determining the degree of nonrandomness in the population. Some of the more common techniques used in analyzing the spatial pattern of mapped data sets include multiresponse permutation procedures and spectral analysis.

Multiresponse Permutation Procedures (MRPP)

Reich et al. (1990, 1992) discuss the merits of using distance-based permutation procedures (MRPP) for characterizing spatial relations among two or more groups in a mapped data sets. In addition to being able to characterize spatial relationships, MRPP can also be used to identify spatial patterns (e.g. random, aggregated, and uniform). Unlike distance sampling, the use of MRPP in detecting nonrandom spatial patterns requires an external reference set with known spatial pattern. This external reference set is similar to the theoretical distributions (e.g. normal, binomial, Poisson, negative binomial, Neyman's type A, etc.) used in some of the more classical distance sampling techniques. It provides a relevant reference distribution against which the observed spatial patterns may be compared.

Reich et al. (1990, 1992) points out that the application of MRPP is very efficient in estimating the spatial relationships in mapped data sets. In addition to testing for nonrandom spatial patterns and association, MRPP is flexible in the type of hypotheses that can be tested. For example, MRPP could be used to compare observed spatial patterns with hypothetical patterns generated using growth and yield models that take into consideration the degree of stand heterogeneity, competition and disease incidence. Such comparisons allow for testing of underlying assumptions or processes thought to influence spatial patterns. Other applications of MRPP include the study of space-time interactions and pattern similarities.

Another application of MRPP comes from the work by Stauffer (1978). Stauffer suggests that an aggregated distribution of trees is better characterized by the presence of holes rather than by the presence of clearly defined clusters. To test this hypothesis, an external reference distribution can be generated using Stauffer's clustering algorithm. This external reference distribution can then be compared with an observed spatial pattern using MRPP. This information could then be used to select an appropriate clustering algorithm for use in distance-dependent growth models and to model the spread and intensification of contagious diseases such as dwarf mistletoe or pitch canker.

GEOSTATISTICAL TECHNIQUES

Pattern recognition provides important clues in understanding multi-resource spatial interactions in ecological systems. It also yields information on the likelihood of connectivity between selected points in the pattern. For example, pattern disturbances over time may be spatially correlated with management practices and/or changes in environmental conditions. In spite of the interest in ecological pattern recognition and comparisons, a relatively small amount of work has been reported on spatial patterns over large geographical areas (e.g., 10^6 to 10^7 ha). Most of the work has been limited to a relatively small area (10^0 to 10^3 ha).

Geostatistical techniques, such as Moran's I statistic (Cliff and Ord 1973), spectral analysis (Ripley 1981), the Mantel test (1967), and wavelet analysis (Bradshaw and Spies 1992), are just a few procedures which permit tests of hypotheses regarding spatial patterns. They describe the structure of the pattern including the presence of directional components at various scales (Legendre and Fortin 1989).

Moran's I

Moran's I statistic has been used by ecologists and geographers alike to test for the presence of spatial autocorrelation in a two-dimensional plane (Cliff and Ord 1973, Jamars et al. 1977, Legendre and Fortin 1989, and Ripley, 1981). A variable is said to be spatially autocorrelated when it is possible to predict the value of this variable at some point in space from the known values at other sampling points whose locations are known (Legendre and Fortin 1989). Moran's I is generally thought to be an extension of the Pearson product moment correlation coefficient with a weighted sum of squared cross products in the numerator divided by a weighted sum of squares. Thus, Moran's I generally varies over the range of -1 to 1, but may exceed these values depending on the characteristics of the weights used in the analysis.

In a review of techniques for analyzing spatial patterns, Jamars et al. (1977) points out that the choice of weights plays an important role in the ability of Moran's I to detect spatial autocorrelation. If for example, one were to choose a specific set of weights such as the Euclidean distance separating two points, autocorrelations at other weights may not be apparent, while if more general weights were to be used (e.g. 0,1) the test for spatial autocorrelation may be weak (Jamars et al. 1977). Cliff and Ord (1973) discusses the choice of weights and suggests that the most powerful test of no spatial autocorrelation is provided when the weights correspond with the autocorrelation pattern under the alternative hypothesis.

Spectral Analysis

Spectral analysis is very similar to time-series analysis (Ripley 1981) in that it can be applied to both one- and two-dimensional data. In analyzing spatial patterns using spectral analysis it is assumed that the variable of interest can be meaningfully represented by sinusoidal waves summed over different frequencies, with a different amplitude and phase at each frequency (Bartlett 1964). The spectral analysis is obtained by Fourier transforming data from a rectangular or triangular lattice (to obtain the coefficients of the sinusoids at a discrete set of frequencies), grouping neighboring frequencies into frequency bands, and estimating various quantities from the Fourier transformed data in one frequency band at a time (Bartlett 1964). Frequencies are grouped into bands to enhance the statistical stability of the estimates (Bartlett 1964, Ripley 1981, Legendre and Fortin 1989).

Spectral density is estimated by computing the average squared amplitude of the sinusoids within a frequency band (Ford and Renshaw 1984). This estimated spectral density is then plotted as a function of frequency. The spectral density indicates how the variation exhibited by the data is distributed over the different frequency bands (Ford and Renshaw 1984, Legendre and Fortin 1989).

The four main components of spectral analysis include (Ford and Renshaw 1984):

1. The autocorrelation function which estimates the correlation between points and their nearest neighbors,
2. The periodogram which shows the extent to which the data contains periodicities at different frequencies,
3. The R-spectrum which highlights the frequency of pattern repeats, and
4. The 0-spectrum which highlights directional components in the data.

While spectral analysis has been used primarily to analyze the spatial pattern of data from a systematic grid it can also be used to analyze point patterns of mapped data sets. In this instance, a fine grid is laid over the map and each cell is coded as a zero or one depending on whether or not it contains an individual. Spectral estimators are then computed in the usual way.

Mantel's Test

Another problem arises in practice when one is given a set of variates X_i, Y_i and wishes to determine whether variates are spatially correlated with one another. In an attempt to answer this question, researchers have frequently resorted to some method for reducing the dimensionality of the variable space, and then employing one of the several tests for spatial autocorrelation (Orloci 1978, Legendre and Fortin 1989).

Legendre and Fortin (1989), for example, advocate the use of the Mantel test (1967) as one method of analyzing the spatial relationship between biological variables such as species abundance and productivity and environmental factors (e.g., drainage, slope, aspect, rainfall, climate, etc.). The test statistic involves two distance matrices, similar to the proximity matrix used by Moran. The first is a matrix of geographical distances (x_i) describing the spatial location of the sample plots from one another; the second is a matrix of ecological distances (y_i). To account for the spatial interaction of the multivariate data the authors advocate combining the data in such a fashion as to derive a quantitative index, or coefficient of association which defines the likeness of sample points as a composite of data collected at the sample points (Orloci 1978). Orloci (1978) points out that the resemblance of a given pair of sample points should be independent from the resemblance of any other pair in the sample. An example, would be the use pest risk and hazard indices to indicate the likelihood of an outbreak occurring and the expected losses that would result. Other techniques for reducing the dimensionality of set of data are described by Orloci (1978).

The Mantel statistic given by

$$z = \sum\nolimits_{(2)} x_{ij} y_{ij} \tag{1}$$

can be standardized as follows:

$$r = \frac{\sum\nolimits_{(2)} (x_{ij} - \bar{x})(y_{ij} - \bar{y})}{(n-1) s_x s_y} \tag{2}$$

where s_x and s_y are the sample standard deviation of the geographical and ecological distances respectively. The P-value under the null hypothesis is obtained using permutation procedures to generate the sampling distribution of Mantel's statistic under the null hypothesis. This is accomplished by randomly assigning the response variables (i.e. coefficient of association) to the geographical location of the sample points and computing the test statistic, r (Legendre and Fortin 1989). The realized statistic is then compared to the simulation distribution of the statistic under the null hypothesis. If the observed statistic is likely under the null hypothesis, then H_0 is accepted, and one would conclude that there is no spatial relationship among the sample data points. If the test statistic is extreme under the null hypothesis, then H_0 is rejected, and one would conclude that there is a spatial relationship among the sample points. If a significant spatial pattern is observed Legendre and Fortin (1989) advocate doing a series of posteriori tests with Mantel's index to determine which of the environmental response variables are important in describing the spatial trend.

Unfortunately, this approach does not address the question of whether or not two or more response variables are spatially correlated with one another. Legendre and Fortin (1989) discuss a procedure referred to in the literature as a partial Mantel test as possible procedure for detecting spatial autocorrelation among two response surfaces. In this test the matrix of geographical (x_i) and ecological (y_i) distances are replaced by residuals from a regression model of the values of two response variables corrected for their geographical proximity to one another. The two residual matrices are then used to compute the Mantel test. The partial Mantel test implicitly assumes a spatial relationship among the two response surfaces which makes it difficult to interpret the test statistic (Legendre and Fortin 1989).

Wavelet Analysis

The wavelet transform and wavelet variance (Bradshaw and Spies 1992) provide additional techniques for examining pattern and scale in spatial data. Wavelet analysis is especially suitable where spatial patterns are irregular (non-cyclic) and trended (non-stationary). The transformation function (Eq. 3) acts as a "moving window" of a given size and amplifies certain pattern features depending on the selected function. Wavelet functions can be selected to identify features such as edges or gradients. Because the analysis preserves information on the relative location of data points (e. g. distance along transect), interpretation is direct; and multiple comparisons can be easily made. By computing a series of transformations with an increasing window size (*a*), the analysis can resolve the spatial scale at which patterns occur and display how patterns at different scales are nested. The wavelet variance (Eq. 4) is a useful technique for simplifying complex, multi-scale patterns and for comparing alternate data sets. At each data point, a wavelet variance is computed as the squared average of the coefficients of the transformation function across scales or between alternate data sets. Wavelet analysis is usually performed on one-dimensional (transect) data, but development of two-dimensional (surface) techniques is proceeding (Bradshaw, per. comm.).

A one-dimensional, discrete wavelet transform can be defined as:

$$W(a,x_j)=\frac{1}{a}\sum_{i=1}^{n} f(x_i)g\left(\frac{x_i x_j}{a}\right) \tag{3}$$

where x_i is distance along a transect and $g(x/a)$ is a window function of scale a centered at x_j.

The wavelet variance for n data sets is computed as:

$$V(a)=\frac{1}{n}\sum_{i=1}^{n} W^2(a,x_j). \tag{4}$$

SUMMARY

Given the complexity of biological populations and the disparity in the methods of collecting and reporting information, no single approach many be sufficient for a through description and analysis of the spatial structures present in a sampled population. Various techniques provide information on point dispersal distributions, spatially relevant trends and patterns, and comparisons between populations. These methods can provide insights on prevailing ecological processes and suggest efficient sampling schemes.

LITERATURE CITED

Ashby, E. 1935. Quantitative analysis of vegetation. Annals of Botany. **49**:779-802.

Bartlett, M. S. 1964. The spectral analysis of two-dimensional point processes. Biometrika. **51**:299-305.

Blacksmith, R. E. 1958. Nearest-neighbor distance measurements for the estimation of animal populations. Ecology. **39**:147-150.

Bradshaw, G. A. and T.A. Spies. 1992. Characterizing canopy gap structure in forests using wavelet analysis. Journal of Ecology. **80**:205-215.

Clark, P. J.and F.C. Evans. 1954. Distribution to nearest neighbor as a measure of spatial relationships in populations. Ecology. **35**: 445-453.

Cliff, A. D. and J.K. Ord. 1973. Spatial autocorrelation. Pion Limited, London

Cliff, A. D.and J.K. Ord. 1981. Spatial processes: Models and applications. London: Pion Limited.

Cole, L. C. 1946. A theory for analyzing contagiously distributed populations. Ecology. **27**:329-341.

Cottam, G.and J.T. Curtis. 1956. The use of distance measures in phytosociological sampling. Ecology. **37**:451-460.

Cottam, G., J.T. Curtis, and B.W. Hale. 1953. Some sampling characteristics of a population of randomly dispersed individuals. Ecology. **34**:741-757.

Curtis, J. T. and R.P.McIntosh. 1950. The interrelations of certain analytic and synthetic phytosociological characters. Ecology. **31**:434-455.

Daniels, R. F. 1978. Spatial patterns and distance distributions in young seeded loblolly pine stands. Forest Science. **24**:260-266.

Ford, E. D. and E. Renshaw. 1984. The interpretation of process from pattern using two-dimensional spectral analysis: Modeling single species patterns in vegetation. Vegetatio. **56**:113-123.

Holgate, P. 1965. Some new tests of randomness. Journal of Ecology. **53**:261-266.

Jumars, P. A., D. Thistle, and M.L. Jones. 1977. Detecting two-dimensional spatial structure in biological data. Oecologia. **28**:109-123.

Legendre, P and M. Fortin. 1989. Spatial pattern and ecological analysis. Vegetatio. **80**:107-138.

Mantel, N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Research. **27**:209-220.

Matern, B. 1960. Spatial variation. Stochastic models and their application to some problems in forest surveys and other sampling investigations. Meddelanden Fran., Statens Skogsforskningsinstitut Band 49-NR5. 135 p.

Mawson, J. C. 1978. A Monte Carlo study of distance measures in sampling for spatial distribution in forest stands. Forest Science. **14**:127-139.

Moore, P. G. 1954. Spacing in plant populations. Ecology. **35**:222-226.

Morisita, M. 1959. Measuring of the dispersion of individuals and analysis of the distributional patterns. Memoirs of the Faculty of Kyushu University, Series E (Biology). **2**:215-235.

Mountford, M. D. 1961. On E. C. Pielou's index of nonrandomness. Journal of Ecology. **49**:271-275.

Orloci, L. 1978. Multivariate analysis in vegetation research. The Hague: Junk. 451 p.

Payandeh, B. 1970. Comparison of methods for assessing spatial distribution of trees. Forest Science. **16**:312-317.

Pielou, E. C. 1957. The effect of quadrat size on the estimation of the parameters of Neyman's and Thomas' distribution. Journal of Ecology. **45**:31-41.

Pielou, E. C. 1959. The use of point-to-plant distances in the study of the pattern of plant populations. Journal of Ecology. **47**:607-613.

Pielou, E. C. 1977. Mathematical ecology. New York: John Wiley and Sons. 385 p.

Reich, R. M, P.W. Mielke, Jr; and F.G. Hawksworth. 1990. Application of permutation techniques in analyzing spatial patterns. Pages 384-389 *in* State-of-the-art methodology of forest inventory: A symposium proceedings. USDA Forest Service General Technical Report PNW-263.

Reich, R. M., P.W. Mielke, Jr, and F.G. Hawksworth. 1992. Spatial analysis of ponderosa pine trees infected with dwarf mistletoe. Canadian Journal of Forest Research. **21**:1808-1815.

Ripley, B. D. 1981. Spatial statistics. New York: John Wiley and Sons. 252 p.

Stauffer, H. B. 1978. Aggregating points to fit Pielou's index of nonrandomness. Canadian Journal of Forest Research. **8**:355-363.

Thompson, H. R. 1956. Distribution of distance to the nth neighbor in a population of randomly distributed individuals. Ecology. **37**:391-394.

FORECASTING THE SPATIAL DYNAMICS OF GYPSY MOTH DEFOLIATION USING 3-DIMENSIONAL KRIGING

ANDREW LIEBHOLD
USDA Forest Service, Northeastern Forest Experiment Station, 180 Canfield St., Morgantown, WV 26505

MICHAEL E. HOHN, LINDA S. GRIBKO
West Virginia Geological & Economic Survey, PO Box 879, Morgantown, WV 6506-0879

Abstract. This paper introduces 3-dimensional kriging as a method for forecasting pest outbreaks. The technique is illustrated with the prediction of defoliation caused by the gypsy moth, *Lymantria dispar* (L.). Forecasts are based on the statistical autocorrelation (persisitence) of defoliation through space and time. Spatial and temporal autocorrelation of defoliation in historical data was first quantified at a variety of scales using semivariograms. These semivariograms were then used to parameterize the geostatistical estimation technique, 3-dimensional simple kriging. Kriged estimates are weighted averages of values from nearby locations and typically are used to interpolate 2-dimensional data. In this study, we used the procedure to extrapolate future defoliation maps into a third dimension, time. Kriged estimates were expressed as probabilities of detectable defoliation. The procedure usually performed well in predicting the spatial distribution of outbreaks in a given year, but the region-wide outbreak magnitude generally lagged a year behind actual values. Though not currently suitable for operational use, this approach represents a novel approach to landscape-level forecasting of insect outbreaks and these models may ultimately outperform current forecasting systems.

Geostatistics are a family of statistical tools for describing and modeling spatial variation in data. These procedures originally were developed for applied problems in mineral and petroleum geology (Journel & Huijbregts 1978, Hohn 1988). In a typical problem there exists a set of spatially scattered points at which there are sample values (e.g. oil yield) and the problem is to interpolate those values at unsampled locations within the same general area. "Kriging" is a geostatistical procedure that provides estimates that are linear models of values at nearby sample locations. As such, Kriging is based on the notion that values at nearby locations are more similar than values at more distant points. This assumption, while generally true for most geological data, also is valid for most biological data. Consequently, many of these techniques have been adapted to ecological problems that involve modeling of spatial patterns (Robertson 1987, Rossi et al. 1992, Kemp et al. 1989, Liebhold et al. 1991).

Most applications of kriging have involved interpolation among data scattered in a single 2-dimensional plane. Kriging also can be used to extrapolate by providing estimates in areas beyond the areas where sample data exist. Furthermore, kriging also can be applied to 3-dimensional data. Using 3-D kriging, estimates are made among sample points located in a 3-dimensional space. These may be dimensions in euclidean space, such as estimation of the boundaries of an oil reservoir in 3-dimensions, or the dimension may be in time. In the latter situation, estimates are provided by interpolating or extrapolating among or beyond points scattered through space and time (Bilonick 1988). In this paper we demonstrate the use of 3-dimensional kriging for extrapolation of a temporal sequence of gypsy moth, *Lymantria dispar* (L.), defoliation maps.

Pages 150-159 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

The gypsy moth is an example of an eruptive species (Price et al. 1990): population densities vary through several orders of magnitude, often reaching epidemic densities that have spectacular effects on their habitat (i.e., total defoliation of host trees). It is not uncommon for gypsy moth populations to persist for many years at densities so low that it may be difficult to detect any life stages except male moths. Occasionally, for unknown reasons, population densities increase, often to defoliating levels in excess of 6000 egg masses/ha, within only a few generations. These outbreak populations may persist for several years before collapsing.

Gypsy moth outbreaks often occur over very large areas and are notoriously difficult to predict (Liebhold & Elkinton 1989). Previous models developed for predicting defoliation have been based primarily on pre-season counts of egg masses (Gansner & Herrick 1982, Williams et al. 1991, Montgomery 1990, Liebhold et al. 1993a). Though there is a significant relationship between egg mass density and subsequent defoliation at the stand level, the variance about this relationship is great. Consequently, considerable error is encountered in using this method for prediction of defoliation. The lack of a more precise method for prediction of defoliation can have a devastating impact on the efficiency of the gypsy moth management program (Ravlin et al. 1987).

Previous models for predicting outbreaks have relied on data collected at a single point and largely have ignored spatial processes. Nearly 25 years ago, Campbell (1967) recognized that the dynamics of gypsy moth populations are affected by population conditions in nearby areas; there is often considerable sychronicity in the yearly fluctuations of gypsy moth outbreaks (Liebhold & McManus 1991). In an attempt to capture these spatial relationships quantitatively, we have adapted 3-dimensional kriging for modeling the spatial dynamics of gypsy moth outbreaks. Historical defoliation data from Massachusetts were used to parameterize a model that is used to extrapolate defoliation maps into the future. This is a novel approach and may provide a useful way of increasing our ability to predict insect outbreaks.

METHODS

DATA. A raster-based geographic information system (GIS), IDRISI, was employed to assemble and collate gypsy moth defoliation data. (Eastman 1987, 1989). A base-map of county boundaries in Massachusetts was used to define the study area; coordinates were projected using the azmuthal equal-distant projection (Snyder 1987). This projection conserves true distance linearly from a designated point (Boston, Massachusetts). A 2 × 2 km grid cell size was selected as standard for all map layers in the GIS. Each map layer was comprised of 198 by 93 cells. The grid size was selected because it represented the minimum dependable spatial resolution of the available defoliation maps.

The Massachusetts Department of Environmental Management annually maps gypsy moth defoliation in all parts of the state using aerial sketch mapping. Mapping processes may vary from region to region and year to year in these sketch maps, resulting in the possibility of data errors from systematic and non-systematic sources (Talerico 1981, Chrisman 1987). The likely presence of these errors dictated the course spatial resolution of the data used in this study (2 x 2 km rasters).

The compilation of the defoliation map layers from 1960-1990 resulted in a 198 x 93 x 30, 3-dimensional matrix of binary (0, 1) data. Because the data were coded as either 0 or 1, depending on whether defoliation exceeded a threshold (30%), the variable is considered an "indicator" variable. A variety of geostatistical procedures is available for quantifying and modeling spatial dependence in indicator values (Issaks & Srivastava 1989, Kemp et al. 1989, Liebhold et al. 1991).

Variography. The entire field of geostatistics is based on the concept that values at nearby points are more similar than values at more distant points. The term "autocorrelation" is used to describe this phenomenon. In order to perform kriging and other geostatistical estimation procedures it is first necessary to quantify the nature of autocorrelation present in the sample data. We quantified spatial and temporal autocorrelation first by dividing the data into distance classes (i.e. sets of pairs of points separated by approximately h distance units) and then calculating the "semi-variogram" value for each distance class:

$$\gamma(h) = \frac{1}{2n_h}\sum_{k=1}^{n_h}\left[i(x_k) - i(x_k + h)\right]^2 \tag{1}$$

where $\gamma(h)$ is a measure of variance; $i(x_k)$ is a value of the indicator variable at location x_k; $i\ (x_k + h)$ is the value (in this case the value is the binary defoliation indicator variable) at a location h units from x_k; and n_h is the number of pairs used in calculating $\gamma(h)$ for a given value of h (Kemp et al. 1989, Liebhold et al. 1991, Ross et al. 1992). Because of the divisor 2, $\gamma(h)$ has been called the "semivariogram" (e.g., Hohn 1988, Liebhold et al. 1991); recent literature simply refers to $\gamma(h)$ as the "variogram" (Isaaks & Srivastava 1989). The variogram was calculated for several values of h, and $\gamma(h)$ was plotted on the vertical axis vs h on the horizontal axis.

Use of the variogram in subsequent estimation by kriging requires fitting a variogram model. We used the exponential model:

$$\gamma(h) = C(1 - e^{-h/a}) \tag{2}$$

and a nugget effect model:

$$\gamma(h) = C_o \tag{3}$$

where a, C and C_o are constants. The exponential model approaches C, the "sill" asymptotically, but to all appearances, reaches C at $h = 3a$, the "range". The nugget effect represents variability in values at a scale smaller than the minimum distance between sample locations; this variation includes both actual small-scaled spatial variation, and measurement error in the data. The nugget effect appears on the sample variogram as a non-zero intercept when values of γ(h) corresponding to small h are projected back to $h = 0$. The complete variogram model had the form:

$$\gamma(h) = \gamma_1(h) + \gamma_2(h) \tag{4}$$

where $\gamma_1(h)$ is the nugget effect and $\gamma_2(h)$ is the exponential model.

Variograms were calculated for a number of directions in space: east (0°), northeast to southwest (45°), north (90°), and northwest to southeast (135°), by partitioning pairs $i(x_k)$, $i\ (x_k + h)$ among four angle classes, each 45° wide and 20 distance classes, each 1 raster unit (2 km) wide. We also computed a variogram along the time axis of the data using 20 distance classes, each 1 raster unit (1 yr) wide. Variogram models were fit by eye using procedures described in Hohn (1988, chapter 2).

Estimation. Kriging is a geostatistical procedure for estimating a value at a particular location as a weighted average of values at nearby locations. These weights are derived from the variogram; nearby locations generally have greater weights than points farther away, reflecting the underlying spatial structure of the data. Much like linear regression, kriging minimizes the estimation error variance (Journel & Huijbregts 1978).

As stated earlier, defoliation status was a binary indicator variable; the value was coded as 0 if it was less than the 30% threshold level, and 1 if it was greater than the threshold. Consequently, kriged estimates of this variable were calculated as probabilities of exceeding the defoliation threshold. We write the defoliation probability at each cell (position in space and time is identified as x_k) in the 198 x 93 x 30 grid as $P(x_k)$; note that location x has two spatial components and a time component. A kriged estimate for $P^*(x_k)$ is a linear combination of the n observed values of $i(x_k)$ in spatial and temporal proximity to location x_k, i.e.:

$$P^*(x_k) = F^*(x_k)\left[1 - \sum_{j=1}^{n} w_j\right] + \sum_{j=1}^{n} w_j i(x_j) \tag{5}$$

in which $P^*(x_k)$ is an estimate of $P(x_k)$ and $F^*(x_k)$ is an estimate of the expected frequency that $i(x) = 1$.

The weights W_j are computed by means of a system of n equations:

$$\sum_{m=1}^{n} W_m \rho(x_m - x_1) = \rho(x_1 - x_k)$$

$$\sum_{m=1}^{n} W_m \rho(x_m - x_2) = \rho(x_2 - x_k)$$

$$\vdots$$

$$\sum_{m=1}^{n} W_m \rho(x_m - x_n) = \rho(x_n - x_k) \tag{6}$$

where:

$$\rho(a-b) = \rho(h) = 1 - \gamma(h) / \sum_{v=1}^{V} (C_v) \tag{7}$$

and C_1, C_2... C_v are constants in the variogram model, and h is the distance between locations a and b. The system of kriging equations is written in matrix form:

$$B \bullet W = D \tag{8}$$

and is solved with:

$$W = D \bullet B^{-1}$$

The geostatistical literature calls the estimation method used here “simple kriging” (Journel & Huijbregts 1978). It differs from the more commonly used procedure, "ordinary kriging" in that it requires a prior estimate of frequency $F(x_k)$ for each candidate grid cell.

Kriging methods have several desirable features regarding the weights, w_j. In general, points closest to x_k have the largest corresponding weights. Variogram models can be anisotropic, that is, component variograms are damped in certain directions, or ranges vary with orientation (Issaks & Srivastava 1989, Rossi et al. 1992). Because the kriging system of equations depends upon variograms fitted to observed data, weights are greatest for directions of least variation. Hence, kriging captures consistent directional trends in variability (see discussion in Hohn, 1988, p. 107).

The effect of anisotropic variograms in kriging is to stretch the coordinate base perpendicular to the direction of minimum variation, and to weight values at points proximal to x_k by distance from x_k. Resulting estimates are mapped in the original coordinates. We exploited this feature of kriging to solve the problem accounting for separation in time relative to distance in space. A single variogram model was fitted in all three dimensions, with different ranges specified for space and time.

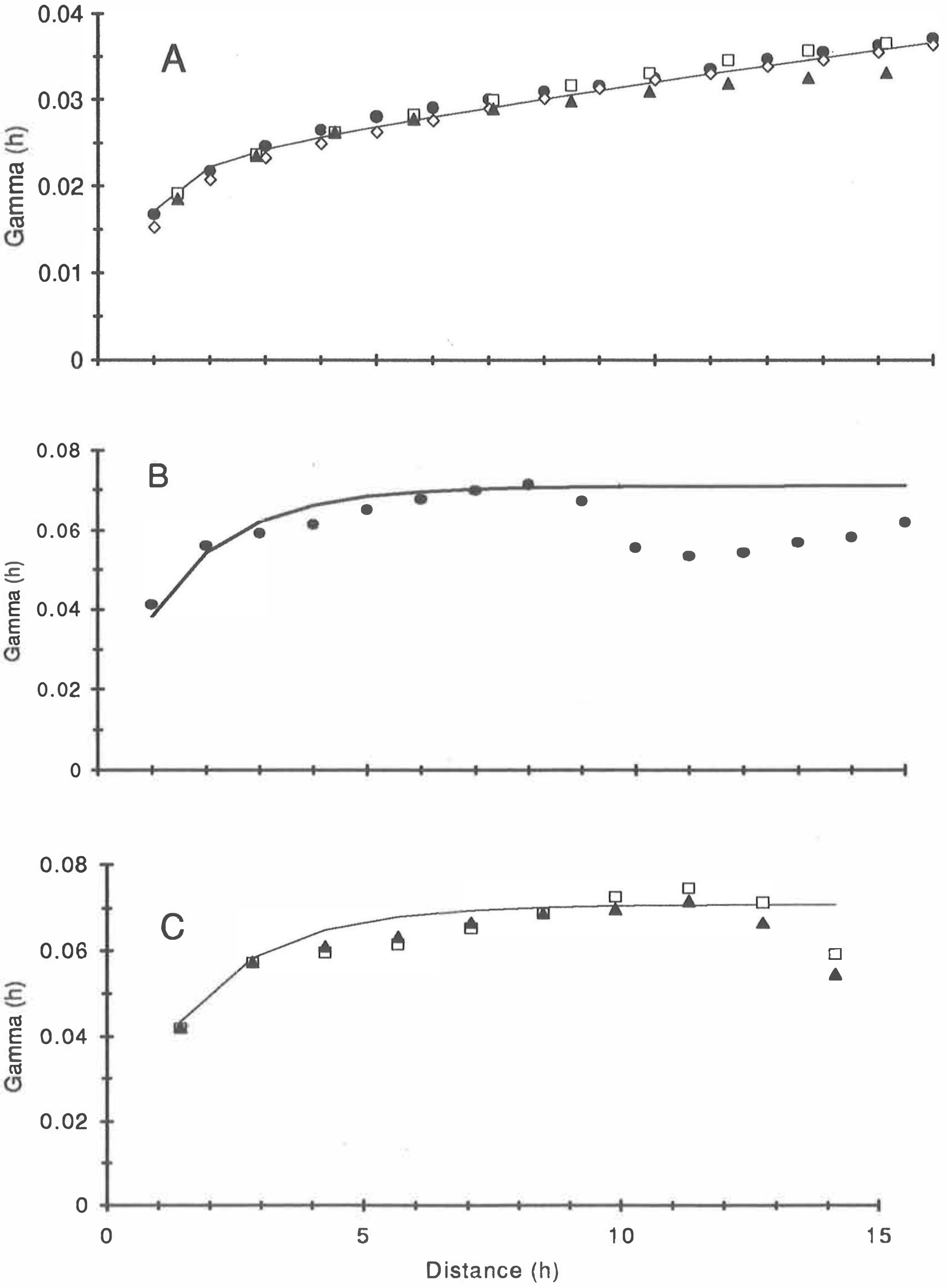


Fig. 1. Sample indicator variograms calculated in various directions from 1960-1990 defoliation data. Units on horizontal axes are numbers of cells (2 km × 2 km × 1 year). **A**. The spatial domain in each of four directions: east-west (0°), northeast-southwest (45°), north-south (90°), northwest-southeast(135°). **B**. The time domain. **C**. The space-time domain (this is the 45° angle in the time × east-west plane).

RESULTS AND DISCUSSION

Observed variograms (Fig. 1a) in the spatial domain exhibited nearly the same shape, and could be fitted with a single, isotropic model; we used a nested exponential model:

$$\gamma(h) = 0.021(1 - e^{-h/0.7}) + 0.050(1 - e^{-h/40}) \tag{9}$$

Although no nugget effect was used in the model, the range of the first exponential term (0.7) is less than the intermodel spacing of one. The small-scale variability in defoliation was not large; the ratio of the sill for this first term (0.021) to the total of the variogram (0.021 + 0.050) was only 30.

The variogram for the time domain (Fig. 1b) manifests an effective range of about five years (3 x 1.7 years), reaches a sill, then declines briefly. This "hole" in the variogram results from the episodic nature of gypsy moth outbreaks; defoliation in an area was usually low to zero, and outbreaks persisted for several years (Fig. 2a). The variogram model for time was identical to that for space except for the shorter range of the second exponential term:

$$\gamma(h) = 0.021(1 - e^{-h/0.7}) + 0.050(1 - e^{-h/1.7}) \tag{10}$$

Together, the two models comprise a single, anisotropic model in both space and time:

$$\gamma(h) = 0.021(1 - e^{-h/0.7}) + 0.050(1 - e^{-h/r}) \tag{11}$$

where

$$r = \frac{r_s r_t}{\sqrt{r_s^2 \sin^2 \phi + r_t^2 \cos^2 \phi}} \tag{12}$$

and r_s = range of spatial variogram = 40.0, r_t = range of temporal variogram = 1.7, ϕ = azimuth of vector separating two locations relative to the spatial plane.

As a check, r for the variogram in the spatial plane is calculated from equation (12):

$$r = \frac{r_s r_t}{\sqrt{r_s^2 \sin^2 0 + r_t^2 \cos^2 0}} = \frac{r_s r_t}{\sqrt{0 + r_t^2}} = r_s \tag{13}$$

Similarly, r for the variogram in the time domain is equal to r_t. The expression for r in terms of r_s and r_t [equation (12)] follows from the definition of a geometric anisotropy (Journel & Huijbregts 1978). Combined space-time variograms (e.g. 45° in the space-time plane) need not be fitted; the space-time model (calculated from equation (12); Fig. 1c) shows an excellent fit to observed variograms in two directions.

The use of an anisotropic variogram model (equation 11) for both spatial and temporal directions avoids the assumption of any innate equivalence between spatial and temporal measurement units. In addition, separate spatial and temporal variogram models can lead to non-unique solutions of the kriging systems of equations (Myers and Journel 1990, Rouhani and Myers 1990)

Before kriging could be performed, a value for $F^*(x_k)$ in equation (1) had to be selected. This term represents an *a priori* expectation of the frequency of defoliation which is adjusted to local conditions in time and location. A number of options exist for calculating $F^*(x_k)$. One approach would be to predict $F^*(x_k)$ from variables that are associated with each grid cell. Examples of such variables include characteristics of the biological or physiographic landscape (Liebhold et al. 1993b), or the frequency could be calculated from census counts [eg. egg mass counts (Liebhold et al. 1993a, Williams et al. 1991)]. A second approach was used in this study: frequencies were calculated as averages from historical defoliation data. The total number of years of defoliation was divided by the total number of years (30) for each of the 6,075 grid cells falling within the state of Massachusetts. The resulting map

(Fig. 2) shows clearly that some areas tend to be defoliated more often than others, reflecting the association of gypsy moth defoliation with specific forest types and physiographic features (Liebhold & Elkinton 1989, Liebhold et al. 1993b).

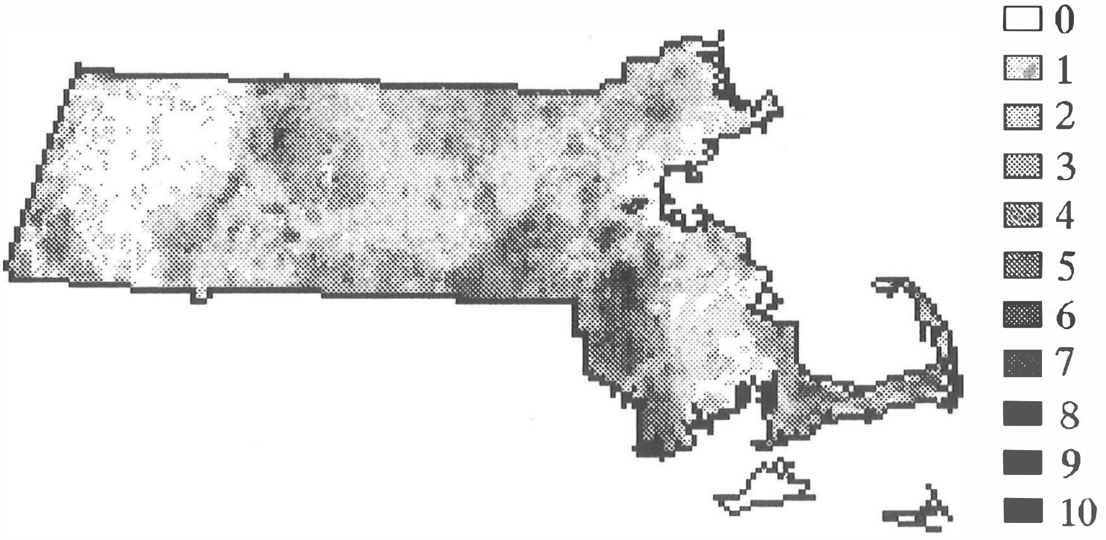


Fig. 2. Defoliation frequencies in Massachusetts from 1961-90 (no. years out of 30 with detectable defoliation).

A kriged estimate for each location x_k in a given year was computed from observed defoliation in the two previous years, and the 49 locations within a 7 x 7 grid centered on x_k. This configuration of cells, or "search radius", was selected because the spatial variogram range [equation (9)] was larger than the temporal range [equation (10)], and locations approaching and beyond the range had near-zero weights and make little contribution to the final estimates. In this manner, defoliation probability maps were estimated from 1963-1990 (Fig. 3).

The sequence of estimates graphed by year (Fig. 3) show that kriging has modified the cumulative defoliation frequencies of Figure 2 to more accurately reflect particular spatial patterns in defoliation during the previous years. In addition, the maps of probabilities often have about the same appearance as the observed maps in the sense that areas of high defoliation probability typically corresponded to areas of observed defoliation (Fig. 2).

The kriging procedure performed best, in terms of delineating areas of predicted defoliation, during the peak years of defoliation (Fig. 3). It showed limited success for the initial years of gypsy moth outbreak. The modeling approach presented here is completely empirical; as such it is completely based upon the persistence and spread of defoliation through time. While specific biological processes are not explicitly modeled, the persistence and spread of defoliation reflects the emergent properties of a multitude of ecological factors. The statistical persistence of defoliation reflects a certain level of stability in high density populations that causes outbreaks to persist for several years (Liebhold 1992). Liebhold and McManus (1991) described the apparent spread of defoliation and presented several mechanisms that might cause it. They concluded that it was unlikely that the observed spread of outbreaks was caused by the dispersal of gypsy moths from high to low density areas. Instead they concluded that populations may rise synchronously over large areas, and the apparent "spread" of defoliation actually was caused by the spatial distribution of susceptibility.

The 3-dimensional kriging procedure described here probably is not suitable for operational use; even though the spatial distribution of outbreak predictions often coincided well with observed defoliation patterns, the region-wide outbreak magnitude generally lagged behind actual values. Nevertheless, we feel that this is a novel approach to forecasting insect outbreaks and that these types of landscape-level models ultimately may outperform traditional forecasting systems. Incorporation of yearly census data into these time-space models should result in forecasts that more closely track actual year-to-year population levels.

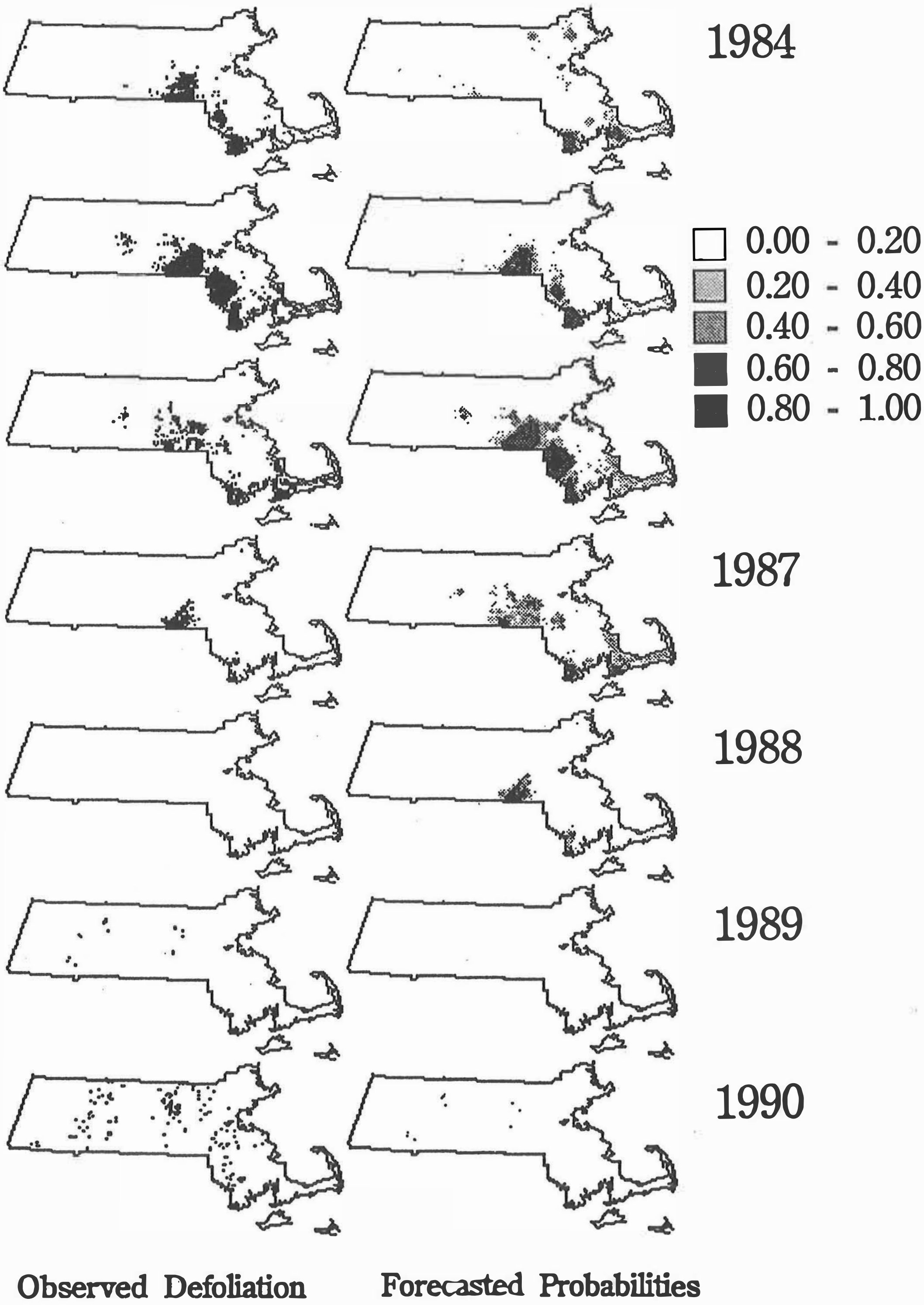


Figure 3. Predicted defoliation probabilities in Massachusetts: 1984-90.

Acknowledgments

We thank the Massachusetts Department of Environmental Management for providing defoliation data, and Eugene Luzader who helped in many aspects of this research. We are grateful to Rick Rossi and Dennis Schotzko for reviewing an earlier draft of this manuscript. This research was funded in part by funds from the USDA Forest Service Gypsy Moth Research and Development program and by grants 89-37250-4533 and 91-37302-6278 from the USDA CSRS Competitive Grants Program.

LITERATURE CITED

Bilonick, R.A. 1988. Monthly hydrogen ion deposition maps for the northastern U.S. from July 1982 to September 1984. Atmospheric Environment **22**: 1909-1924.

Campbell, R.W. 1967. The analysis of numerical change in gypsy moth populations. For. Sci. Monog. **15**. 32 pp.

Campbell, R.W. and J.P. Standaert. 1974. Forecasting defoliation by the gypsy moth in oak stands. USDA For. Serv Res. Note NE-193. 7 pp.

Chrisman, N.R. 1987. The accuracy of map overlays: a reassessment. Landscape and Urban Planning **14**: 427-439.

Clark, I. 1979. Practical Geostatistics. Applied Science Publications Ltd., London.

Eastman, J.R. 1987. Access to technology: the design of the IDRISI research system, Proc. GIS/LIS-87. p. 166-175, ASPRS/ASCM, San Francisco.

Eastman, J.R.1989. IDRISI: a Grid-Based Geographical Analysis System. Clark University, Worcester, MA.

Gansner, D.A. and O.W. Herrick. 1982. Predicting the rate of change in timber value for forest stands infested with gypsy moth. U.S. Dept. Agric. For. Serv. Res. Note. NE-311.

Hohn, M.E. 1988, Geostatistics and Petroleum Geology. Van Nostrand Reinhold, New York.

Isaaks, E. H. and R.M. Srivastava. 1989. An Introduction to Applied Geostatistics.Oxford University Press, New York.

Journel, A.G., and Huijbregts, C.J., 1978, Mining Geostatistics, Academic Press, London.

Kemp, W.P., T.M. Kalaris, and W.F. Quimby. 1989. Rangeland grasshopper (Orthoptera: Acrididae) spatial variability: macroscale population assessment. J. Econ. Entomol. **82**: 1270-1276.

Liebhold, A.M. 1992. Are North American gypsy moth poulations bimodal? Environ. Entomol. **21**: 221-229.

Liebhold, A.M. and J.S. Elkinton. 1989. Characterizing spatial patterns of gypsy moth regional defoliation. For. Sci. **35**: 557-568.

Liebhold, A.M. and M.J. McManus. 1991. Does larval dispersal cause the spread of gypsy moth outbreaks? N. J. Appl. For. **8**: 95-98.

Liebhold, A.M., X. Zhang, M.E. Hohn, J.S. Elkinton, M. Ticehurst, G.L. Benzon, and R.W. Campbell. 1991. Geostatistical analysis of gypsy moth (Lepidoptera: Lymantriidae) egg mass populations. Environ. Entomol. **20**: 1407-1417.

Liebhold, A.M., E. Simons, A. Sior, and J. Unger. 1993a. Predicting gypsy moth defoliation from field measurements. Environ. Entomol. 22: 26-32.

Liebhold, A.M., G.A. Elmes, J.A. Halverson, and J. Quimby, 1993b. Landscape characterization of forest susceptibility to gypsy moth defoliation. For. Sci. (in press).

Myers, D.E. and A. Journel. 1990. Variograms with zonal anisotropies and noninvertible kriging systems. Math. Geol. **22**: 779-785.

Montgomery, M.E. 1990. Role of site and insect variables in forecasting defoliation by the gypsy moth. pp. 73-84 *in* A.D. Watt, S.R. Leather, M.D. Hunter, and N.A.C. Kidd, editors, Population Dynamics of Forest Insects. Intercept, Andover.

Price, P.W., N. Cobb, T.P. Craig, G.W. Fernandes, J.K. Itami, S. Mopper, & R.W. Preszler. 1990. Insect herbivore population dynamics on trees and shrubs: new approaches relevant to latent and eruptive species and life table development. Pages 1-38 *in* E.A. Bernays, editor, Insect-Plant Interaction, vol. 2. CRC Press, Boca Raton, Florida.

Ravlin, F.W., R.G. Bellinger, & E.A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation and recommendations. Bull. Entomol. Soc. Am. **33**: 90-98.

Roberston, G.P. 1987. Geostatistics in Ecology: interpolating with known variance. Ecology **68**: 744-748.

Rossi, R.E., D.J. Mulla, A.G. Journel, and E.H. Franz. 1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecological Monographs. **62**: 277-314.

Rouhani, S. and D.E. Myers. 1990. Problems in space - time kriging of geohydrological data. Math. Geol. **22**: 611-623.

SAS Institute. 1987. SAS/GRAPH Guide for Personal Computers, Version 6 Edition. SAS Inst., Cary, NC.

Snyder, J.P. 1987. Map Projections - A Working Manual. U.S. Geol. Surv. Prof. Pap. 1395.

Sokal and Rohlf. 1981. Biometry. Freeman & Co., San Francisco.

Talerico, R.L. 1981. Methods of gypsy moth detection and evaluation. Pages 31-63 *in* C.C. Doane and M.L. McManus, editors. The Gypsy Moth: Research Toward Integrated Pest Management. USDA For. Serv. Tech. Bull. 1584.

Williams, D.W., R.W. Fuester, W.W. Metterhouse, R.J. Balaam, R.H. Bullock and R.J. Chianese. 1991. Oak defoliation and population density relationships for the gypsy moth. J. Econ. Entomol. **84**: 1508-1514

A SPOT-GROWTH MODEL FOR SOUTHERN PINE BEETLE

JOHN M. PYE

Southeastern Forest Experiment Station, USDA Forest Service, Research Triangle Park, NC 27709

Abstract. Currently available models of the growth of southern pine beetle spots are either spatially naive or too complex for regional generalization. By spatially applying spot growth rates from an aspatial spot growth model, interactions between landscape structure and SPB spot growth can be simulated. Because the stochastic, aspatial model is driven by readily available, regional data, model results are explicitly linked to statistically compatible location and ownership measurements, and incorporate key sources of variability. By simulating SPB impacts under several scenarios of landowner response to infestation, the impact of different intensities of suppression on landscape structure can be evaluated. Spatial analysis is performed outside the model through output of generic raster landscapes. Spatial measures illustrated here using IDRISI include change in amount of pine edge and frequency with which spots spill over into adjoining stands. Although empirically obtained landscapes could be used by the model, a module was constructed which generates artificial landscapes. Southeastern stand size by age distributions are used to construct replicate landscapes of varying cover densities and complexities.

INTRODUCTION

Over the past decade the forestry community has seen dramatically increasing pressure on both ethical and budgetary fronts. On the ethical side, we are increasingly challenged to incorporate broader ecosystem impacts into forest management decisions, including impacts on wildlife, recreation, and water quality. On the budgetary side, public involvement in forestry must increasingly be justified based on physical externalities or efficiencies of scale.

Key to addressing these concerns is understanding how stand level processes propagate upward to the surrounding landscape and in turn are controlled by their broader surroundings. Effects of forest fragmentation on bird populations is one example of a forest management impact which can only be understood through landscape scale study. A parallel issue relevant to policy is that of potential long term benefits of area-wide pest control, where a landowner's risk of infestation this year may rely on suppression activities undertaken by neighbors in years past.

Spot growth represents one of several behaviors of the southern pine beetle with potential to alter landscape structure and to cross stand borders. For analysis of southern pine beetle policies it would be useful to obtain quantitative estimates of how SPB alters landscape structure, and how frequently spots spill over from one stand to the next. The former measure is important to assessing how spots perforate or simplify landscapes under varying levels of suppression, while the latter might shed light on how frequently suppression of a spot prevents damages by that spot to adjoining stands and ownerships.

Direct empirical data on these questions is scarce. No direct measures have been found, although comparison between sizes of stands and spots might shed indirect light. Figure 1 shows frequency distributions from two sources. On the left are shown the frequency distribution of potential host stands in the Southeastern U.S. by area of stand, obtained by the Southeastern Forest Experiment Station's Forest Inventory and Analysis Unit. The bars show the relative amount of pine and oak pine acres which occur in stands of different sizes (extent). Data were collected in the late 1980's to early 1990's.

Pages 160-171 *in* A.M. Liebhold and H.R. Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

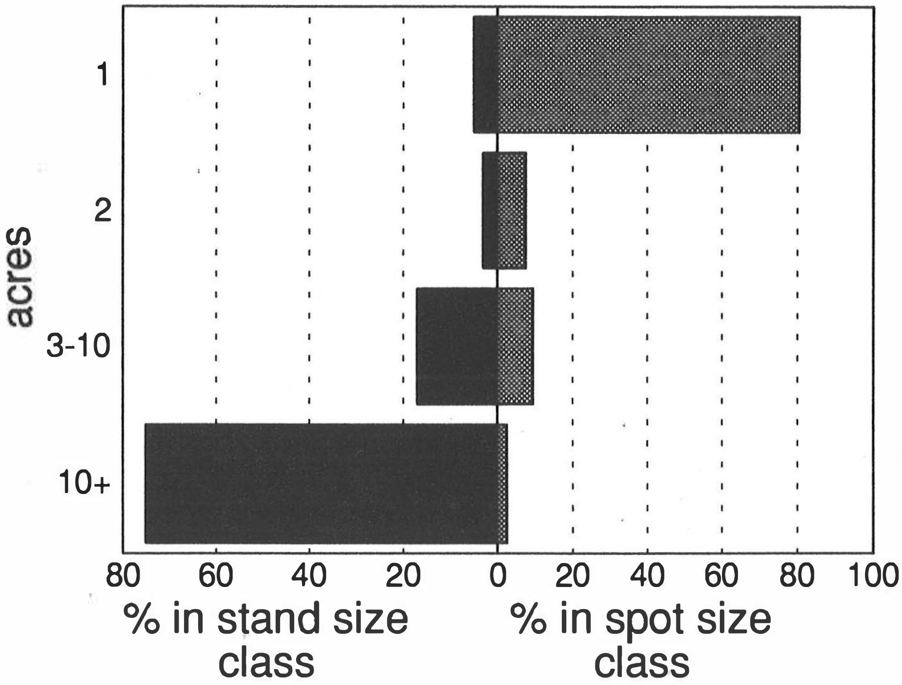


FIG. 1. Comparison of frequency distributions for stand size (left) versus spot size (right). Stand size data describes pine and oak-pine types in the five Southeastern states, as obtained from the Forest Inventory and Analysis Unit, Asheville, NC. Spot size data were obtained from Porterfield and Rowell (1981).

On the right side of the graph is the frequency distribution of SPB spot sizes in acres (Porterfield and Rowell 1981). As shown by this and other data on spot size (Leuschner and others 1976), most SPB spots are much smaller than most host stands. On the face of it this would suggest that spots crossing stand borders would be relatively rare. However, large spots may occur disproportionately in small stands, or spots may prefer stand borders to interiors. Neither of these can be ruled out, but there are more fundamental limitations to the comparison.

Most data describing spot size are obtained from detection programs, which focus on observing spots soon after they are initiated. Such observations would not show how large spots might ultimately become. Secondly, broad scale observations of spots understandably cannot require private landowners to withhold spot suppression or salvage operations. There are no empirical with-and without suppression comparisons available. In the absence of clear empirical information, simulation appears the most promising route to evaluating spot and suppression effects on landscape structure.

This paper describes the rationale, approach, and preliminary results of a spatially explicit model of southern pine beetle (SPB) spot growth in modern landscapes. Called SPBLAND, it is designed to estimate how spot growth responds spatially to landscape structure and how spot growth in turn alters those characteristics. Because the model seeks to describe processes in modern landscapes, it also estimates how impacts of spot growth on landscape structure are in turn affected by spot suppression or other landowner responses. In order to address regional policy concerns, a key requirement for the model is generalizability to conditions across the region.

SPB has been a popular subject of modelers (Stephen and others 1980). However, none of the existing models include all four of these characteristics: SPB spot growth, landscape structure, landowner response, and regional generalizability. CLEMBEETLE (Hedden 1985) and the Arkansas spot model (Hines and others 1980) both simulate spot growth but do not incorporate spatial characteristics of host stands. TAMBEETLE incorporates the spatial arrangement of host trees (Feldman and others 1980), but cannot readily be generalized due to detailed data and processing requirements. Two models have simulated SPB populations regionwide but neither incorporated spatial characteristics of stands or landscapes (Reed and others 1980; de Steiguer and others 1987). Coulson and others (1993) describe a conceptual model of SPB which explicitly addresses the spatial characteristics of landscapes but focuses on processes which initiate new spots and maintain area-wide populations (Coulson and others, 1993; Rykiel and others 1988). Several landscape models are available which simulate generic disturbances, but these do not explicitly simulate SPB processes or landowner responses (Turner and others 1989; Graham and others 1991).

MODELING APPROACH

There are several additional criteria which influence the modeling approach employed.

1. Driving variables should be obtained from regional scale data sources whenever possible, and ideally should permit explicit disaggregation to more narrowly defined groups.
2. While simplifications are inevitable, aggregation methods should recognize key nonlinear and stochastic processes. Extreme cases may dominate overall effects.
3. As a research tool, flexibility of construction and analysis take preference over user friendliness. Flexibility in spatial analysis is particularly important due to the pace of development in this field.
4. Extensive data collection is not feasible at this phase. Should preliminary efforts prove promising, later collection of new data for validation or model refinement might be undertaken.

To meet these criteria and objectives, a raster-based, stochastic simulation approach was chosen, to be implemented as a collection of modules of code linked via ASCII format files. The two principal modules were written in the Interactive Matrix Language (IML) of the Statistical Analysis System version 6.04 (SAS, Cary, NC). These modules respectively construct the initial landscapes and simulate beetle behavior on landscapes. Modified landscapes are output in raster format for analysis. Spatial analyses have thus far been performed using IDRISI GIS (Clark University, Worcester, MA), although other spatial analysis tools may be used in future.

Temporal and spatial scales are critical characteristics of the model. The following extents and resolutions were chosen based on physical and logistic criteria:

TABLE 1. Spatial and temporal resolution of simulations.

	Extent	Resolution
temporal	one year	one month
spatial	1080 acres	1/30th acre

Temporal scale was chosen based on a combination of beetle and human factors. Growth of most SPB spots ceases in the late fall as temperatures decline, and new spots are created beginning in the early spring and continuing through the fall. Detection flights and subsequent suppression activities respond to this pattern, with intervals between spot initiation and suppression separated by months rather than days (de Steiguer and Hedden 1988). A temporal resolution of one month is sufficient to capture these processes.

The spatial resolution employed in the model is dictated by availability of data on spots. Spots of less than 10 trees are typically unreported in regional surveys because they are more likely to go inactive and create little damage (Hedden and Billings 1979; Pye 1993). Small spots should also show short lived effects on the landscape due to rapid ingrowth by surrounding trees. Based on the average densities of pine in the Southeast (Bechtold and Ruark 1988) 10 trees corresponds to an area of about 1/30th acre.

Spatial extent is to some degree a logistic determination. Larger landscapes pose fewer problems with border effects. However, in version 6.04 of SAS/IML for the PC, arrays are constrained to 180 by 180 cells, resulting in landscapes of 1080 acres. This is large enough to include multiple stands and minimize border interactions for most scenarios of interest, with necessary replication achieved through multiple landscapes.

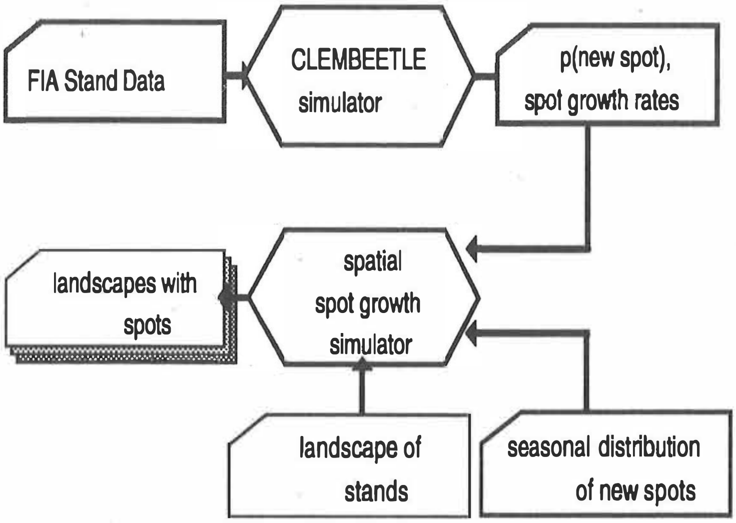


FIG. 2. Components of SPBLAND's spatial spot growth simulation module. See text for explanation.

Beetle Module

The principal components of spot growth in the beetle module are summarized in Figure 2, and consist of the following four features:

1. initiation
2. growth rate
3. growth direction
4. growth duration

Spot initiation- Spots are initiated randomly within the beetle season but following a seasonal pattern identified by expert survey (de Steiguer and others 1987). SPBLAND does not simulate processes of spot creation or proliferation. In SPBLAND the total number of spots in a landscape is exogenously determined. The model does determine where in that landscape spots occur using a randomization procedure. The model randomly selects a location within the landscape. If the location is pine or oak-pine the model then either accepts or rejects that location by comparing the relative risk of the host type at that location with a randomly drawn number. This is repeated until the indicated number of spots are established. Simulations thus far have included two spots per landscape.

Spot growth rate- The model described here is not so much a spot growth model as a spatial addition to an existing, aspatial, spot growth model--CLEMBEETLE (Hedden 1985). CLEMBEETLE assumes a homogeneous stand where spot growth is unaffected by spatial characteristics of the stand. SPBLAND takes CLEMBEETLE projections of areal rates of spot growth and applies them in a spatial context. CLEMBEETLE also provides the relative risk of spot formation in stands of different susceptibilities.

The projections of CLEMBEETLE were obtained as part of a previous simulation project which estimated regional costs and benefits of SPB suppression (de Steiguer and others 1987). For that effort, CLEMBEETLE projected spot initiation probabilities and growth rates for each of over 16,000 pine and oak-pine stands in the South. Although three levels of regional outbreak were simulated, only projections for one level are used, that of two spots per thousand acres of susceptible host type. The variables describing stand risk factors were drawn from Forest Inventory and Analysis (FIA) surveys of the Southeastern and Southern Forest Experiment Stations (Asheville, NC and New Orleans, LA respectively).

By basing spot growth projections on FIA data, projections were generated for a statistically defined and well replicated population of stands from across the region. These linkages between each projection and its state, survey unit, and ownership characteristics allow hooks to economic models of landowner behavior, as well as permit comparison of results between different subregions or ownership assemblages.

To reduce data storage needs, 500 plots for each of three susceptibility classes were selected randomly from those in the Southeast and their predicted spot growth rates stored in a table. As each spot is initiated in SPBLAND, the susceptibility class of that location is checked and a growth rate randomly drawn from the 500 values for that class. Growth is assumed constant throughout growth of that spot.

Spot growth direction- Spots in SPBLAND are assumed to grow in a contagious fashion but with direction determined randomly each spatial step. Addition of cells is restricted to (non-spot) host cells. In short, growth is assumed to follow a self-avoiding random walk, with direction randomly redrawn for each new cell. The contagious nature of spot growth is a well recognized consequence of aggregation pheromones. Less certain is its direction, although random direction is consistent with one publication (Coulson 1981). Prolonged winds may in reality impart a greater consistency of direction, particularly for rapidly growing spots, although data to confirm this has not been located.

There are three exceptions to random direction of growth. Spots:

1. avoid expanding outside of landscape
2. avoid expanding into non-host cells
3. turn toward an adjacent cell of higher susceptibility

In all cases the spot only responds to conditions in immediately adjacent cells. Validity of this "myopic" behavior would likely depend on reception distances for both host and aggregation pheromones. Should host pheromones be important at distances greater than a cell (about 12 yards) then spots might in practice preferentially turn toward stand centers. This model provides a neutral model for such comparison.

More suspect than myopic host response is the model's assumed lack of response to aggregation pheromones from nearby spots. It is more likely that at some separating distance aggregation clouds of nearby spots overlap and the spots cease to behave independently. This simplification in the model's present structure may be a particular problem in extremely severe outbreaks. Comparing the spatial patterns it predicts under assumed spot independence with empirical observations should provide a test of spot independence. Nonindependence should appear as a greater degree of convergence of nearby spots over that predicted by the model.

spot growth duration- Landowner response to beetle infestation can take three forms: no control, spot suppression, or stand harvesting and regeneration. Spot suppression is assumed here to occur two months after the spot is formed, allowing for lags for both detecting the spot and actually implementing salvage or cut and leave actions. For simplicity at this phase, these actions are assumed fully effective.

Under the no control scenario, once spots are initiated they are assumed to grow at a constant rate until the end of the year. Under the suppression option, spot growth is stopped two months after it starts. For the harvest option, the entire stand is assumed reset to the youngest age class. Each of the first two options is simulated for the same input landscape, producing output of three matched landscapes: initial, no control, and with suppression. The harvest option has minimal impact on the spatial characteristics of landscapes, and is therefor handled externally via recoding in IDRISI of infested patches to the lowest risk class. For measures of landscape characteristics which do not distinguish risk classes, the harvest option is assumed to yield measures identical to those of the initial landscape, and this recoding is unnecessary.

Landscape Module

The beetle module requires raster-based landscapes with cells classified using three strata of susceptible host plus one of non-host. In these simulations age class has been used as the stratifying variable of susceptibility. As explained above, the full variability of spot growth rates are maintained through the randomization process. The "susceptibility class" designation merely serves to link the spatial characteristics of the stand (eg. size, shape, etc.) to the beetle module.

Landscapes meeting the above criteria could be obtained through remote sensing or GIS, so long as suitable susceptibility strata can be determined. Existing cell classifications might be reclassified to match the age classes already employed in the spot growth tables (0-20, 20-40, and 40+ years). Alternatively, tables could be constructed based on some other stratifying characteristic, so long as a common characteristic can be derived from both FIA and landscape sources. Age was chosen here for its relevance to both stand size and economic value, although pine BA might be a useful alternative.

One difficulty with using remote sensing or GIS sources is the expense of broad scale data, and particularly data which includes information useful for predicting landowner response. Digitized data on National Forests are increasingly available, but these lands make up a small percentage of the SPB range (USDA Forest Service 1988) and have spatial characteristics quite different from those of privately held forestlands (Pye and Lee 1992). An alternative approach was undertaken where simulated landscapes were created based on FIA data from the Southeast.

Most measures in FIA surveys are point-based and therefor unsuitable for landscape scale analyses. However, several measures are collected which shed light on surrounding characteristics. In the Southeastern states, one particularly useful item is "extent of forest condition," shown in Figure 1. Basing landscapes on these data provides several benefits:

1. direct compatibility with risk measures from CLEMBEETLE
2. a statistically defined, regional population
3. compatibility with a standard unit of management
4. linkage to ownership class

Simulating the landscapes also allows independent manipulation of various landscape characteristics, such as patch size distribution, patch shape, and percent cover.

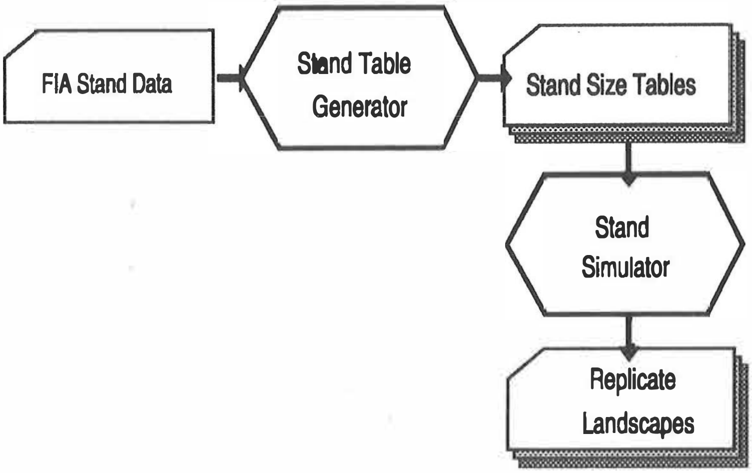


FIG. 3. Components of SPBLAND's landscape simulation module. See text for explanation.

Figure 3 shows the basic components of the landscape simulation process: generation of target stand characteristics, and locating and "growing" stands.

The module creates each landscape by randomly picking an initial point in the landscape and contagiously expanding outward from that point, assigning the susceptibility class assigned to the stand. Expansion continues until the target stand area is reached, incorporating only non-host cells into the stand. Previously established stands are avoided, as are landscape boundaries. Each stand is created in turn.

target stand characteristics

SPBLAND uses stand tables to tell it how many stands are required in a landscape and the age and target size of each stand. Although replicate stands can be generated from a single table, in these simulations new tables were randomly created were each initial landscape. The number of stands in a landscape is calculated from the target total acreage of host stands in the landscape divided by the average stand area.

To randomly assign each stand a final area and susceptibility class, frequency distributions were generated from FIA data for the five states in the Southeast for which stand area data is available. Area-weighted frequencies were generated by six classes of "size of forest condition" and three classes of age. Midpoint sizes were assigned to each size class, with a maximum allowable stand size of 55 acres.

locating and "growing" stands

SPBLAND uses the values in the stand table to sequentially generate stands, following the contagious expansion sequence outlined in the landscape module overview. However, it is the details of this procedure which determine the shape of each stand. FIA data provides no quantitative information on the shape of stands, even though this may have an important effect on landscape structure and spot growth.

The model addresses this lack of shape information through sensitivity analysis. Two alternative contagious expansion algorithms are provided, each with different implications for patch shape. Altering the fraction of a stand's area constructed with each of these algorithms creates landscapes with different degrees of complexity. This capability permits SPBLAND to predict the influence of shape complexity on spot behavior, and may allow calibration of shape complexity to match empirically observed values.

The two algorithms are referred to as branching and widening. The branching algorithm uses the self-avoiding random walk employed in the beetle module. Starting at an initial point, the algorithm creates a string of host cells. In contrast to spot growth, this algorithm periodically jumps to a different existing stand cell and starts a new branch. This produces complex, branching patches. The widening algorithm is a simpler contagious approach which randomly selects existing stand cells and tries to add an adjacent cell to the stand. This widening approach produces patches of simple shape. The branching algorithm is first applied until either the branch approach cannot continue or the switch point is reached. Then the widening algorithm continues until the target stand size is reached.

By using average stand size to determine the total number of stands in a landscape, stand size has precedence over total cover amount. That is, for a given target cover amount, each replicate landscape will be composed of the same number of stands. However, as the actual size of each of these stands is drawn randomly from regionwide distributions, some landscapes will be composed of smaller stands and some larger, with variation in realized cover percent for each landscape. The randomization procedures ensure that stand size distributions and cover percent over all simulated landscapes converge on the target amounts.

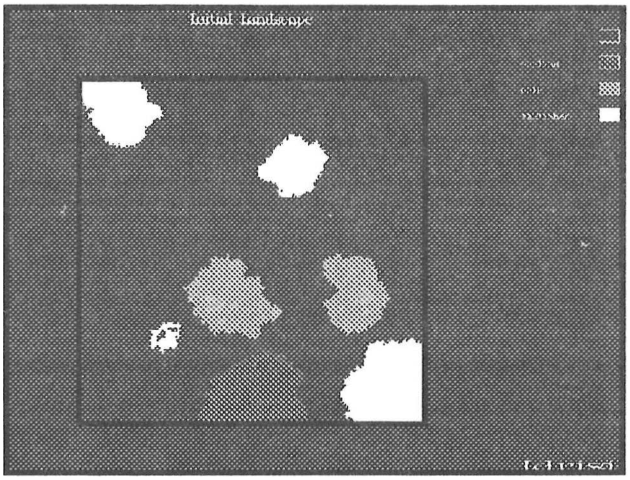


FIG. 4. Screen-shot of display from IDRISI showing a simulated landscape before spot growth was simulated.

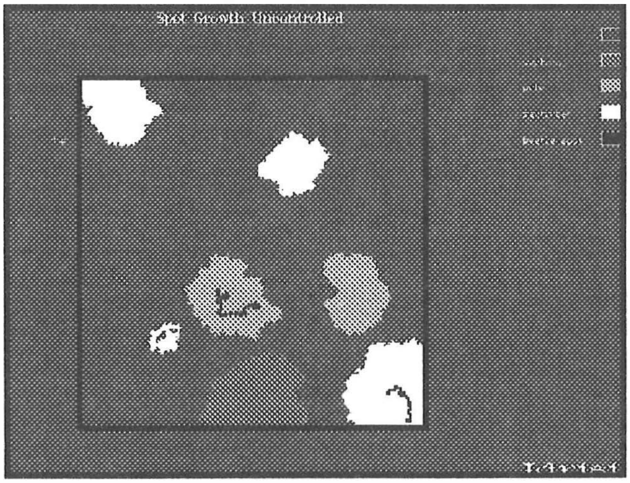


FIG. 5. Screen-shot of display from IDRISI showing the landscape from figure 4 after simulation of two spots under the "no suppression" scenario.

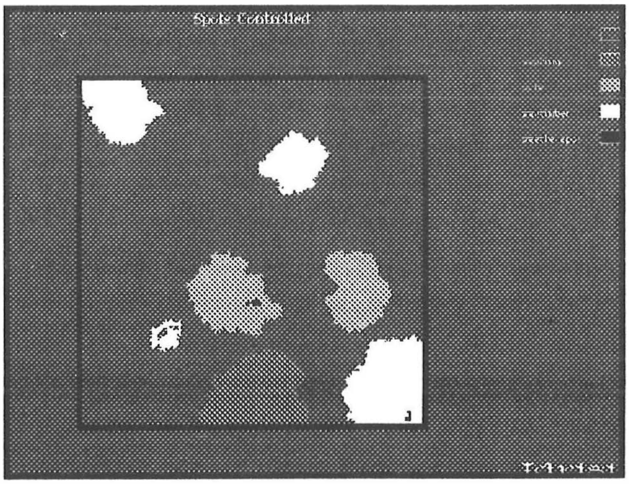


FIG. 6. Screen-shot of display from IDRISI showing the landscape from figure 4 but where simulated spot growth was controlled two months after initiation.

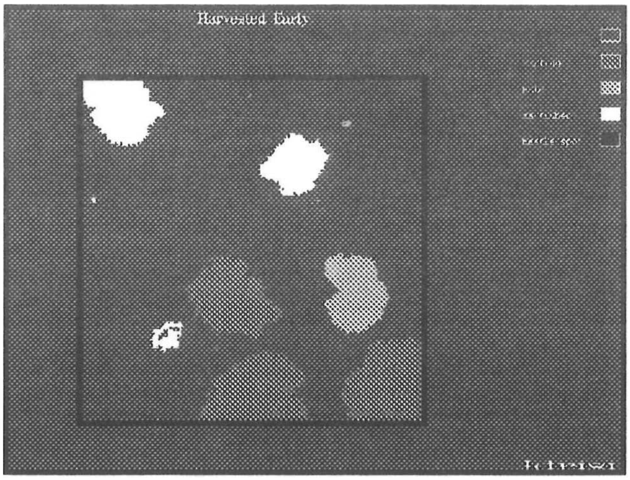


FIG. 7. Screen-shot of display from IDRISI showing the landscape from figure 5 after the harvest and regeneration scenario, where infested spots are cut and regenerated.

scenarios of cover and shape

Most of the simulations conducted thus far have used a switch point of 0.7. This level was chosen based on visual comparison of shape complexity from different switch points. Unfortunately, there is little directly comparable data available for calibration of stand shape. Most landscape scale data distinguishes patches of conifers (Turner and Ruscher 1988) but not stands, and shape characteristics of stands may differ from those based on coarser categories of forest.

Two levels of host cover have been simulated thus far: 20% and 50%. The lower was chosen as regionally representative of pine types, based on data for the Southeast (USDA Forest Service 1988; Bechtold and Ruark 1988). The higher fraction was used to represent more localized concentrations of host, such as might occur in areas where SPB outbreaks are more common.

PRELIMINARY RESULTS

Thus far only twenty sets of landscape have been simulated for each of the two cover amounts, so results are only preliminary. Figures 4 through 7 illustrate one sequence of treatments based on 20% cover and a switch point of 0.7. Figure 4 is the initial landscape from which the other three landscapes were derived. In this case the landscapes are composed of seven stands, with representatives from each susceptibility class. Note that the smaller spot in the bottom left has an inclusion of the non-host matrix. Figure 5 shows the landscape after simulating unrestrained spot growth. Two relatively lengthy spots can be seen in the bottom center and bottom right. By suppressing the spots after only two months of growth, damages were considerably reduced (Figure 6). Figure 7 illustrates the impact of harvesting and regeneration of the two infested stands, although this operation was not evaluated for the full set of simulations.

The resulting 120 landscapes (2 cover levels x 3 responses x 20 replicates) were imported into IDRISI. Amount of non-pine to pine edge were calculated by IDRISI for each landscape and converted into percentage increase above edge in the initial landscape. Figure 8 illustrates the results. As both the 20 and 50% cover levels received the same number of spots, the 20% landscapes began with less edge and saw a greater relative increase in edge. However, in both the 20 and 50% scenarios, suppression of spot growth cut the relative increase in edge in half.

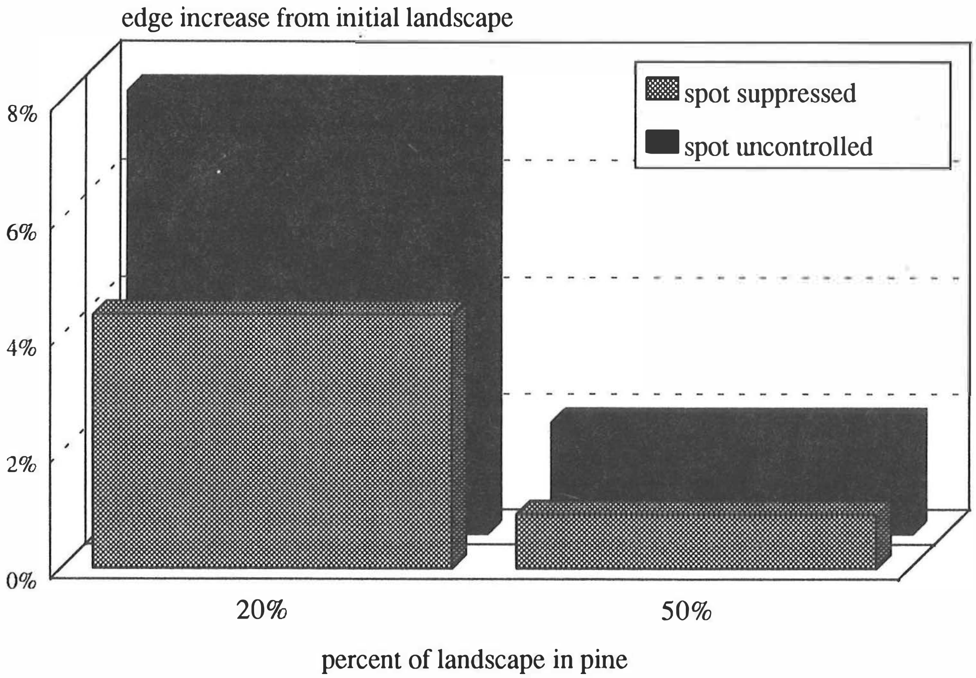


FIG. 8. Impact of spot growth with and without suppression on amount of pine forest edge for landscapes of two pine cover densities. Results are expressed as a percent of pine edge before spot growth.

Perhaps more important than the means is the variability of these estimates. The coefficient of variation for these twenty replications averages 78%, reflecting the high stochasticity of the driving variables. Greater number of replicates will be needed in future.

Visual inspection of resulting landscapes allowed tallying the number of times spots reached stand-to-stand borders. Table 2 below shows that at least for the limited replications available, increasing the frequency with which stands border one another also increases the likelihood of "border incursions" by spots. It is interesting that suppression did not prevent any of the high cover incursions, although it did prevent one in the lower cover runs.

TABLE 2. Number of times when 40 simulated spots reached a stand-to-stand border, by percent of landscape occupied by susceptible stands. Two scenarios are shown: "No control" where spot growth continues to end of season, and "with suppression" where spot growth is stopped after two months.

	20%	50%
no control	3	5
with suppression	2	5

DISCUSSION AND FUTURE DEVELOPMENT

As is often the case, preliminary results show several areas where model processes need improvement. Principal among these are scale of spot width and matrix inclusions.

Scale of spot width refers to how the width of spots should vary for spots of differing growth rates. By contagiously expanding each cell one after the other and simply varying the number of cells added per month, spots vary in length but not width. That is comparable to (incorrectly) assuming that spots grow faster by accelerating their generation time. Instead, rapid growth occurs through greater numbers of simultaneously active trees. Thus spot width should be scaled to the rate of spot growth. This will produce spots of more similar shape across different growth rates.

Matrix inclusions refers to remaining non-host matrix wholly surrounded by a stand. Although inclusions may be common in the field, FIA observations are not likely to recognize small ones. Worse, in the simulations inclusions appear principally in small stands, while in the field they should be more common in large ones. This bias appears to result from scaling changes in the spatial response to the switch point. Inclusions in larger stands are more easily removed by the widening algorithm even for the same proportional opportunity. The best remedy would be to periodically include a filter in all stand creation sequences which removes small inclusions.

Some system limitations may also prove short lived. The next version of SAS for the PC should remove limitations on size of array. While larger landscapes are one useful application of this change, a more fundamental one is use of lookup tables. At present each cell is represented in the matrix by its susceptibility class. With more than one digit permitted in each cell, cells can store their respective stand or spot number. With this change, susceptibility, age, or other factors can be referenced from an augmented stand table. This will provide greater flexibility in modeling response and also facilitate analysis by explicitly retaining original stand and spot identities.

Explicit stating of processes and linkages often proves heuristicly useful, as it has here. It has revealed several gaps in data on the spatial nature of SPB behavior, such as the shape and directionality of growth of SPB spots and preference for edge versus interiors of stands. Also missed is information on the shape of pine stands and how often they adjoin other pine stands. As these data are obtained revisions will be needed to the code.

Several areas have been identified where improvements are required. Most of these are fortunately tractable. Once completed, sensitivity analyses and validation are needed. However, until the basic processes of the model have been validated, its results cannot be interpreted as more than theoretically interesting.

LITERATURE CITED

Bechtold, W.A. and G.A. Ruark. 1988. Structure of pine stands in the Southeast. Asheville, NC: USDA Forest Service Research Paper SE-274. 185 p.

Coulson, R.N. 1981. Population dynamics. pages 71-105 *in* Thatcher, R.C.; Searcy, J.L.; Coster, J.E., and Hertel, G.D., editors, The Southern Pine Beetle. Washington, DC: USDA Forest Service Technical Bulletin 1631. .

Coulson, R.N. and and others. 1993. Spatial analysis and integrated pest management in a landscape ecological context. Pages 93-991 *in* A.M. Liebhold and H.R. Barrett, editors. Proceedings: Spatial Analysis and Forest Pest Management. Radnor, PA: USDA Forest Service General Technical Report NE-175.

de Steiguer, J.E. and R.L. Hedden. 1988. Effects of aerial detection schedules on the age of southern pine beetle infestations. Forest Science **34**: 229-235.

de Steiguer, J.E., R.L. Hedden, and J.M. Pye. 1987. Optimal level of expenditure to control the southern pine beetle. Asheville, NC: USDA Forest Service Research Paper SE-263. 30 p.

Feldman, R.M., G.L. Curry, and R.N. Coulson. 1980. The use and structure of the TAMBEETLE spot dynamics model. Pages 20-29 *in* Stephen, F.M., Searcy, J.L., and Hertel, G.D., editors, Modeling Southern Pine Beetle Populations: Symposium Proceedings. Washington, DC: USDA Forest ServiceTechnical Bulletin No. 1630.

Graham, R.L., C.T. Hunsaker, R.V. O'Neill, and B.L. Jackson. 1992. Ecological risk assessment at the regional scale. Ecological Applications **1**: 196-206.

Hedden, R.L. 1985. Simulation of southern pine beetle-associated timber loss using CLEMBEETLE. pages 288-291 *in* New Orleans, LA: USDA Forest Service General Technical Report SO-56.

Hedden, R.L., and R.F. Billings. 1979. Southern pine beetle: factors influencing the growth and decline of summer infestations in east Texas. Forest Science **25**: 547-556.

Hines, G.S., H.A., Taha, and F.M. Stephen. 1980. Model for predicting southern pine beetle population growth and tree mortality. Pages 4-12 *in* Stephen, F.M., Searcy, J.L., and Hertel, G.D., editors, Modeling Southern Pine Beetle Populations: Symposium Proceedings. Washington, D.C.: USDA Forest Service Technical Bulletin No. 1630.

Leuschner, W.A., H.E. Burkhart, B.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. The Southwestern Entomologist **1**: 141-149.

Porterfield, R.L. and C.E. Rowell. 1981. Characteristics of southern pine beetle infestations southwide. Pages 87-108 *in* Coster, J.E. and Searcy, J.L., editors, Site, stand and host characteristics of southern pine beetle infestations. Washington, D.C.: USDA Forest Service Technical Bulletin 1612.

Pye, J.M. 1993. Regional dynamics of southern pine beetle populations. Pages 111-124 *in* A.M. Liebhold and H.R. Barrett, editors. Proceedings: Spatial Analysis and Forest Pest Management. Radnor, PA: USDA Forest Service General Technical Report NE-175.

Pye, J.M. and K.J. Lee. 1992. Influence of urbanization on forest landscape characteristics in the U.S. South (abstract). Pages 125-126 *in* Fourth North American Symposium on Society and Resource Management, May 17-20. Madison, WI: University of Wisconsin.

Reed, D.D., R.F. Daniels, R.L. Hedden, H.E. Burkhart, and W.A. Leuschner. 1980. A regional southern pine beetle damage projection system. Pages 132-144 *in* Stephen, F.M., Searcy, J.L., and Hertel, G.D., editors, Modeling Southern Pine Beetle Populations.Washington, D.C.: USDA Forest Service General Technical Report No. 1630.

Rykiel, E.J.Jr., R.N. Coulson, P.J.H. Sharpe, T.F.H. Allen, and R.O. Flamm. 1988. Disturbance propogation by bark beetles as an episodic landscape phenomenon. Landscape Ecology **1**: 129-139.

Stephen, F.M., J.L. Searcy, and G.D. Hertel, editors. 1980. Modeling Southern Pine Beetle Populations. Symposium Proceedings. Washington, D.C.: USDA Forest Service, Technical Bulletin No. 1630.

Turner, M.G., R.H. Gardner, V.H. Dale, and R.V. O'Neill. 1989. Predicting the spread of disturbance across heterogeneous landscapes. Oikos **55**: 121-129.

Turner, M.G. and C.L. Ruscher. 1988. Changes in landscape patterns in Georgia, USA. Landscape Ecology **1**: 241-251.

USDA Forest Service, 1988. The South's Fourth Forest: Alternatives for the Future. Forest Resource Report No. 24. Washington, DC: USDA Forest Service. 512 pp.

TWO APPROACHES TO LANDSCAPE CHARACTERIZATION OF SUSCEPTIBILITY TO GYPSY MOTH DEFOLIATION

GREGORY A. ELMES
Department of Geology and Geography, West Virginia University, Morgantown WV 26506

ANDREW M. LIEBHOLD AND MARK J. TWERY
USDA Forest Service, Northeastern Forest Experiment Station, 180 Canfield St., Morgantown, WV 26505

ABSTRACT. Susceptibility of hardwood forests to defoliation by the gypsy moth, *Lymantria dispar* (L.) is related to components of the landscape. In order to clarify processes operating at different geographical scales, results from two studies are presented: 1) at the forest community scale and 2) at the regional scale. First, a model of stand susceptibility is built on the basis of the relationship of forest species composition to topographic features. Second, a relative frequency model of susceptibility is investigated for Pennsylvania. Both approaches use geographical information system (GIS) operations as a integrative tool for environmental modeling. Because forest species composition is a difficult and expensive set of data to obtain for large areas, GIS is particularly valuable in cases where maps of forest species are deficient. Forest species groups occupy locations differentiated by growth requirements; these distinctions can be estimated from elevation, slope, and aspect. Digital elevation model (DEM) data is interpreted in a GIS, along with other pertinent information to construct most-likely species composition units. In the first study, DEM data at 1:24,000 for the West Virginia University Forest were converted to a triangular irregular network structure (TIN). Slope position and aspect were calculated seperately from the TIN. An ecological unit classification was generated from a combination of slope and aspect. Forest types associated with these ecological units were used to estimate susceptibility. In the second study, susceptibility was characterized at the regional landscape scale. Maps of gypsy moth defoliation in Pennsylvania from 1969-89 were assembled in a raster-based GIS. Boolean algebra was applied to determine the total defoliation frequency for 2 by 2 km grid cells over the twenty-one year study period. Average defoliation probabilities were calculated for each of 6 major forest types occurring in Pennsylvania. Pitch pine, oak-pine, and oak-hickory types were the most susceptible to defoliation; maple-birch-beech, aspen-birch, and non-forest types were the least susceptible. Forest type areas were further cross-tabulated by elevation classes. The three most susceptible forest types exhibited decreased susceptibility at elevations lower than 200 m. Although these studies illustrate directions for landscape methods in susceptibility assessment, the quality of spatial data of forest type is a limiting factor and is an essential component for future development.

INTRODUCTION

The concept of susceptibility is central to resource evaluation, conservation, and protection in forest pest management. Because of the widespread distribution of gypsy moth (*Lymantria dispar* L.) in North America, a number of questions have been generated about the characterization of forest susceptibility at different scales. This paper presents results from two studies of susceptibility that have particular emphasis on the influence of the landscape. In each example, defoliation by the gypsy moth is related to components of the landscape to study processes operating at local and regional scales. Knowledge of forest species association, landscape features, and defoliation patterns are integrated in geographic information systems (GIS) for analysis, hypothesis testing, and modeling. To establish links between the two approaches, we first review the botanical and geographical precursors of susceptibility. Second, we

---

Pages 172-183 *in* A.M. Liebhold and H.R.Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

examine topographic relationships to defoliation at the stand level, and propose a model to estimate susceptibility in the absence of detailed forest species data. Third, a regional landscape approach is reported using defoliation data collected in Pennsylvania during a twenty-year period and digital elevation data in a GIS.

Since the time of its accidental introduction near Boston in 1869, the gypsy moth has expanded its range to include all of New England and adjacent southeastern Canada, and is currently spreading across the Middle Atlantic states to Ohio, West Virginia, Virginia, and North Carolina (Liebhold et al. 1993). A second isolated defoliating infestation exists in Michigan. In 1991, an Asian variant was inadvertently introduced to the northwestern US. In many forests where this species has become established, populations sporadically reach very high densities and cause extensive defoliation of their host trees. Outbreaks increase tree mortality, reduce tree growth, decrease scenic quality, and create nuisance to residents (Campbell and Sloan 1977, Twery 1991). Scientific interests in the effects of gypsy moth range from the economic and ecological effects of losses of timber, consequences for species diversity, the level of scenic impacts, destruction of wildlife habitat, and the deleterious effects on watersheds. Because of the intensity and importance of these impacts, considerable effort is expended to reduce gypsy moth populations to non-defoliating densities. Pest control options and management options are in part dependent on the degree to which susceptibility can be estimated.

Unfortunately, although a substantial literature exists on insect-host relationships at the plant scale, little information exists on either gypsy moth dynamics or the distribution of susceptible forests at the regional level (Liebhold and Elkinton 1989).

Studies of the association of forest characteristics with gypsy moth defoliation have largely focused on site characteristics at the stand level (i.e. woodlots of 10-100 ha). Little is understood of the relationship between landscape-scale features and gypsy moth defoliation. Understanding relationships among landscape processes across spatial scales is necessary to develop more meaningful ecological models. Furthermore, emphasis is increasing on region-wide planning of natural resource management, including gypsy moth management (Forman 1988; Ravlin 1991; Reardon et al. 1987). An ability to forecast gypsy moth defoliation at different scales will be a valuable contribution to these region-wide systems.

MEASURES OF SUSCEPTIBILITY

The gypsy moth is a polyphagous insect; North American populations feed on over 300 different tree and shrub species (Leonard 1981) but despite this breadth of host preference, there is considerable variation within northeastern North American forests in their susceptibility to defoliation. A working definition of susceptibility begins with measures of defoliation probability. One operational definition of susceptibility, "the likelihood that a stand will be defoliated", is based on the relative frequency that stands with similar characteristics are defoliated (Gottschalk, 1986; Mason and Gottschalk, 1986). Clearly, susceptibility is insect species-specific (the same location may be susceptible to one pest and resistant to a second) but it is also location and scale dependent. Whereas locations vary in susceptibility at one scale of resolution (e.g. at the tree level), a different areal unit will result in different estimations of susceptibility. The appropriate choice of areal units depends on the information needs of resource managers. The degree of mortality or growth loss is termed vulnerability and, although both susceptibility and vulnerability are important to management decisions, the scope of this paper will be restricted to susceptibility.

For the purposes of constructing a model of forest susceptibility, the measurement of susceptibility at the stand level may be developed from botanical, geographical, and silvicultural precursors.

Botanical Precursors

Many studies have focused on characterization of the various components of stand susceptibility. These studies have implicated tree density, host species tree density, the abundance of tree structural features (e.g. bark flaps), and various site characteristics (e.g. soils) as important factors for predicting defoliation in a given woodlot (Bess et al. 1947; Valentine and Houston 1979; Herrick and Gansner 1986). Botanical characteristics have a significant and direct control on susceptibility at a given location, especially species (type and composition), and age (Gottschalk 1988).

Susceptibility is not equal for all tree species (Gansner et. al. 1987) and is principally determined by gypsy moth larval feeding preferences (Mosher 1915; Montgomery 1991). Twery (1991) presented three susceptibility classes, *susceptible*: comprising forest species readily eaten by gypsy moth larvae during all larval stages; *resistant*: species fed upon when preferred foliage is not available or only by some larval stages; and *immune*: species that are rarely fed upon. Table 1 groups the major North American forest species according to this classification. The preference of gypsy moth for oak species (Quercus spp.) is well established, but it should be noted that not all oaks are equally preferred. The survival of the first instar is dependent on the availability of susceptible species (Mason and Gottschalk, 1986). Although susceptibility among and between species may vary with numerous leaf characteristics, the ratio of sugar to tannin in young foliage plays a significant role (Lechowicz 1983). As the sugar/tannin ratio is affected by various stresses (drought, previous defoliation, fire, etc.) the susceptibility of the individual tree, and even of leaves within the crown, may vary from growing season to growing season. The relationship of high tannin levels to higher susceptibility is also supported by Montgomery (1991). White oak is highly preferred by gypsy moth larvae because of its leaf chemistry and structural features of the tree. Montgomery (1991) has found that most oaks are suitable hosts with regard to larval growth, survival, and developmental progress.

TABLE 1. Categorization of gypsy moth host preferences (after Twery, 1991)

Susceptible:	
Overstory	apple, basswood, bigtooth and quaking aspen, gray, paper and river birch, larch, mountain ash, all oak species, sweetgum, willow.
Understory	hawthorn, hazelnut, hophornbeam, hornbeam, serviceberry, witch-hazel.
Resistant:	
Overstory	beech, black and yellow birch, blackgum, buckeye, butternut, sweet and black cherry, eastern cottonwood, cucumbertree, elm, hackberry, all hickory species, boxelder, Norway, red and sugar maple, pear, sassafras, black walnut, chestnut, eastern hemlock, all pine species, all spruce species.
Understory	blueberry, pin and choke cherry, paw, persimmon, redbud, sourwood
Immune:	
Overstory	all ash species, bald cypress, northern catalpa, eastern red cedar, balsam and fraser fir, American holly, horsechestnut, Kentucky coffeetree, black and honey locust, mulberry, sycamore, yellow poplar.
Understory	all azalea species, dogwood, elderberry, grape, greenbrier, juniper, mountain and sheep laurel, mountain, silver, and striped maple, rhododendron, all rubus species, spicebush, sarsaparilla, all viburnum species.

Relationships within the stand, including tree location, canopy position, leaf biomass, and even leaf position, have all been shown to influence susceptibility at the individual plant scale.

Geographical Precursors

Site factors play a critical role in susceptibility. In most landscapes currently infested by defoliating gypsy moth populations, trees grow in mixed stands strongly influenced by growing conditions. Forest composition is influenced by the relative proportions of controlling variables such as light, growing degree days, moisture availability, and nutrients. The absolute and relative quantities of the controlling variables are themselves directly and indirectly influenced by topographic characteristics. Therefore, species composition is strongly related to topographic variables such as aspect, elevation, and slope position. Soil type, quality, and drainage properties, inherently tied to topography and vegetation, also influence susceptibility.

Forest composition with regard to the proportion and distribution of susceptible trees will directly influence the overall or areal susceptibility which is in turn influenced by the scale of analysis. Interdependence effects in time and space (spatial autocorrelation, multicollinearity, temporal lags) are not yet well understood and create significant difficulties in estimating causal relationships between variables influencing forest composition and hence susceptibility.

TOPOGRAPHIC APPROACH TO SUSCEPTIBILITY

In general, GIS investigation is enabled by the processing of multiple layers of geographical data (map layers) each coordinated to the others by means of geo-reference points. Digital Elevation Model (DEM) data consist of regular arrays of elevations aligned on a geographic coordinate system that can be manipulated and associated with other map layers in a GIS (Elassal and Caruso, 1983). Raster-based (grid cell) algorithms to find ridges and valleys have evolved from 2x2 moving windows to mathematically straight forward and more complex drainage basin models (Band 1986). In contrast to the raster-based approaches, Frank, Palmer, and Robinson (1986) proposed the use of edges and nodes contained in a triangulated irregular network (TIN) to define topographic features. Diffluent edges, where slopes are negative on both sides of the edge, define ridge lines; confluent edges identify valleys and transfluent edges indicate longer slope facets. Slope position and aspect are derived from the DEM through the manipulation of the attributes of edges and vertices in the TIN. The TIN partitions the DEM into irregular triangles with vertices situated at significant points. Local spatial relations depend on the elevation of the vertices and the distance and direction between them. Edge length, slope, relation to adjacent TIN facets, facet slope, and aspect are each derived from these local relations. Relations between edges and facets are established by means of relational joins between tables in the database using primary keys such as edge and facet identification labels. Selection by specific criteria is then possible using a database query language.

A set of rules derived from expert opinion has been used to predict species composition on a 3000 hectare forest in northern West Virginia. These rules, incorporated into ARC-INFO, a geographic information system, processed DEM data to generate and evaluate probable species composition. The sets of rules to relate topographic units to forest species composition encompass the topographic province (e.g. Allegheny Plateau); local topographic variables, for example elevation, aspect, slope, and slope position; Potential species associations; and most likely local species composition identified on the basis of regional and local topographic characteristics (Twery et. al., 1991).

A slope position map layer was generated with standard ARC-INFO functions, such as buffering and overlay, in combination with the rules encoded as database queries, e.g. reselection on the basis of percentage slope and slope length thresholds appropriate to the physiographic province. Five classes of slope position were established: ridge, upper slope, mid-slope, lower slope, and channel. Digital elevation data for the West Virginia University Forest at 30 meter resolution were converted to TIN structure. Database queries were conducted on the attribute tables to identify those TIN arcs having divergent and convergent slopes. First, ridge lines were identified using rules to extract divergent edges from the arc attribute table. A second query isolated divergent edges forming relatively horizontal ridge tops. The two queries yielded a map coverage with 800 arcs which were then buffered to define ridge tops and upper slope areas. A similar set of queries was developed to extract channels from the data set. Buffer widths were chosen empirically at this stage to reflect the determination of landscape scale by the character of the topographical province, in this case the Allegheny Plateau. A boolean join operation was performed on the buffered ridge and channel coverages. Conditions for a classification of slope position based on the intersection of ridge and channel buffer zones are listed in Table 2.

TABLE 2. Slope position classification. Class, Percentage of study area, and number of polygons (in parentheses).

		CHANNEL		
		BOTTOM	MID	NOT
RIDGE	TOP	conflict 11.67 (886)	upper slope 11.76 (1484)	ridge 10.54 (763)
	MID	lower slope 6.65 (1429)	midslope 18.61 (1542)	upper midslope 20.93 m (1045)
	NOT	channel 2.30 (322)	lower midslope 6.58 (780)	neither 10.96 (174)

An aspect map generated from the DEM was also joined to slope position to produce a composite slope position-aspect map. The areal units of this map were considered to be rudimentary ecological units as they contain information about some major influences controlling forest species. Using data gathered from forestry literature a look-up table was created linking slope position-aspect units with the most-likely forest cover type (Table 3). Table 3 became the basis for a reclassification of the ecological units into an estimated forest species map, and hence of susceptibility to gypsy moth defoliation.

TABLE 3. Predicted cover type by aspect, slope position, and percentage of oak in the stand. (from Twery et al. 1991).

	SLOPE POSITION				
	Cover Type* (percentage oak in stand)				
ASPECT	RIDGE	UPPER SLOPE	MIDSLOPE	LOWER SLOPE	CHANNEL
N	55 (50)	55 (40)	59 (30)	57 (15)	58 (5)
NE	55 (50)	55 (40)	55 (40)	57 (20)	58 (10)
E	52 (60)	52 (60)	55 (50)	57 (25)	57 (15)
SE	52 (70)	52 (60)	55 (60)	59 (30)	57 (20)
S	44 (80)	44 (70)	52 (70)	55 (40)	57 (25)
SW	44 (90)	44 (80)	44 (70)	52 (50)	59 (25)
W	44 (80)	52 (60)	52 (50)	59 (30)	59 (25)
NW	55 (50)	52 (50)	59 (30)	57 (20)	58 (10)
NONE	52 (60)	N/A	N/A	N/A	58 (10)

* SAF cover type (Eyre 1980) classifications:
44 - Chestnut oak (*Quercus prinus*)
52 - White oak (*Q.alba*), Black oak (*Q. velutina*), and Northern red oak (*Q. rubra*)
55 - Northern red oak
57 - Yellow-Poplar (*Liriodendron tulipifera*)
58 - Yellow-Poplar, Hemlock (*Tsuga canadensis*)
59 - Yellow-Poplar, White oak, Northern red oak

Attempts were made to refine the quantitative definition of ridge and channel on the basis of geographical dictionaries (Monkhouse, 1970). Dictionary definitions were found to be sufficiently imprecise to permit only arbitrary quantitative definitions. Band (1986) recognizes the need for objective criteria for ridge and valley identification. Similarly Frank, Palmer, and Robinson (1986) discuss the difficulties in describing geomorphological features in English and suggest that refined definitions are needed before quantitative analysis of these features is possible. Further experimentation and rules development for buffer size and slope criteria may provide insight for this particular study. Geographers are again faced with serious questions of the theory of landscape and the spatial language necessary for its description and analysis.

This method lends itself to an incremental approach to knowledge acquisition and is applicable across scales. Some success in validation has been achieved through the addition of digitized hydrology data. Additional sources, such as soil maps, are currently being incorporated to improve correlations with forest composition. Similar arguments can be presented for the inclusion of rules describing the control of geology, pedology, hydrology, and climate on slope form at both the meso and micro scales. A promising model using decision tree analysis has recently confirmed the value of rule based methods for predicting vegetation classes in eastern Australia (Moore et al.,1991). Modelling ecological units using topographically derived variables, combined with geological data and vegetation samples is now clearly established and may be extended to susceptibility analysis.

LANDSCAPE ANALYSIS OF REGIONAL SUSCEPTIBILITY

The IDRISI software (Eastman, 1987, 1989) was employed to assemble, collate, and analyze gypsy moth defoliation data at the regional scale. IDRISI is a raster-based (grid cell) GIS for capturing, storing, analyzing and displaying geographical data, designed for research applications. A base map of Pennsylvania county boundary coordinates was used to define the study area. A 2 x 2 km grid cell size was selected as standard for all map layers in the GIS. The grid size selected represented the minimum dependable spatial resolution of the defoliation data available from the Pennsylvania Department of Forest Resources.

Spatial error is unavoidably generated in the process of recording defoliation on sketch maps from aircraft (Talerico 1981). Error occurs with respect to the exact location, degree, and areal extent of defoliation, but this locational error is generally less than 1 km in magnitude. The choice of such a coarse scale of resolution raises serious issues concerning data accuracy and the cascading effect of errors as data layers are manipulated. Without corroborating evidence at a fine scale of resolution it is not possible to provide accurate estimates of the errors.

The Pennsylvania Department of Forest Resources monitors gypsy moth defoliation annually in all parts of the state using aerial sketch maps in late July when defoliation is at its peak. Thirty percent (30%) defoliation is considered the lower threshold for detection from the air. In situations where there is doubt as to the cause of the defoliation, ground checks for the presence of gypsy moth life stages are made. Initially the aerial sketch maps are overlaid on standard U.S. Geological Survey (1:24,000) topographical maps. Subsequently a composite mosaic is generated for the entire state at 1:1,000,000 scale. Mapping processes vary from region to region and year to year within Pennsylvania, resulting in a strong likelihood of significant data errors from systematic and non-systematic sources. The likely presence of these errors dictated the coarse spatial resolution of this study (2 x 2 km grid cells).

To create a uniform set of geographically referenced defoliation data, the composite maps for the period 1969 to 1989 were first transferred to mylar stable-base sheets and scanned. Data were transformed to a common base map resolution and projection by "rubber-sheeting". In transforming maps of various scales and projections, IDRISI resamples each scanned defoliation image to match the location of the four geo-reference points on the base map (Eastman 1987).

Elevation data for Pennsylvania were obtained from U.S. Geological Survey 1:250,000 Digital Elevation Models (DEM) (Elassal and Caruso, 1983). The sampling interval was 270 meters providing at least fifty (50) sampling points within each 2 km grid cell. Rubber-sheeting procedures were again used to resample these data into the same scale of resolution and projection as the base map.

Forest cover type information was extracted from a 1:7,500,000 scale map published by the Society of American Foresters (SAF) (Eyre 1980). This map delineates the distribution of the major forest types of the United States. Data collected by the U.S. Forest Service Forest Inventory and Analysis (FIA) project in 1967 were used to generate this map (Kingsley, 1985). FIA recognized six forest types in Pennsylvania: 1) Pine, 2) Oak-pine, 3) Oak - hickory, 4) Maple - beech -birch, 5) Aspen -birch and 6) non-forest ("land that has never supported forests and land formerly forested which is now developed for other uses" [Eyre 1980]). Any designation of an area as a specific forest type from these data is subject to uncertainty because the FIA map is highly generalized both in its spatial resolution and in its designation of forest types in broad catagories. For example, the oak hickory type used in the FIA map within Pennsylvania encompasses at least 12 more specific forest types in the SAF system (Eyre 1980). Nevertheless, this forest type map does represent a valuable classification system of forests for a large area, such as used in this analysis. The forest type map was digitized as a vector map and converted to a raster image in the IDRISI system (Figure 1).

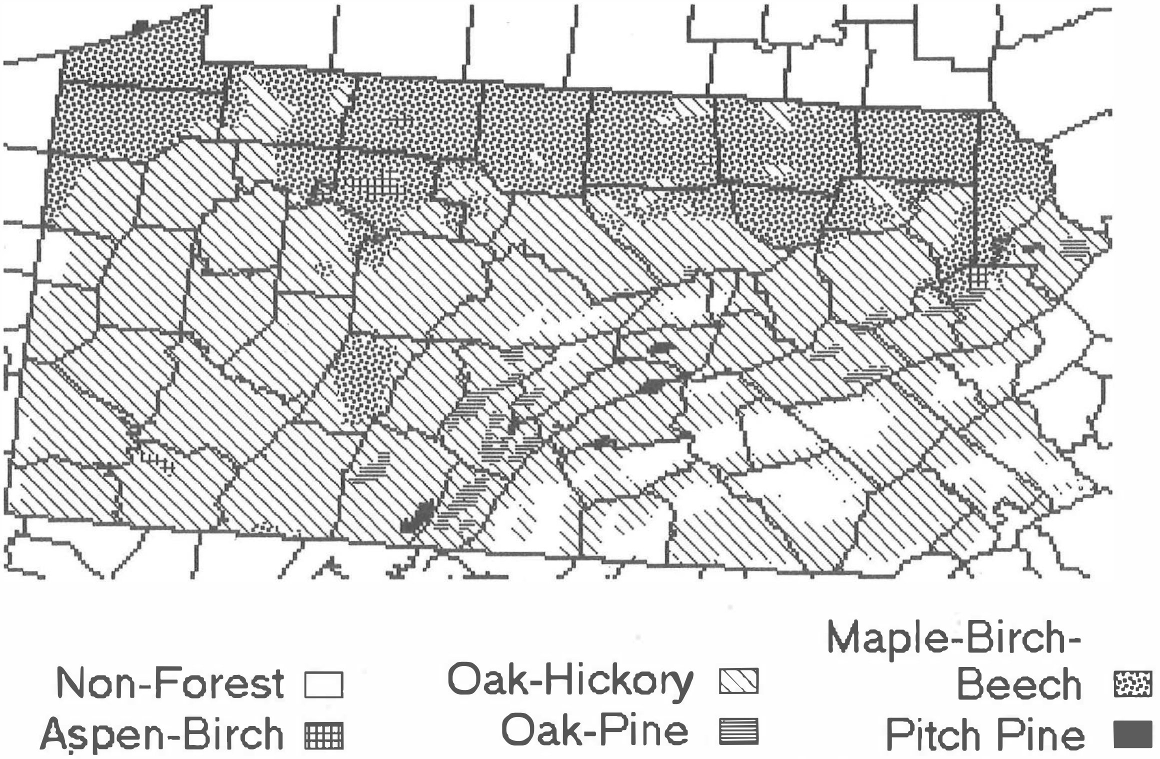


FIG. 1. Forest types of Pennsylvania (data prepared by U.S.D.A. Forest Service, Northeastern Forest Experiment Station; digitized from Eyre (1980)).

MAPPING SUSCEPTIBILITY TO GYPSY MOTH

Because consistent interpretation of the intensity of defoliation was unavailable, defoliation was assigned a simple binary classification (0 = no defoliation, 1 = defoliation). The modified defoliation maps from 1969 - 1989 were overlaid and coincident grid cells summed to obtain the total number of years of defoliation for each grid cell (Figure 2). Maps of cumulative defoliation derived from a relatively long time-series, such as is used here, describe the regional distribution of susceptibility to gypsy moth. Areas having a high total number of years of defoliation are relatively susceptible to gypsy moth (Liebhold and Elkinton 1989). An unavoidable assumption of this technique is that pest management and suppression activities have not introduced any systematic bias at the chosen scale of analysis.

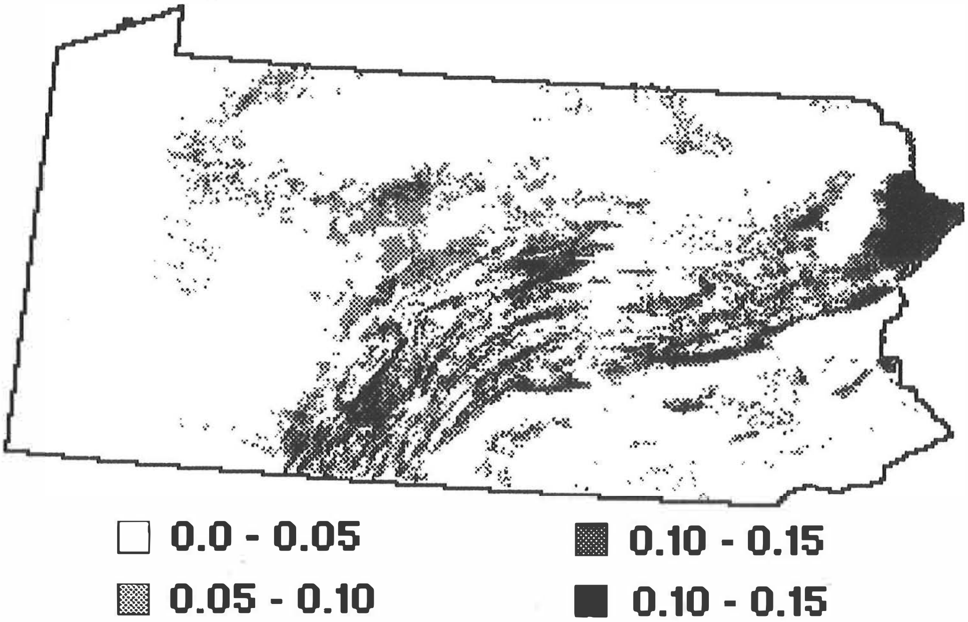


FIG. 2. Total years of defoliation in Pennsylvania (1969-89).

An identifiable potential source of bias in using the accumulated defoliation map as representing susceptibility is that gypsy moth populations have not been present in all parts of Pennsylvania over the study period. The range of gypsy moth has slowly expanded southwestward across the state during this interval. On an annual basis, the U.S. Department of Agriculture designates portions of the country that are part of the "generally infested area" for purposes of enforcement of quarantine regulations in this area. A detailed description and analysis of these data are described elsewhere (Liebhold et al. 1992). Since an area is designated as quarantined when relatively low densities of gypsy moth life stages are detected, there is arguably a lag period between the time of quarantine and the time of first defoliation in an area. We estimated this lag as the intercept, b_0, of the linear model,

$$D_i = b_0 + Q_i$$

where D_i is the year of first defoliation in county i and Q_i is the year of first quarantine in county i. By forcing a slope of 1, b_0 was estimated as 5.04 ± 0.24 using a linear regression procedure on the 45 counties in Pennsylvania. To maintain consistent levels of precision, we rounded this value to 5 for all further analyses.

Results from the linear model were incorporated to calculate an enhanced index of susceptibility for each grid cell (Figure 3). The value was calculated as the sum of the years defoliated divided by the number of years at risk to defoliation. Here we defined the number of years at risk to defoliation as the number of years during the sampling interval (1969-1989) during which the county in which the grid cell was located was quarantined, minus 5, the estimated value of the defoliation lag in years. Extrapolating gypsy moth susceptibility from an interval of less than 10 years leads to spurious results because of the sporadic spatial and temporal distributions of defoliation. Comparison with the simple accumulated defoliation frequencies shows that adjusting for years at risk caused many areas in the south-central portion of the state to increase susceptibility to levels similar to the northeast, as would be anticipated on the basis of forest distribution.

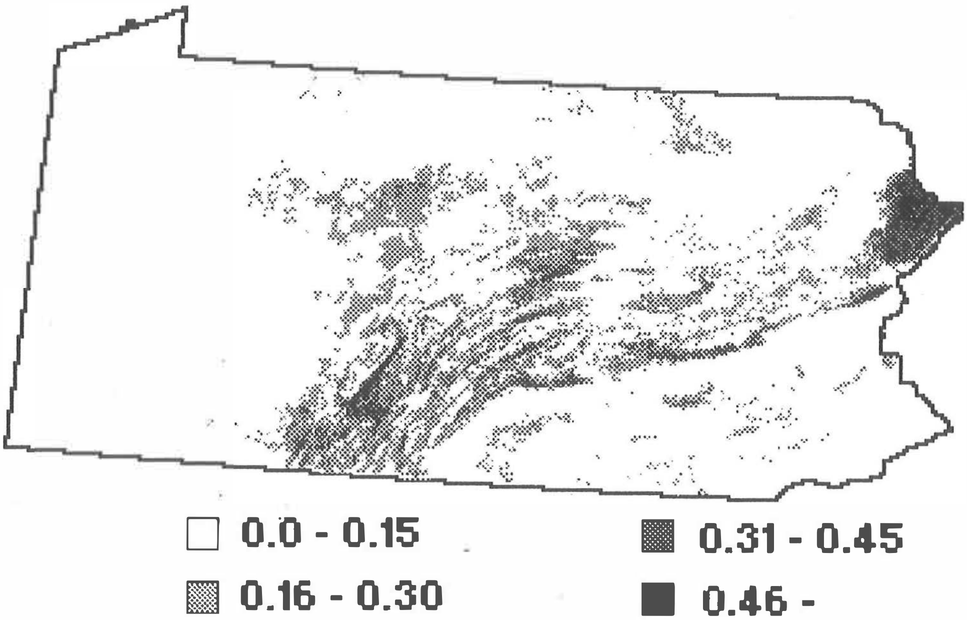


FIG. 3. Adjusted defoliation frequency (total years defoliated divided by years at risk to defoliation).

Association of Susceptibility with other Landscape Features

The relationship between forest type and gypsy moth susceptibility was determined by overlaying the susceptibility map layer (Figure 3) with the forest type layer. The relative levels of regional susceptibility reported in Table 4 agreed with previous empirical studies of susceptibility at the stand level (Bess et al. 1947, Valentine and Houston 1979, Herrick and Gansner 1986). Defoliation frequency was greatest in the pine, oak-pine, and oak-hickory types, and was least in the maple-birch-beech, aspen-birch, and non- forest types. The finding that the non-forest areas were defoliated at all reflects the coarse spatial scale of the forest type map. There are undoubtedly host trees within areas classified as "not forested".

TABLE 4. Area and gypsy moth defoliation statistics for the six major forest types in Pennsylvania. All data extracted only from portions of Pennsylvania which were quarantined by 1975 (see text for explanation).

Forest Type	No. of km^2	Mean Defoliation Frequency	Adjusted Defoliation Frequency[1]
aspen-birch	664	0.19 ± 0.44	0.036 ± 0.084
non-forest	10,884	0.31 ± 0.76	0.044 ± 0.105
maple-birch-beech	25,750	0.33 ± 0.67	0.056 ± 0.114
oak-hickory	62,812	1.35 ± 1.52	0.200 ± 0.220
oak-pine	2,200	1.98 ± 1.74	0.286 ± 0.225
pine	380	2.64 ± 1.93	0.415 ± 0.226

[1] Adjusted frequency = Defoliation frequency divided by years at risk. Years at risk is defined as years quarantined - 5.

Because the forest type categories used in Figure 1 are so broad, we attempted to extend our landscape characterization of defoliation susceptibility by including elevation information. The resultant map was then combined with gypsy moth susceptibility and the average susceptibility was calculated for each forest type - elevation combination (Figure 4). Averages calculated from less than 15 raster cells (2 x 2 km) per forest type - elevation combination were not included.

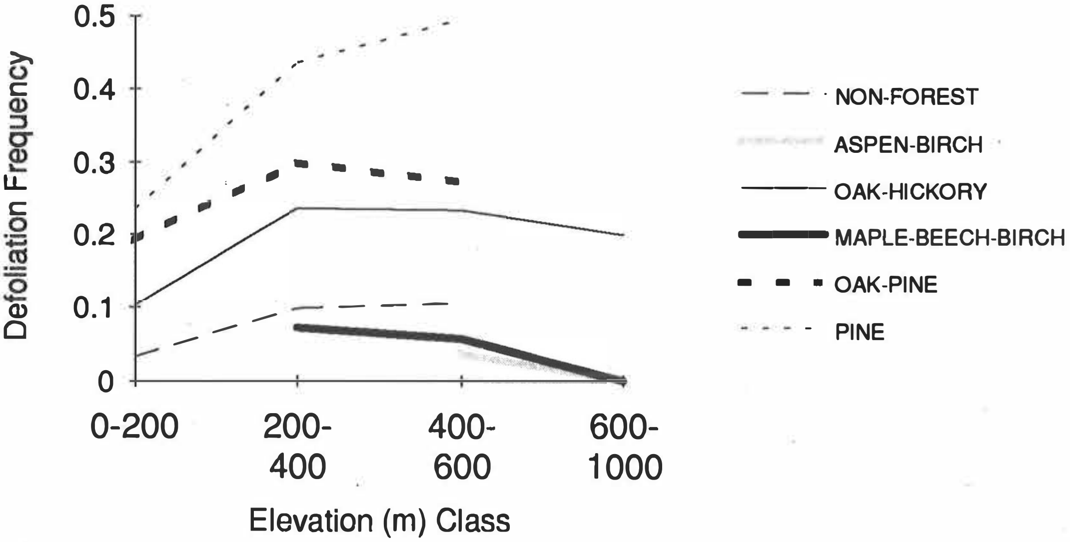


FIG. 4. Defoliation frequency of each forest type - elevation combination in Pennsylvania. OLD 9

The pine type consistently had the highest susceptibility at all elevations though this type covered a very small total area. The oak-pine and oak-hickory types both had high susceptibilities at all elevations, peaking in the 201-400 m. elevation class. The non-forest, oak-hickory, oak-pine, and pine types all exhibited reduced susceptibility at the lowest elevation class. The aspen-birch and the maple-beech-birch defoliation frequencies both declined at the highest elevation class. These patterns reflect the broad nature of the 6 forest types represented in Figure 1. Areas covered by each of these types are actually composed of many other, more detailed types, (Eyre 1980); the prevalence of these sub-types is likely different at various elevations. Furthermore, these sub-types undoubtedly vary in their susceptibility. For example, the black locust, chestnut oak, and yellow-poplar types recognized by SAF (Eyre 1980) are represented by the same oak-hickory type described by FIA. The black locust and yellow-poplar types are more common at low elevations and both are considered types resistant to gypsy moth defoliation. In contrast, the chestnut oak type is less common at low elevations and is highly susceptible to defoliation (Houston and Valentine 1977). This type of difference would thus explain the decreased defoliation frequency lower elevations within the oak-hickory type. In addition, what is recorded as a pine type in Pennsylvania is actually a mixture of chestnut oak and pitch pine, usually found on ridge tops. Although the pine itself is rarely defoliated, there is ample chestnut oak to support outbreaks of gypsy moth.

CONCLUSIONS

There was a high similarity between the landscape-level characterization of forest susceptibility and previous characterizations performed on a stand level (Bess et al. 1947, Valentine and Houston 1979, Houston and Valentine 1977, Herrick and Gansner 1986). At the landscape level oak-pine forests are generally the most susceptible to defoliation and, as expected on the basis of food preference, forests with a low component of oak are the least susceptible. As demonstrated by the first study, these forest types are strongly influenced by slope position and aspect. Lower susceptibility at elevations less than 200 m indicates the relationship between forest type and elevation and demonstrates how a GIS can be used to refine the representation of forest susceptibility by incorporating additional landscape characteristics. In the future, stand type characterizations derived from remotely sensed data may provide more detailed predictions of susceptibility on the landscape level. The integration of multiple types and sources of information now feasible through GIS should be useful for predicting with greater accuracy what portions of the currently uninfested portions of North America will ultimately be at higher risk to defoliation by gypsy moth. This information, along with predictions of the future expansion of the gypsy moth-infested region, will be useful in long-range planning in currently uninfested areas and in multiple agency, regional control efforts. While these studies illustrate promising directions for research in landscape methods for susceptibility assessment, the quality of spatial data of forest type has been a limiting factor for verification and validation. Improved forest type information at a regional scale is an essential component for future developments of these approaches and for their integration into management methods.

LITERATURE CITED

Band, L.E. 1986. Topographic partition of watersheds with digital elevation models. Water Resources Research. **22**(1): 15-24.

Bess, H..A., S.H. Spurr, and E.W. Littlefield. 1947. Forest site conditions and the gypsy moth. Harvard Forest Bull. **22**. 56 p.

Campbell, R.W., and R.J. Sloan. 1977. Forest stand responses to defoliation by the gypsy moth. Forest Science Monograph **19**. 34 pp.

Carter, J.R. 1988. Digital representations of topographic surfaces, Photogrammetric Engineering and Remote Sensing, **54**(11):1577-1580.

Chen, Z. 1989. A spatial low pass filter working for Triangular Irregular Network (TIN) and restricted by break lines. Proceedings of Auto Carto. **9**:138-145.

Frank, A.U., B. Palmer, and V.B. Robinson, 1986. Formal methods for the accurate definition of some fundamental terms in physical geography. Pages 583-599 *in* Proceedings of the Second International Symposium on Spatial Data Handling.

Eastman, J.R. 1989. IDRISI: a Grid-Based Geographical Analysis System. Clark University, Worcester, MA.

Elassal, A.A., and V.M. Caruso. 1983. Digital elevation models. U.S. Geol. Surv. Circ. **895-B**. 40 pp.

Elmes, G.A., E.K. Fugikawa, and M.J. Twery. 1991. Forest cover type estimation from digital elevation data. Pages 389-395 *in* Proceedings of the Eleventh Annual ESRI Conference, Redlands, CA..

Eyre, F.H. 1980. Forest Cover Types of the United States and Canada. Society of American Foresters, Washington. 148 pp.

Forman, R.T.T. 1988. Landscape ecology plans for managing forests. *in* Is Forest Fragmentation a Management Issue in the Northeast?. Degraaf, R.M and Healy, W.M. editors. USDA For. Serv. Gen. Tech. Rep. NE-140.

Herrick, O. W. and D.A. Gansner. 1986. Rating forest stands for gypsy moth defoliation. USDA For. Serv. Res. Pap. NE-583. 4 pp.

Houston, D.A., and H.T. Valentine. 1977. Comparing and predicting forest stand susceptibility to gypsy moth. Can. J. For. Res. **7**:447-461.

Kingsley, N.P. 1985. A Forester's Atlas of the Northeast. USDA For. Serv. Gen. Tech. Rep. NE-95. 96 pp.

Leonard, D.E. 1981. Bioecology of the gypsy moth. Pages 9-29 *in* The gypsy moth: Research toward integrated pest management. Doane, C.C. and M.L. McManus, editors.. USDA Tech. Bull. 1584.

Liebhold, A.M. and J.S. Elkinton. 1989. Characterizing spatial patterns of gypsy moth regional defoliation. For. Sci. **35**:557-568.

Liebhold, A.M., J.A. Halverson, and G.A. Elmes. 1993. Gypsy Moth Invasion In North America: A Quantitative Analysis. J. of Biogeography 19: 513-520.

Monkhouse, F.J. 1970. A Dictionary of Geography, 2nd ed. Chicago: Aldine Publishing Company.

Moore, D.M., B.G. Lees, and S.M. Davey. 1991 A new method for predicting vegetation distribution using decision tree analysis. Environmental Management. **15**(1):59-71.

Ravlin, R.W. 1991. Development of monitoring and decision-support systems for integrated pest management of forest defoliators in North America. Forest Ecology Management. **39**:3-13.

Reardon, R., M. McManus, D. Kolodny-Hirsch, R. Tichenor, M. Raupp, C. Schwalbe, R. Webb, and P. Meckley. 1987. Development and implementation of a gypsy moth integrated pest management program. J. Arbor. **13**:209-216.

Scarlatos, L.L. 1990. An automated critical line detector for digital elevation models. ACSM-ASPRS Technical Papers-Cartography, Bethesda, MD. **2**:43-52.

Skidmore, A.K. 1989. A comparison of techniques for calculating gradient and aspect from a gridded digital elevation model. International Journal of Geographical Information Systems. **3**(4):323-334.

Skidmore, A.K. 1990. Terrain position as mapped from gridded digital elevation models. International Journal of Geographical Information Systems. **4**(1):33-49.

Talerico, R.L. 1981. Defoliation as an indirect means of population assessment. Pages 38-49 *in* The gypsy moth: Research toward integrated pest management. Doane, C.C. and M.L. McManus, editors. USDA Tech. Bull. 1584.

Twery, M.J. 1991. Effects of defoliation by gypsy moth. Pages 27-39 *in* K.W. Gottschalk, M.J. Twery, and S.I. Smith, editors. Proc. U.S. Dept. Agric. Interagency Gypsy Moth Research Review - 1990. U.S. Dept. Agric. For. Serv. Gen. Tech. Rep. NE-146.

Twery, M.J., G.A. Elmes, and C.B. Yuill. 1991. Scientificexploration with an intelligent GIS: predicting species composition from topography. AI Applications in Natural Resource Management **5**(2):45-53.

Valentine, H.T., D.R. and Houston. 1979. A discriminant function for identifying mixed-oak stand susceptibility to gypsy moth defoliation. Forest Sci. **25**:468-474.

SUMMARY OF WORKSHOP DISCUSSIONS ON THE FUTURE OF SPATIAL ANALYSIS AND FOREST PEST MANAGEMENT

compiled by:
ANDREW M. LIEBHOLD
USDA Forest Service, Northeastern Forest Experiment Station, Morgantown, WV 26505

On the final day of the "Spatial Analysis and Forest Pest Management" workshop, discussions were held to synthesize material from the paper presentations and identify needs for future research and development in spatial analysis applications to forest pest management. These discussions were held in three groups that were assigned one of three topics: 1. use of landscape data in hazard-rating, 2. spatial structure of monitoring and decision-making systems, and 3. spatial statistics and models. The following represents a summary of discussions by workshop participants. This material documents the work and ideas of all participants. The organizers of the workshop commend the participants for their insight and dedication to this topic.

EVALUATING HAZARD TO FOREST PESTS

Characterizion of landscape susceptibility and or hazard to forest pest outbreaks is an area where spatial analysis will become increasingly useful. Several examples can be found in these proceedings where groups have used landscape-level data assembled as map layers in a geographical information system (GIS) to map pest hazard.

Spatial scale is an important consideration when studying landscape susceptibility. Susceptibility can be viewed from the individual tree level, the stand level, the district level, or even larger regional levels. Most of the examples to date have focused on the examination of susceptibility / hazard at the stand level because this is the resolution of most available data (e.g. National Forests collect compartment data). Other spatial scales may also be important, depending upon the nature of forest management. More research is needed on how pest impacts (such as water-quality, wildlife, regional socio-economic impacts) measured at the stand level manifest themselves at larger spatial scales (i.e. regional scales). There is a need to study how pest susceptibility / hazard is affected by processes operating on a variety of spatial scales. Various of multi-scale models could be developed to answer these questions. Another important area for future research is development of an understanding of how landscape heterogeneity and connectivity affect susceptibility to forest pests.

While the advent of GIS and other tools have greatly facilitated a landscape perspective of susceptibility / hazard, more landscape-level data is needed to solve these problems effectively. A major data gap exists in areas outside of National Forests. Typically, National Forest lands have available compartment data that describe each stand, but outside of National Forests the forest data is much more sparse. Forest Inventory and Analysis (FIA) plot data are designed to measure forest composition on a scale slightly larger than the typical county. Remotely sensed data are the most likely source for characterizing forests across large landscapes. While there have been isolated attempts (usually with considerable success) at characterizing forest vegetation using remotely sensed data, there are no uniformly developed maps for the entire nation. Extraction of forest composition and structure from remotely sensed data over all of the U.S. is therefore a high priority for future development.

Pages 184-186 *in* A.M. Liebhold and H.R.Barrett, editors. 1993. Proceedings: Spatial Analysis and Forest Pest Management. USDA Forest Service General Technical Report NE-175.

The Forest Service National GIS Plan ("Project 615") will greatly expedite our ability to characterize hazard across complex landscapes. The availability of GIS hardware and software to forest managers should be useful tools. However, as stated above, serious data gaps still exist in many areas. Furthermore, data standards should be established so that data is collected using the same standards in different areas.

MONITORING AND DECISION MAKING

Spatial analysis can play a major role in forest pest monitoring and decision making processes. Increasingly, pest managers are recognizing the utility of monitoring pest populations across a network of permanent plots, spatially stratified across the management area. The actual census method (e.g. pheromone traps, visual counts, etc.) varies depending upon the pest biology and management considerations. By using these monitoring networks, managers are able to pin-point "hot spots" that merit consideration for action. The ultimate result is a pest management program that is more effective and more environmentally benign because outbreaks are halted before damage occurs and treatments can be restricted to specific areas. Without such a system, pest management has been traditionally reactive; management action typically has been initiated after the damage has occurred.

When establishing monitoring networks, there are several factors to consider. There is obviously a trade-off between sampling intensity and cost. One must consider how to stratify placement of census points relative to variation in the ecological and physiographic landscapes. Ecologists are just now beginning to explore various methods for interpolation of census data. Some of these methods allow incorporation of secondary landscape data (i.e. vegetation, elevation) when forming estimates. All of these problems provide valuable subjects for future research .

Landscape level damage assessment is also an important component of a region-wide approach to forest pest management. Examples of damage data are defoliation maps for defoliators or spot maps for bark beetles. Very often, these damage maps may be one of the best sources of information for predicting where future damage will occur. For this purpose and for purposes of large-scale regional planning, these mapping exercises are important. There is a need to develop data standards both for monitoring networks and for damage maps. The Forest Service should take an active role in defining and coordinating the collection and assembly of these data across the nation.

Pest monitoring and damage assessment should be integrated more closely with the Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP) and the Forest Service Forest Health Monitoring (FHM) program. The consensus of the workshop was that permanent monitoring of selected forest pests would be logically done at the FHM monitoring plots located through out the country. This network of plots should provide an adequate network of plots for region-wide pest management as discussed above. If this activity is beyond the purposes of FHM then it would be logical that the Forest Pest Management field offices oversee collection of these spatially referenced data.

There are several decision support systems currently under development for use in management of selected forest pests. Each of these projects include procedures that use spatially referenced census, damage, and habitat data to guide the decision-making process. Most of these systems are intimately connected to GISs and are designed to access landscape-level data that are available in GIS format. It may be logical to ultimately combine decision support systems for different pests when they co-occur in the same area (example: southern pine beetle and gypsy moth). These decision support systems will probably evolve to a form in which they are not stand-alone systems but they will instead be integrated into general forest management procedures.

SPATIAL STATISTICS AND MODELS

Several of the papers in these proceedings focus on how spatial data can be used in models that are useful to forest managers. There is also considerable interest in more theoretical approaches that are designed to elucidate ecological interactions through the use of spatially explicit models. Thus, there are two major approaches where incorporation of spatial relationships will be important: 1) simple analytical / theoretical models (process) and 2) Predictive models (empirical, statistical). In the past, few groups have explicitly included space in these modeling approaches.

There are two apparent approaches to modeling spatial processes: Under the first approach, the model records cells that are fixed in space. These cells might be land grid cells or trees or other fixed objects. The book-keeping in these models are such that pest numbers are added and subtracted from the summary statistics kept for each cell. Generally, there is no "memory" of pest movement.

Under the second approach, the movement of individuals is modeled more explicitly. The book-keeping records the position of each individual (or population) in space. This approach maintains a "memory" of past movement. This approach is well suited to object-oriented programming languages and is obviously computer intensive. This approach is characterized by "emergent properties" that are evident after numerous simulation iterations.

In any spatially explicit process-oriented model movement is a very important component. Many researchers have adopted diffusion models which assume random dispersal but directed movement and advection can be incorporated. An interesting area of future development would be modeling movement which is affected by land cover and determining how landscape connectivity / heterogeneity affects redistribution.

Spatially explicit process models may also trace effects of habitat spatial heterogeneity on reproduction and survival. Predator and pathogen numbers can also be modeled as could reactions to conspecifics, such as aggregation and repulsion due to competition. An area that is largely unexplored but could be very informative is how the spatial structure of genotypic variation in host vegetation and pest populations affects changes in pest numbers over time.

Of course, spatial scale is an important consideration in spatially explicit process models. Trophic interactions change drastically among different spatial scales. Movement changes with spatial scale. More research is needed on developing our understanding of scale relationships to dynamical patterns. Certain types of nested models might be useful in this regard.

Models that are useful for actual pest management decision making are badly needed. These models should be simple, they should use empirical data, and that they should incorporate spatial statistics principles. One of the main impediments to the development and implementation of these types of models will continue to be a lack of data: insect census data, damage assessment data and habitat data.

Liebhold, Andrew M.; Barrett, Hope R., eds. 1993. **Proceedings: Spatial analysis and forest pest management**; 1992 April 27-30; Mountain Lakes, VA. Gen. Tech. Rep. NE-175. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 186 p. https://doi.org/10.2737/NE-GTR-175

Twenty papers on the application of spatial analysis to forest insect and disease problems presented at a workshop on spatial analysis and forest pest management.

Headquarters of the Northeastern Forest Experiment Station is in Radnor, Pennsylvania. Field laboratories are maintained at:

Amherst, Massachusetts, in cooperation with the University of Massachusetts

Burlington, Vermont, in cooperation with the University of Vermont

Delaware, Ohio

Durham, New Hampshire, in cooperation with the University of New Hampshire

Hamden, Connecticut, in cooperation with Yale University

Morgantown, West Virginia, in cooperation with West Virginia University

Orono, Maine, in cooperation with the University of Maine

Parsons, West Virginia

Princeton, West Virginia

Syracuse, New York, in cooperation with the State University of New York, College of Environmental Sciences and Forestry at Syracuse University

University Park, Pennsylvania, in cooperation with The Pennsylvania State University

Warren, Pennsylvania

"Caring for the Land and Serving People Through Research"