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DEVELOPMENT OF A GEOGRAPHIC INFORMATION SYSTEM FOR STATE-WIDE ASSESSMENT OF RISKS ASSOCIATED WITH GYPSY MOTH INFESTATION IN MICHIGAN

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DEVELOPMENT OF A GEOGRAPHIC INFORMATION SYSTEM FOR STATE-WIDE ASSESSMENT OF RISK ASSOCIATED WITH GYPSY MOTH INFESTATION IN MICHIGAN

By

Bradley O. Parks

A DISSERTATION

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ABSTRACT

DEVELOPMENT OF A GEOGRAPHIC INFORMATION SYSTEM FOR STATE-WIDE ASSESSMENT OF RISK ASSOCIATED WITH GYPSY MOTH INFESTATION IN MICHIGAN

By

Bradley O. Parks

A model of risk due to gypsy moth infestation was designed which describes in spatial terms the functional relationships between host, pest, environmental, and management variables. The model is based on five co-determinants of risk associated with this forest insect pest; host capability, habitat suitability, habitat susceptibility, host vulnerability, and infestation acceptability. It was designed to support the development and use of a computerized geographic information system (GIS) to carry out risk analyses on diverse data which have obvious spatial properties expressed over large land areas, but whose causal relationships to gypsy moth infestation and consequent risk are complicated and poorly understood. A geographic information system and a state-wide risk analysis data base were constructed in order to test the model for use in predicting gypsy moth impacts throughout Michigan. The design, development, construction, and implementation of the risk model and its supporting GIS technology are described, and a preliminary evaluation is made of the resulting Gypsy Moth Risk Information System (GMRIS).

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INTRODUCTION

Problem Statement

This study is the first of a series of planned research projects designed to help prevent or resolve problems raised by the presence of gypsy moth *(Lymantria dispar)* in Michigan. Michigan gypsy moth populations have reached levels sufficient to be obvious on a sporatic but widespread basis. Coupled with this increased visibility has been a simultaneous change in federal and state management policies acknowledging that much of Michigan is now infested at low levels and that the gypsy moth should henceforth be considered a native ("permanent") rather than an exotic pest.

This policy shift occurred in recognition of the "uncontained" character of this forest pest and of the futility of attempting to eradicate or even to closely control populations of gypsy moth in Michigan's Lower Penninsula. Suspension of federal eradication programs has reduced federal funds for cooperating state agencies and has provoked a movement in state policy away from centralized regulatory programs, leaving to local governments and property owners the responsibility of initiating management actions. It is also now widely accepted that an integrated pest management (IPM) approach to gypsy moth is most appropriate for future actions (MCFPMT, 1986, p.1-2). Implementation of this approach has been begun by Michigan's Cooperative Forest Pest Management Program whose members had earlier predicted such policy changes and who are now joined by the Michigan Department of Agriculture, as lead agency for gypsy moth management (Simmons, 1980, p. 12, and MCFPMT, 1986, p. 2). Integrated pest management for gypsy moth in Michigan requires that additional research be done, and that methods be implemented , to enhance population assessment capabilities, refine population development forecasting techniques, develop risk prediction models, and improve stand impact and defoliation assessment technology (MCFPMT, 1986, p. 2). Risk and impact prediction models are vital in forest pest management decision making for three reasons. First, and foremost, they are needed to fully integrate pest management considerations early in the forest planning process when the full range of options is available to the resource manager. Second, sound data on risks and impacts of pest ourbreaks are required for land managers to make on-the-ground decisions for appropriate treatment tactics. Third, public officials and program managers need impact information to secure adequate funding for treatment efforts (Hamilton et al., 1985, p. 2).

Effective management of gypsy moth in Michigan requires that various levels and combinations of risks be discriminated and prioritized, and that scarce pest management resources be appropriately allocated to the satisfaction of expectant and perhaps competing interest groups. Of particular importance in minimizing gypsy moth impact and public conflict over the methods and means of doing so, is the need to use public education to pre-empt local initiatives which could produce potentially uncoordinated, misdirected, or counterproductive forest or pest management efforts. However, effective educational and other management activities must be predicated upon "predictive" risk assessment knowledge which will allow gypsy moth problem areas to be accurately forecasted, compared and prioritized, and appropriate interventions to be targeted for each (MCFPMT, 1986, p. 1-2).

Several prerequisites can be identified for a useful gypsy moth risk assessment system for Michigan. First, it must facilitate collection and processing of many different kinds of data representing large unit areas of potentially risk-prone forested lands. Second, it must allow analysis of the locational and areal properties of such data in order to reveal spatial risk relationships predicated on limited bio-ecological knowledge of Michigan gypsy moth populations. Third, the preceding qualifications must also be met by a system that facilitates modification, up-dating, and iterative analyses so that new knowledge does not make prior work obsolete. All of these prerequisites are, in concept, satisfied by geographic information systems or GIS's which are essentially computerized natural resource information management systems with the unique ability to manipulate mapped data.

The task of this study is one of developing and pilot testing a geographic information system (the Gypsy Moth Risk Information System - GMRIS) and a method for its use (a spatial model of risks due to defoliating forest insect pests) in a specific kind of problem-solving application (projecting risks due to gypsy moth infestation). Specifically, this study is intended to develop new methods to carry out and combine broad scale resources inventory, forest pest monitoring, and integrated pest management decision support for gypsy moth. The research problem which follows from the task above is one of determining whether a GIS-based gypsy moth risk assessment system can be made operational and, if so, how it should be implemented, and whether its use can better meet forest pest management risk assessment objectives.

Research Needs Assessment

Successful management of forest resources can depend, in part, upon effective management of insect pests. Much of the data required in resource management in general, and in forest pest management specifically, is spatial in nature (Pence, et al., 1983, p. 1). Of those insect pests which together make up Michigan's entire "forest defoliator complex", gypsy moth is one whose effective management is particularly dependent upon its predictability in the spatial dimension (Lambur, et al., 1983, p. 2-3). Understanding the location and distribution of actual or potential gypsy moth influences and impacts over extensive forested land areas is critical for four reasons:

1. The life cycle and the reproductive behavior of the gypsy moth is well suited to Michigan's extensive transportation system and the high mobility of its citizens and visitors. (Sapio, et al., 1984, p. 3). Gypsy moth life stages overwinter in protective egg masses which are produced in late summer, the time when many people vacation in or move from infested areas in Michigan or other states. These egg masses are often attached to man-made objects and other commodities which are then transported to new destinations. Thus, despite the gypsy moth's limited dispersal ability (the female moth being essentially flightless), it can rapidly be spread great distances by unknowing travelers and shippers. This may have the effect of cancelling the retarding influence of time and distance, thereby effectively placing nearly all forest lands, irrespective of their distance from existing infestations, within some category of potential risk.

2. The gypsy moth is polyphagous and quite flexible in its feeding behavior (Coulson and Witter, 1985, pp. 354,355). This means that non-food variables can become decisive in the successful expansion of its range. One consequence of this is that, as better information and decision making tools become available, forest and pest managers must shift their reliance away from preferred hosts (tree species) as the sole or primary means of predicting the movement and influence of this pest, including with host type a variety of other contributors to and indicators of risks (Campbell and Sloan, 1977, p. 329). To do so managers will have to interrelate climate, soils, land use and a variety of other kinds of data within schemes that become more complex as the number of such risk indicators increases. Current scientific understanding of these complicated influential relationships is still limited, but it is possible to begin by building data bases and models which will help to examine the position and extent of their occurrences in the landscape and, by doing so, to apply and test existing knowledge and to identify additional research needs (Simmons, 1980, p. 1,5).

3. Gypsy moth populations can expand quickly under certain conditions to reach high densities. Under other conditions their numbers can quickly decrease. (Elkinton, 1982, p. 3-4). At high population densities risks associated with gypsy moth may become greatly increased. Conversely, risks may rapidly decrease, perhaps becoming insignificant, when populations collapse, as they periodically do (Campbell, 1981, p. 81). The effect of this is that the intrinsic threat of gypsy moth is increased by its potential for rapid change. As the rate of change in gypsy moth populations (and their effects) increases, particularly when coupled with the high "transportability" of this pest, the likelihood decreases that all such changes will be quickly detected and usefully analyzed. Such a dynamic pest requires that populations and their impacts be continuously monitored with precise timing throughout large areas in order to reveal all possible trends in the expansion or contraction of actual and potential impact areas (Hannah, 1981, p. 106).

4. Michigan forest and pest management agencies and experts agree that, within the context of Michigan's forest-pest systems, the gypsy moth poses what can best be described as a

"people problem". Leading managers are unanimous on the point that the actual impact of gypsy moth on the survival and long term economic value of the state's forest resources is likely to be much less important than its perceived impact, or the conflict which infestations may create with human expectations and values (MCFPMT, 1986, p. 1-2). As a result, the problem of finding biologically sound successful management responses may actually be compounded. The potential for wide dispersal and rapid population change can combine with the ubiquity of humans in the forest landscape and their diverse expectations to create what in the northeastern U.S. has been characterized as an ever escalating, highly combative orientation in which "...public anxiety and entomological salesmanship go hand-in-hand" (Dunlap, 1980, p. 126). To prevent such occurrences, a well prepared and well reasoned strategy for managing gypsy moth will require answers to urgent questions such as: how severe will the problem be?, who will be affected?, and where will it occur next? These kinds of questions raised in response to gypsy moth may outstrip the capabilities of current non-spatial information and decision making systems to provide adequate answers or guidance. Such systems can not overcome several difficulties unique to gypsy moth management. First, the opportunities for gypsy moth to be introduced into new areas as a result of largely uncontrollable human activity, combined with their ability to survive on a great range of hosts, makes them effective "opportunists" which in turn suggests that very large land areas must at this time be considered as marginal, if not better, habitat and thus potentially at-risk. Second, the rate at which gypsy moth populations can change in size and effect makes it difficult to continuously monitor such change over the kind of large land area already implicated, without the advantage of suitable computer-based information processing technologies. Third, the great range of bio-ecological and socio-economic relationships that may be influential in determining the nature of risks associated with gypsy moth is large and the difficulty of understanding, managing and communicating the spatial relationships underlying such complexities requires the geographical representation of both problems and proposed solutions.

The operational requirements for a risk information system which can adequately address gypsy moth induced risks for the State of Michigan parallel and compound these difficulties. First, to develop a comprehensive understanding of gypsy moth risk it is necessary that the first implementation of a spatial analysis capability take a broad view of Michigan's forest lands. This requires a state-wide spatial data analysis capability. Second, it is important that the resulting risk assessment system be one which can be updated and reinterrogated as criteria or requirements change. Third, to identify and understand complex trends or changes over time, it is necessary that multiple spatial data sources be employed on a multi-temporal basis whenever possible.

Conventional tabular forest pest data are seldom amenable (without extensive modification) to these automated spatial analysis operations, and manual preparation of such tabular data for spatial operations is inefficient, prone to error, and extremely cumbersome (Daniel, et al. 1983. p. 3). In addition, a review of the literature indicates most risk assessment models developed to use forest pest management data have not been designed for, and do not provide, a highly refined means of determining the geographic properties of risks. In contrast, geographic information systems and models for their use have evolved from precisely these kinds of complex spatial problems involving natural resources issues which are characterized by many spatial and temporal factors operating over large geographical areas.

Research Approach Used

The strategy used in this study was to simultaneously demonstrate and empirically test a new means of examining the spatial properties of gypsy moth-related phenomena in Michigan. The urgent need to plan for wise management of gypsy moth in Michigan provides the ideal context for such a study. Full geographic information system technology has not previously been applied to forest pest problems in Michigan although gypsy moth populations exhibit strong spatial characteristics and research support facilities housing geographic information systems already exist and are fully operational at Michigan State University. In addition, both forest resource management and pest management practices in Michigan are in need of tools which can enable efficient and extensive resource inventory, analysis, and management decision support. This project is intended to help establish procedures and identify additional data needed to apply geographic information system technology to gypsy moth management needs in such a way as to facilitate its transfer, if warranted, to other forest pest management applications as well.

Specifically, this study focuses on three objectives: development of a sound cartographic model of risks; appropriate use of existing spatial data and data collection systems; and the implementation of a gypsy moth risk information system by utilizing geographic information system capabilities currently available at Michigan State University and by enhancing institutional linkages between Michigan's forest pest management agencies.

Limitations of the Study

Six important limitations were anticipated early in the project or were encountered and adjusted for during the course of the investigation. These limitations involve the accessibility or use of data and the development and refinement of a spatial model of risks due to gypsy moth infestation. Each of these limitations is described below to further clarify the scope of research activities.

Limitations imposed by data quality and availability

1. The study was planned to make maximal use of secondary data thus restricting the scope of analyses that could be undertaken. Collection of original data was excluded from consideration because the project was conceived to evaluate the adaptability of currently available GIS resources and to make recommendations for additional data and other requirements. The significant cost of acquiring new data was considered unlikely to yield a correspondingly great improvement in the quality of risk analysis that could be derived at this time. In addition, it was determined very early that several of the data sets which were being considered for use had to be rejected because they would require extensive preparation and reprocessing. This further reduced the pool of existing data.

2. The resolution or level of detail which could be supported by the data base initially proposed was, in effect, predetermined by prior work completed at Michigan State University's

Center for Remote Sensing (CRS). CRS made available several data sets that had been prepared for multiple-purpose analysis format and were thus available "off-the-shelf". One of these proved to be the only available state-wide digital land cover inventory which proved useful not only for its forest cover contents, but also because it had been designed to serve as a base map for other data sets which we also hoped to use. Creating such a state-wide landcover data set was imperative to, but well beyond the means of this study, so we adopted the standards used by the CRS and build our geographic information system to be compatible with theirs. By doing this we were able to make use of the earlier efforts of others, and to maintain compatibility with, and therefore access to, useful data which might be prepared in the future by persons who had also adopted and built upon CRS's standard. The price of this compatibility was the acceptance of the 1 square kilometer grid cell size designated by CRS. As a "minimum resolvable unit area" this standard was perfectly consistent with our own objectives. As a metric, rather than english unit, which was inconsistent with other of our data sets, this standard was considered an inconvenience justified by other cost and time savings we would gain.

3. Our original intent was to construct a geographical information system which was, in a limited sense, a hierarchical one. We had planned to create the capability of obtaining a coarse, or low resolution "view" of most, if not all of Michigan, and the capability of viewing more closely (at higher resolution and smaller map scale) multi-county areas of particular interest which had been identified in our initial broader view. A source was found for data which contained greater detail and a smaller map scale than the 1 km^2 resolution we had adopted for our planned state-wide coverage, and which was available for a number of Michigan counties. Our early plan was to use certain of these county data sets as test cases in which we would identify high priority risk areas within a state-wide context and then we would move to the next level in our hierarchical information system and carry out more detailed and more localized spatial analyses, in effect, working at a higher "magnification". However, the time and expense of developing such a capability, coupled with the still undefined risk assessment requirements of multi-county areas led us to cancel this portion of our original plan.

4. An important limitation of areal coverage of our planned GIS occurred later in the study. A previously undetected error was found in the geo-referencing system used for the Upper Pennlnsula portion of the land cover data set which we had adopted as a common base map. Because considerable time would be required to correct this error, we were forced to omit Michigan's entire Upper Peninsula from our immediate analysis. Actually, use of the Upper Peninsula portion of our information system, had it been included within this study, would have been incomplete in any case because critical pest population data for the Upper Peninsula were later unexpectedly, and unavoidably omitted from field work carried out by Michigan's Department of Agriculture. This has had the obvious effect of making our planned 1 km^2, non-hierarchical GIS something less than truly state-wide at present but the broad scope necessary for risk prediction over the entire lower peninsula remains unaffected and is, without question, the more urgent need. Fortunately, we have been able to proceed with development of risk assessment capability for the Upper Peninsula independent of, but nearly in parallel with our work on the Lower Peninsula. Future studies will include the Upper Peninsula data analysis capabilities with those we have already completed for the Lower Peninsula.

Limitations imposed by modeling constraints

5. The ability to model risks with a high degree of precision depends in part upon having a knowledge base concerning the phenomenon in question which is both complete and exact. Neither of these requirements can currently be well satisfied with regard to gypsy moth in Michigan. Little bio-ecological research has been done on Michigan populations of gypsy moth. In the absence of knowledge which such research could provide, it has been necessary to generalize to Michigan, the knowledge gained about gypsy moth in the northeastern U.S. Because of this, few specific numerical thresholds can be attached to factors which are thought to be influential to gypsy moth population dynamics or impacts on host tree species. The result is that modeling of gypsy moth risks in Michigan must at present, be done on a strictly comparative or relative basis. Research is currently being planned which, if supported, will provide valuable base

line data on gypsy moth bio-ecology in Michigan, but for now studies such as this one must rely on expert judgement in "borrowing" knowledge from dissimilar environments and upon limited qualitative, non-probabilistic models that can be built from our scant knowledge of such biological systems as they occur in Michigan.

6. A second closely related limitation of the effort to assess gypsy moth risks is the lack of knowledge necessary to confidently employ risk models developed in other states or to validate models developed for Michigan. Models of gypsy moth risks which have been designed for systems in other areas assume conditions which may not be characteristic of Michigan. They also usually require detailed data on forest and pest characteristics which are not now available for Michigan. This means that studies such as ours must use models which are specific to Michigan and which are predicated on existing resources. Unfortunately, without the knowledge and data which allow thorough testing of a model of the gypsy moth forest pest system, it is not possible to say yet whether such a model accurately depicts "real world" occurrences and therefore, whether it actually "works". Strictly speaking, the model building process includes the procedure of validation and is not complete without it, but there are not yet sufficient historical data for Michigan to allow empirical tests of the model used in this study.

Despite its limitations, our model provides the immediate advantages of: allowing full use of existing knowledge and data, facilitating the use of innovative management tools and practices, and providing the best available spatial evaluation of Michigan's gypsy moth pest system.

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LIFE HISTORY AND IMPACTS OF GYPSY MOTH

Life Cycle

The gypsy moth, *Lymantria dispar (L.)*, is in the order Lepidoptera whose members are characterized by complete metamorphosis, their larvae transforming to pupae and then metamorphosing into adult butterflies or moths. Among Lepidopterans, gypsy moth is one of the family Lymantriidae whose larvae feed on tree foliage. Commonly called tussock moths because of prominent tufts of hair found on the larvae, representatives of this family are found in temperate regions throughout much of the world. The species name for gypsy moth, *dispar*, derives from the latin word meaning "to separate" in apparent recognition of the visible differences in coloration, size and other features between male and female moths. The gypsy moth, like most temperate forest defoliating insects, has one generation each year which includes egg, larvae, pupae, and adult (moth) life stages.

Adults (moths)

The male gypsy moth which is generally brown, and the female which is nearly white, emerge from pupae in midsummer. Both sexes live for about one week. During that time they drink water but their digestive system is not functional and they do not feed. Male moths emerge earlier than females and commence reproductive activity almost immediately. Males exhibit a zig-zag searching flight during daylight hours in response to female sex pheromone, and to vertical objects such as tree trunks.

Females are larger in size (with a wingspan of 5 cm as compared to 3.75 cm in males), and emerge with fully formed wings although they do not fly. This flightlessness is a common adaptation among insects, which is thought to shunt energy reserves normally expended in flight into increasing the insect's reproductive capacity. Several hours after emerging, females begin releasing sex pheromone in bursts of "calling" activity. This chemical attractant can draw males from great distances. Males locate females by tracking in a searching flight pattern the increasingly strong gradient of the pheromone to its source, aided visually at close range by the female's light color contrasted against the (often) darker surfaces of trees. The reproductive period of the female is about three days after which the potency of her pheromone diminishes. However, since males emerge sooner, the probability is increased that receptive males will be available when females emerge, and the effectiveness of the sex pheromone during that interval insures that most females will mate (Leonard, 1981, pp. 11,12).

Eggs

Eggs are deposited in late summer usually in masses containing 75 to 800 eggs each. Most of these egg masses are deposited on the trunks and limbs of trees, but they can also be found under stones, inside hollow trees and stumps, on leaves, and on various man-made objects (Talerico, 1978, p.10). Most eggs are laid within 24 hours after mating. Eggs are usually deposited in a single egg cluster measuring about 3.75 cm in length and 1.9 cm in width. Unfertilized females will also oviposit but their eggs will often be scattered and will not hatch. Masses of eggs are covered by a dense protective coating of scales from the female's abdomen giving them a velvet-like appearance. Because females are flightless, egg clusters are commonly found only a few feet from the empty female pupal cases.

Embryonation begins soon after oviposition with larvae becoming fully formed inside the egg in about a month. Following embryonation development ceases in preparation for diapause during which larvae within eggs reduce their water content to survive the freezing temperatures of winter. Although a few eggs hatch in the fall these larvae do not survive. Most larvae spend 8 or 9 months in the egg and emerge after winter temperatures have moderated and about the time trees begin producing new leaves (Leonard, 1981, pp. 12,13).

Larvae (caterpillars)

Egg hatch begins in response to spring heating which causes larvae to resorb water and to chew through the membrane of the egg and the enclosing mat of protective hairs. Hatch can occur within the period of a week but may also extend as much as a month in places where spring heating is slowed. Typically hatch occurs in late April or early May about the time oak leaves are expanding (Talerico, 1978, p.10). Gypsy moth larvae exhibit two particularly important characteristics; they show a tendency to disperse, and they grow through successive molts to accomodate their increasing size.

Newly hatched larvae, when they leave the vicinity of the eggs, are positively phototropic and negatively geotropic. That is, they display a tendency to move toward more intense sunlight and against the pull of gravity. Larvae hatching from eggs laid on trees move upward to the tips of branches. Those hatching on objects other than trees will also climb upward but even upon encountering no food source at their destinations, will not climb downward. Many larvae will disperse regardless of whether they find suitable foliage after their vertical movement (Leonard, 1981, pp. 12,13). This dispersal is accomplished by "ballooning" or sailing on wind currents. When disturbed, newly hatched larvae will spin down on silk threads, a behavioral trait which, along with a very small body size and long body hairs, makes them "buoyant" and very susceptible to airborne dispersal by winds (Talerico, 1978, p.10).

Although very small after hatch, gypsy moth larvae grow from about 3 mm to about 5 cm in length, reflecting over a thousandfold increase in weight. Since their bodies are largely non-elastic, growth must be accomplished by molting their exoskeleton. Molts occur at about weekly intervals and some are accompanied by important behavioral changes. Larval stages between molts are characterized as "instars" which are designated by the number of previous molts, thus newly hatched larvae are in the first instar, having yet to undergo their first molt. The gypsy moth larva displays some variability in the number of instars it undergoes before reaching the pupal stage. Males usually have five instars (four molts) and females, six instars (five molts) but one additional instar is common for both sexes and seven or more can sometimes occur (Leonard, 1981, pp. 14,15). As the number of instars in a population rises, so does the size and appetite of the larvae, and with it, their objectionable capacity to defoliate trees.

Growth and development of larval instars is influenced by environmental factors, the vigor or quality of individual insects, and the quantity and quality of food. Young larvae feed on new leaves exclusively during daylight hours. When not feeding, first, second and some third instar larva remain on the underside of leaves where they produce, and rest, under a mat of silk. In contrast, fourth and some third instar larvae undergo a change in both feeding and non-feeding behaviors. These later instars switch to nocturnal feeding and they change their resting locations from positions in the leafy canopy of the tree to sheltered locations such as bark flaps further down the tree's stem. Cued by decreasing light levels at dusk, these later instars vacate their resting sites moving up the tree to the canopy to feed through the night and retrace their paths as light levels increase at dawn (Leonard, 1981, pp. 14,15).

Feeding by early instar larvae is not heavy and can easily go unnoticed. However, as larvae grow, they consume increasing amounts of foliage, and in the last instar they eat more than all previous instars combined. The last instar female is capable of the heaviest feeding since they are larger than males, weigh over twice as much, and their last instar is longer in duration than is the male's. It is estimated that a larva consumes about 1 m^2 of foliage during development (Leonard, 1981, p. 15). If feeding is heavy enough to completely defoliate trees before the larval life stage is finished, larvae will leave bare trees to find other food sources. These crawling larvae can create an additional "swarming" nuisance for humans as they congregate on household and other outdoor objects (Talerico, 1978, p.10). Near the end of their life stage, feeding stops entirely and larvae spin a loose silk net and void their gut in preparation for the prepupal stage.

Pupae

After about 2 days in a quiescent prepupal stage, the pupa emerges from its former larval skin. This tear-shaped, brownish pupa which resembles neither the larva nor the moth, remains held in its loose silk net for the 2 weeks (16-17 days for females) required for morphogenesis.

When this developmental process is complete the adult inside takes in air and expands to split the pupal skin. Adult moths emerge fully formed and reproductively functional (Leonard, 1981, pp. 15,16).

Population Dynamics

Gypsy moth populations in North America are capable of achieving stable densities at both high and low populations. Historical data on gypsy moth infestations in the eastern U.S. reveal four distinct features within overall trends - two relatively stable modes (outbreak and innocuous) and two transient phases (release and decline) (Campbell, 1981, p. 65). All of these stages will be referred to hereafter as phases.

Once successfully introduced to an area via artificial or natural means, gypsy moth population levels may build slowly to low levels in an "innocuous" or "endemic" phase which may escape detection altogether or which may be evident by only minor defoliation. Such a sparse population can remain stable indefinitely although the processes that produce such low-density stability have their least effect along the advancing front of the generally infested area (Campbell, 1981, p. 65). This endemic state may periodically give way, when conditions are favorable, to a "release" phase characterized by rapid population increase. This trend has been seen, in the eastern states, to produce an "epidemic" or "outbreak" phase, in which populations may greatly increase in a single year with defoliation becoming widespread and often severe. Once underway, influential processes can sometimes maintain such outbreaks for up to a decade (Campbell, 1981, p. 65). After the outbreak phase there inevitably follows a "decline" or "collapse" phase in which populations rapidly decrease. This overall chain of events leading from innocuous to decline phases generally operates on an irregularly repeated or episodic basis with the net effect that populations fluctuate between endemic and epidemic phases (Elkinton, 1982, p. 3).

The successful establishment of a gypsy moth population in a given area (innocuous phase) is first dependent upon the presence of a reasonable number of preferred host tree types within the general composition of the forest. The ultimate limit of density achieved (outbreak phase) is determined by the amount of foliage available (Elkinton, 1982, p. 3). Between these extremes other factors have a part in initiating or maintaining transitional phases.

The conditions which may control the release of innocuous gypsy moth populations are not yet well understood (Campbell and Sloan, 1977, p. 329). It is clear that during the innocuous or endemic phase, predators and parasites do have a role in suppressing gypsy moth population levels. However, despite many generalizations concerning the effect of parasites on the maintenance of low population levels between outbreaks, no supporting data have ever been published in the American or foreign literature (Reardon, 1981, p. 96). Predators, particularly small mammals and birds, are considered a major suppressive force but even though predators may regulate gypsy moth populations, they cannot regulate them on a permanent basis and they do not regulate them alone (Smith and Lautenschlager, 1981, pp. 124,125).

The limited influence of predators and parasites on innocuous gypsy moth populations can be easily imagined if one considers that, of the several hundred eggs in any one gypsy moth egg mass, only one female egg must survive to maturity for the population to remain stable. Gypsy moth populations will expand unless mortality over any given generation exceeds 99 percent. Predators and parasites seldom account for such high levels of mortality (Elkinton, 1982, p. 4).

During the epidemic and decline phases, starvation and epizootics are the factors which are most influential in checking population growth. Predation has no impact (Smith and Lautenschlager, 1981, pp. 96-97). As rapidly expanding gypsy moth populations exhaust their food supply, starvation begins to kill many larvae which cannot locate or reach alternate food sources. The stress of starvation also acts to reinforce the action of virus which can spread rapidly through dense populations causing larvae to "wilt" and disintegrate.

Other factors undoubtedly influence gypsy moth populations. These may include weather conditions; changes in the nutrient quality of tree foliage; qualitative changes in the nutrient reserve and fertility of the gypsy moth itself before, during and after an outbreak; and other factors (Elkinton, 1982, p. 4). Few of these forces which are known or thought to influence population dynamics are well understood - particularly as they may apply to gypsy moth populations in Michigan.

Impacts

The fact that gypsy moth is best known for its adult or moth lifestage is a potential source of confusion when discussing its impacts. Although the pupal, egg and moth life stages can be found by people to be objectionable, these "forms" of the gypsy moth are not the reason that this organism has achieved the position of a prominent forest pest. These life stages are, in fact, most worrisome in that they are indicators or reminders of the larval lifestage which is the potentially damage producing and intrusive one because it can feed heavily on foliage and will inhabit human environments.

Impacts of gypsy moth infestation are often divided into either nuisance or non-nuisance, categories depending on the kind and the magnitude of the consequences. Nuisance impacts generally imply trivial, or short term impacts that will probably not have irreversible effects. Other impacts which represent more than just nuisances typically constitute long range, often economic impacts, which may have irreversible effects. Most important among the later group are impacts on the wood producing, recreational, or associated tourism potential of forested regions. Accounts of the historical impacts felt in the eastern U.S. are included elsewhere in this study but it is important to note here that massive defoliation with attendant high mortality throughout expansive forest areas is not expected by forest pest managers in Michigan. The following descriptions of arboreal and terrestrial impacts are predicated on this assumption and are intended to present an impression of more attenuated, isolated pockets of impact as they might be observed on a local basis in Michigan.

The exact nature and thresholds for impacts due to gypsy moth vary with location, according to differences among hosts and their environments and according to the attitudes and interests of people living in affected areas. It is nevertheless possible to describe the general kinds of negative or objectionable consequences of infestations which qualify gypsy moth as an insect pest. The following briefly characterizes only the larval lifestage and its more immediate impacts, it does not cover long-range or more subtle ecological impacts, such as influences on forest succession,which are outside the scope of this study.

Arboreal activities and their consequences

First larval instars which are blown into a tree canopy or those which hatch on limbs and crawl upward to the canopy will chew small holes in the surfaces of leaves. Older larvae feed on leaf edges, consuming entire leaves except for the larger veins or the middle rib (Talerico, 1978, p. 11). As a result of their feeding activity dense populations of gypsy moth larvae produce large quantities of fecal material or "frass" as well as unconsumed foliar debris which falls to the ground or collects on homes or other objects beneath infested trees. This material is considered by many to carry an unpleasant odor and to be unsightly, creating both perceived and real maintenance and health problems. When feeding is heavy, chewing activity may even become audible (sounding like raindrops) to those nearby adding a troublesome "noise" dimension to the problem. As feeding by later instars continues, more leaves are stripped from the trees and the consequences of defoliation become more apparent. Loss of leaf surface area within the canopy results in less shading of the areas in and below the canopy. This reduces cooling effects on dwellings and forest users, forces wildlife to find more temperate habitat, and alters aesthetic or visual values. In a dense population many larvae eventually die, particularly from nucleopolyhedrosis virus. In a heavy infestation the odor of decomposing larvae can permeate an outbreak area (Leonard, 1981, p. 19).

Defoliation can also have negative consequences for the vigor of trees. Over time these consequences can also become apparent to forest dwellers and users in ways which affect them more directly. An example of this would be a decrease in property value or additional tree removal or replacement expense as a result of tree mortality. Although gypsy moth larvae do exhibit preferences for the foliage of certain tree species, this preference can change somewhat in later instars and in any case, gypsy moth larvae are polyphagous and will thus eat most any foliage in the absence of a more preferred type.

Both deciduous and coniferous trees can be defoliated (the latter only by late instars) but these tree types differ greatly in their ability to survive defoliation. In general, deciduous trees are able to survive up to 3 repeated defoliations but conifers are less able to recover from even a single defoliation. Conifers store a large portion of their food reserves in their older needles which are removed during defoliation. They will refoliate only in the spring and they accumulate needles over several years. It would thus require several years to reacquire a full set of needles following defoliation. In contrast, deciduous trees store a greater proportion of nutrients in their roots and have the capability, if damage is severe enough, to quickly refoliate, replacing all their leaves in a few weeks time (Elkinton, 1982, p. 6).

But tree species or type is not the only determinant of tree survival capability nor is defoliation by gypsy moth the only determinant of tree mortality. Trees which are already under stress from competition, drought, construction disturbance, attacks by other forest pests, or other factors will likely be less able to withstand defoliation (Elkinton, 1982, p. 6). Similarly, defoliation by gypsy moth will usually only weaken trees but in doing so it may make them more susceptible to attack by other insects, such as the two-lined chestnut borer, or by diseases, such as the shoestring root rot, agents which are often the final determinants of tree mortality following gypsy moth infestation ((Elkinton, 1982, p. 6-7 and Leonard, 1981, p. 18).

Terrestrial activities and their consequences

Late instar gypsy moth larvae moving to or from their resting places or those which have exhausted their food supply and are searching for a new source will often be encountered on the ground or on the lower portions of objects in the area. In sparse populations late instar larvae will congregate on sheltering objects or will wander about climbing over structures, outdoor objects, plants and other obstructions. In dense populations these daytime activities are intensified as larvae become "hyperactive" incessantly moving up and down trees or following polarized light to find and climb objects in their vicinity (Leonard, 1981, p. 19). Such a concentration of larvae can affect both residential and non-residential users of forest resources who may experience either an "entomophobic" revulsion or simply an unwelcome interruption of their normal activities. Some who actually come in contact with the larvae may also experience a skin irritation from the protective hairs of the larvae (Elkinton, 1982, p.7).

Management Responses

Gypsy moth is now considered well established as a serious defoliator of forest, shade, and fruit trees and ornamentals over much of the northeastern U.S. and it is the only forest insect under regulation by the USDA Federal Domestic Quarantine . Despite a long history of unusually intensive study and control programs, gypsy moth continues to expand its range (McManus and McIntyre, 1981, p. 1). It is now considered to be permanently established in all or parts of 14 states and isolated infestations are known to occur in 13 other states from the mid-Atlantic States and Great Lakes Region to the West Coast (the USDA Forest Service and the USDA APHIS, 1984, p. 1). Following is a brief, uncritical chronology of the gypsy moth's 117 year management history (research activities and accomplishments are not included).

Origin and past management of gypsy moth in the United States

The gypsy moth is native to temperate regions of Europe, southern Asia, and Africa where it has long been considered a forest pest (Coulson and Witter, 1985. p. 353). Gypsy moth was the first of three species of lymantriids to be introduced into North America from Europe. The other two species are the browntail moth, *Euproctis chrysorrhoea* (L.), which was introduced in about 1890, and the satin moth, *Stilpnotia salicis* (L.), which was introduced about 1910 (Leonard, 1981, p. 9). Of these exotic forest pests, gypsy moth has emerged as the most successful colonizer. The browntail moth underwent a great recession in range shortly after its spectacular initial infestation of the Northeast, and has now become an isolated curiosity. The satin moth has become established over a wider range and will undergo infrequent outbreaks, but it is generally considered a comparatively minor forest pest (Leonard, 1981, p. 9). In contrast, the gypsy moth has earned the distinction of being one of the three most destructive forest pests in North American history and the record of its management is nearly a chronicle of American economic entomology (Dunlap, 1980, p. 116).

In 1869 gypsy moth was accidentally introduced to the United States by a French astronomer working at Harvard. He lost some of the gypsy moth eggs he had imported for his hobby, the crossbreeding of silk-producing caterpillars, allowing the first population to become established in Medford, Massachusetts. For the first twenty years their presence was regarded as a curiosity but by 1889 this population had exploded causing so much damage that the public demanded action (Dunlap, 1980, p. 116).

The first gypsy moth management efforts in the U.S. began in 1890 when the Massachusetts Legislature appropriated funds for its eradication (Elkinton, 1982, p. 1). For nearly a decade efforts were made to achieve the first attempted extermination (complete elimination) of an insect from North America. This undertaking emphasized the use of early pesticide spray technology and ultimately cost an estimated $1.2 million. Although this vigorous eradication campaign was successful at reducing the moth's status to that of a minor threat, the Massachusetts legislature grew impatient with the prospect of continued spending and terminated the project in 1900 choosing, as Dunlap characterizes it, "..to halt on the brink of success." (1980, p. 116, 119). This decision is considered by many to have been a "fatal" mistake in that it allowed the moth to make a comeback (McManus and McIntyre, 1981, p. 2).

After termination of its eradication campaign, gypsy moth populations increased dramatically in Massachusetts and new infestations were found in surrounding states. As a result, a second control campaign was begun in 1905-1906. This new effort differed from the first because numerous spreading populations had rendered eradication infeasible and because the federal government became actively involved in a joint program emphasizing biological controls (release of predators and parasites) (Dunlap, 1980, p. 120). Biological methods proved slow and difficult to implement and by 1912 it was thought that a delaying tactic was necessary resulting in the enactment of a federal domestic quarantine designed to reduce the accidental long-range transport of gypsy moth life stages on regulated commodities (McManus and McIntyre, 1981, p. 2). By the 1920's biological controls began to have some effect on pest populations but by then lack of a simple, quick and inexpensive solution to the problem had again reduced the confidence and patience of the New England legislatures. Existing problems were exacerbated by World War I which hampered the importation of predators finally causing the campaign to fall back on conventional methods until some better control could be discovered (Dunlap, 1980, p. 122).

The generally infested area had spread through New England and westward to the New York boundary by 1922 (McManus and McIntyre, 1981, p. 2). At a meeting in New York, members of the USDA and representatives from infested states and Canada decided to reinforce the holding action begun with the 1912 guarantine by establishing a barrier zone extending from Canada to Long Island along the Hudson and Champlain River Valleys. The intent was to confine the moth to its established range east of the barrier by eradicating infestations within and to the west of the barrier (Dunlap, 1980, p. 123). Populations levels fluctuated in the years between 1922 and 1940 but the moth's range continued to expand. Defoliation in New England dropped dramatically in the mid 1920s, but reinfestation of these areas continued. A large infestation which was discovered in Pennsylvania, far beyond the barrier zone, launched another large cooperative federal-state eradication project but after a cost of $4.5 million, extermination was still incomplete. By 1939 the barrier zone itself became generally infested and by 1941 federal appropriations had been reduced to the point that the entire effort was terminated (McManus and McIntyre, 1981, p. 3).

In the mid 1940s experimentation began with the new chemical, DDT. Its efficacy so impressed officials that thoughts were again entertained of eradicating gypsy moth from North America. In 1944 the War Department alloted a quantity of DDT to determine its value to eradication work in Pennsylvania. Use of DDT continued until 1948 when this infestation was thought to have been eradicated. However, control was not complete and Pennsylvania's infestations have spread ever since (McManus and McIntyre, 1981, p. 3).

Following an explosion of gypsy moth populations throughout the Northeast in 1951-52, the USDA undertook a thorough appraisal of the problem. It was determined that the Adirondack Mountains and their extension into the Allegheny Plateau provided the only natural barrier to continued spread of gypsy moth to the south and west. A seven point plan was designed which also recommended that the management concept of a barrier zone be revived. This plan was enacted in 1953, in so far as funds allowed, by the Regional Coordinating Committee on Gypsy Moth control of the Council of State Governments. Individual States were urged to encourage Congressional funding of the proposed plan (McManus and McIntyre, 1981, p. 4).

By the early 1950s the USDA had formally announced that eradication of gypsy moth was their eventual goal principally as a result of the confidence engendered by DDT. Despite such claims and the continued application of pesticides, the period between 1953 and 1957 witnessed the spread of gypsy moth to large, previously uninfested areas along the leading edge of the generally affected area. A more distant infestation was also identified in central Michigan (see discussion below of origin and past management of gypsy moth in Michigan). In 1956 Congress appropriated funds for an eradication program which had as its scheduled long-range goal the eradication of gypsy moth from the U.S. The program included a limited contingency plan for eradicating all outlying infestations back to the Connecticut-New York barrier line - if complete extermination failed in 2-3 years time. DDT was to be the principal tool in meeting these goals and throughout 1956-57 over 1.4 million hectares were treated aerially. Defoliation in 1958 was recorded on only 50 hectares of the entire infested area, the lowest level since 1924 (McManus and McIntyre, 1981, p. 4).

Use of DDT brought great criticism from the public and from some scientists and public officials who voiced grave concerns about residues of such persistent pesticides (Dunlap, 1980, p. 123). After 1958, DDT was phased out in favor of carbaryl as the pesticide of choice. Except for a brief respite in 1966-68, infestation increased steadily throughout the next decade reaching outbreak levels by 1969 when simultaneous defoliations were recorded in several states. In response to this developing outbreak a federal-state committee was formed which later became the National Gypsy Moth Advisory Council. In 1969 and 1970 the council laid plans for a 5-year accelerated research and development program. In 1971 the USDA redirected $1 million for research and increases were made to the base funding of several participating federal agencies (McManus and McIntyre, 1981, p. 5).

Gypsy moth infestation worsened through the early 1970s with over 400,000 hectares of annual defoliation from 1971 through 1973 . Although damage was unevenly distributed in the Northeast, this outbreak was truly regional in scope. The severity of the developing gypsy moth problem of the time, coupled with the simultaneous occurrence of several other grave pest problems in other regions of the U.S., caused the USDA to further organize and focus its resources. It initiated the Expanded Gypsy Moth Program as part of the Combined Forest Pest Research and Development Program. The expanded program was designed to complement the accelerated program already underway and to better identify objectives which could be met in a 4-year time frame. The ultimate goal of the program was to incorporate new knowledge and technology into an integrated pest management (IPM) system for application to gypsy moth infestation both before and behind the leading edge (McManus and McIntyre, 1981, p. 5). Much of the information used in our study has been drawn from work sponsored by these two research programs.

Origin and past management of gypsy moth in Michigan

The first known, and still inconclusive evidence of gypsy moth in Michigan is thought to have been provided by an unlabeled container of larvae left at Michigan State University by an unidentified individual during the summer of 1952. It was not possible to determine where the larvae had been collected and no infestations or defoliations were reported in the following year, thus the presence of gypsy moth in Michigan as early as 1952 is suggested but not substantiated. The first verified occurrence of gypsy moth in Michigan came in the spring of 1954 when specimens from an infestation reported near Lansing, Michigan were identified as *Lymantria dispar L.* (Hanna, 1982, p. 193).

As in other states, a federal-state cooperative effort was begun in response to detection of gypsy moth in Michigan. The agencies involved were the Michigan Department of Agriculture, Plant Industry Division (MDA-PID) and the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA-APHIS-PP&Q). Joint federal-state arrangements were made to delimit the area of infestation using an emergency roadside survey made from slow-moving vehicles (O'Dell, 1955, p. 170). The area inspected included the cities of East Lansing and Lansing in Ingham County and rural sections of eastern Eaton County. It was concluded from this survey that gypsy moth infestation occurred over 43.71 hectares of Ingham County and the adjacent portions of Clinton and Eaton Counties (Hanna, 1982, p. 194).

The spread of gypsy moth to Michigan was considered to be artificial (life stages transferred by attachment to man-made or other objects ("commodities") which are themselves then moved, being exempted from or insufficiently inspected under quarantine regulations) because in 1954 the easternmost edge of the naturally infested area (the line to which gypsy moth life stages had advanced by their own mobility) was located in central Pennsylvania (Michigan Department of Agriculture, 1984, p.1). In conformity with the USDA's revived strategy of eradicating outlying, artificial infestations, urgent plans were made by cooperating pest control agencies for the "permanent elimination" of gypsy moth from the state by means of pesticide applications (Hanna, 1982, p. 194). An emergency proposal for funding of eradication activities was made to a special, limited session of the state legislature which subsequently appropriated $150,000 for an aerial spray campaign and follow-up surveys (O'Dell, 1955, p. 170-171). In the summer of 1954 approximately 58,000 pounds of DDT were aerially applied to over 40.47 hectares of land within the delimited area (Dreistadt, 1983, p. 143).

Despite the initial eradication campaign, gypsy moths continued to be found in subsequent years. From 1954 through 1962 the Michigan Department of Agriculture employed an average of 5,000 gypsy moth traps per year. These traps were baited with the natural sex attractant (pheromone) extracted from adult female gypsy moths and served the purpose of identifying gypsy moth infestation locations and delimiting treatment areas. Based on these trap surveys during this 8-year period, 107,244 hectares of land were identified for and subjected to aerial spraying with DDT (Dreistadt, 1983, p. 143-144).

After 1962 several changes were made to what had become an on-going gypsy moth control program. First, widespread concern had grown regarding the adverse effects of persistent pesticides such as DDT. A related incident occurred in 1962 when a farmer in the treatment area obtained a legal judgement against the USDA for loss sustained when milk was condemned due to DDT contamination. As a result, the use of DDT against gypsy moth was permanently discontinued in Michigan (Hanna, 1982, p. 194). The second change occurred in 1963 when natural pheromone bait was replaced by use of Gyplure, a synthetic pheromone trap bait. Gyplure was used in traps from 1963 through 1971 and, with the exception of 1966, produced no moth catches (Dreistadt, 1983, p. 144).

In 1966, mistakenly encouraged by lack of positive trap results obtained using Gyplure and confident that vigilant eradication efforts had been effective, the Michigan Department of Agriculture prepared and distributed a public information folder titled: "Where Oh Where did the Gypsy Moth Go?" which reported to the Michigan taxpayers the successful eradication of the gypsy moth (Hanna, 1982, p. 194). At about the same time a gypsy moth infestation was reported in Calhoun county. This proved to be an area previously treated with DDT. Trapping in this location did subsequently capture a few moths and in 1967, in an effort to avoid the risk of not applying enough insecticide, 4,856 hectares were aerially sprayed with carbaryl (Sevin) (Hanna, 1982, p. 194, and Dreistadt, 1983, p. 144). Gypsy moth was believed to have been eradicated from this spot in 1967 and no moths were detected in Gyplure baited traps in use through 1971 (Simmons and Fowler, 1986, p.1).

Beginning in 1972-73 several additional changes were made to Michigan's gypsy moth control efforts. Traps were redesigned and a new synthetic pheromone and improved chemical keeper (to extend pheromone life) were adopted to replace Gyplure. These improvements coupled with a doubled trapping effort produced 1,828 moth catches in 21 counties extending the length and breadth of Michigan in 1973 (Simmons and Fowler, 1986, p.1). Changes were also made in the use of insecticides and in the goals to be achieved with them. In response to positive results achieved with Disparlure as trap bait, applications of carbaryl and/or difiubenzuron (Dimlin) were initiated in 1973. Also, the former definition and goal of eradication was changed from one of eliminating gypsy moth from the state to one of "reducing gypsy moth populations in Michigan to nondetectable levels" (Dreistadt, 1983, p. 145).

Between 1973 and 1984 treatment of infestations with synthetic pesticides continued, with the exception of 1978 when the Organic Growers of Michigan and Citizens Against Chemical Contamination (CACC) obtained a temporary restraining order which caused the cancellation of scheduled eradication activities, and 1984, when *Bacillus thuringiensis* (a bacterial pesticide) was used on one 110 hectare spray block (Hanna, 1982, p. 195, and Simmons and Fowler, 1986, p. 2). Trapping activity for the period 1974 to 1984 was expanded in order to better detect and delimit new infestations. Approximately 1/3 of Michigan's Lower Penninsula and portions of the Upper Penninsula were trapped each year deploying from 16,000 to 99,308 traps in any one year. By 1984 moths had been caught in 76 of Michigan's 83 counties including all Lower Penninsula counties (Simmons and Fowler, 1986, p. 1).

Several related changes occurred in 1985-86 which are expected to strongly influence future control efforts. The precipitating change came on the part of the USDA-APHIS which had previously participated in cost-sharing programs with MDA on the pretext that gypsy moth could be eliminated from the state (one of several outlying infestations in the U.S. targeted for removal). However, late in 1984 APHIS communicated to MDA that the gypsy moth had become so widely distributed in Michigan that further attempts to eradicate it from Michigan's lower penninsula were considered (by the USDA) to be economically infeasible. Notice of this policy shift and its accompanying withdrawl of federal financial support was so sudden that MDA was unable to carry out planned eradication activities in 1985. Responding to increasing public pressure for action, Michigan's legislature mandated that MDA develop a management program to be implemented in 1986 which would reduce defoliation and nuisance impacts of gypsy moth. Accordingly, MDA has devised a plan whereby local governments share costs and decision making responsibility for control programs supervised by MDA. These policy and procedural shifts have been accompanied by a new philosophy of managing gypsy moth by attempting to limit defoliation but not to achieve eradication (Simmons and Fowler, 1986, p. 2). A complementary change occurred in 1985 when MDA began deploying traps in the Lower Penninsula portion of a system of permanent gypsy moth monitoring sites uniformly distributed across the state. In 1986 traps for the Upper Penninsula portion of this system will be deployed. This permanent monitoring system is expected to undergird a cooperative effort by Forest Pest Management Agencies in Michigan to establish a strong policy and research basis for an IPM approach for Michigan's gypsy moth problems.

In the 34 years since 1952, gypsy moth has created little noticeable defoliation in Michigan. However, defoliated acreages beginning with the first measurable occurrence in 1979 show a dramatic increase from 4.5 to 7,471 hectares in 1985. By 1990 it is expected that the acreage harboring gypsy moth populations high enough to create defoliation will grow to encompass 15 counties (Simmons and Fowler, 1986, p. 2).

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DESIGN OF A GIS-BASED RISK ASSESSMENT SYSTEM FOR GYPSY MOTH

Concept and Function of a Geographic Information System

The collection, storage, analysis, and display of spatial data are common decision-support tasks for workers who must make decisions involving distance, direction, adjacency, relative location, area, and other more complex spatial concepts on a regular, but often intuitive basis. In the past, such processing of location-related data has been done by means of a manual system consisting of a map and a human interpreter (Marble, et al. 1984a, p.(1-1) and Marble, 1982, p. (1-3)). The spatial data sets thus processed were/ are typically in the form of a paper "analog" map document. Integration of two or more of these map data sets has traditionally been done by transforming them to a common map scale, creating a transparent overlay for each set, registering all the overlays so their coordinate systems are aligned, and then manually creating a composite overlay sheet that shows those areas where various spatial data elements or phenomena occur in juxtaposition (Steinitz, 1977, p. 445).

Although the information stored on maps is often of critical importance, experience with this process has demonstrated that while it can be easy to retrieve small amounts of data, the retrieval of larger numbers of map elements, or attempts to quantitatively determine the complex relationships between map elements, is so slow and cumbersome that it is utilized far less than might be expected (Marble, 1984b, p. 18). In addition, analog maps have the disadvantages of being expensive and time consuming to change when modifications must be made to a spatial data base. Despite the high level of development achieved in technology for the creation and use of analog map documents, these and other fundamental disadvantages have never been overcome (Marble, 1984b, p. 18).

During the past two decades the development of modern computing technology has provided the basis for a new type of spatial information system: emphasizing quantitative or numerical (rather than qualitative) data, permitting storage of large quantities of data with rapid retrieval and analysis, and stimulating the development of new data creation techniques (such as digitization of mapped data) and data analysis techniques (such as models of complex systems) (Shelton, 1980, p.11-12). These new computer-based systems have come to be known as geographic information systems or GIS's. Although many such GIS's have been developed for the purpose of managing natural resources, they are equally useful in a great many other applications. Put most simply, a geographic information system represents a system, commonly computer-based, particularly adapted for handling spatial data (Marble and Peuquet, 1983, p. 926). In these systems spatial data elements are identified as points, lines, and areas; their locations are determined on the basis of a standard coordinate system such as latitude, longitude and elevation above sea level; and their aspatial attributes are measured and recorded in association (Marble, 1984b, p. 18). All complete GIS's are capable of performing four fundamental operations:

1. Data input - The capability to collect and/ or process spatial data derived from existing analog maps, aerial photographs, satellite imagery, field surveys, etc.
2. Data storage and retrieval - The capability to organize spatial data in a form which permits it to be quickly retrieved by the user for subsequent analysis, as well as enabling rapid and accurate updates and corrections to be made to the spatial data base.
3. Data manipulation and analysis - The capability to change the form of the data through user-defined aggregation rules or to produce estimates of parameters and constraints for various space-time optimization or simulation models.
4. Data reporting - The capability to display all or part of the original database as well as manipulated data and the output from spatial models in tabular or map form (Marble, 1984b, p. 19).

These operations provide the criteria for a full or complete GIS which exclude, by definition, several other information handling devices. GIS's can be distinguished from other information or data management systems such as MIS's (management information systems for business applications) or DBMS's (data base management systems now in widespread use on microcomputers) by virtue of their explicit focus on spatial entities and relationships (Marble and Peuquet, 1983, p. 927). Data management systems do not require the location distinctions upon which GIS's are predicated (Campbell, 1982 (?), p. 6). Other systems may have certain functions in common with true GIS's but may meet only part of these criteria. Digitizing systems whose purpose is data capture and which have minimal data storage capacity, do not qualify. Neither do most remote sensing or image processing systems which focus only on one broad category of data aquisition and analysis. Similarly, thematic mapping devices which concentrate on the production (rather than analysis) of complex computer maps are not equivalent to a true GIS (Marble, 1984b, p. 20).

The foregoing criteria describe the minimal capabilities of a full GIS, but in order for a qualifying GIS to be competitive, it must not only be capable of these fundamental operations, it must perform efficiently in all four areas (Marble, 1984b, p. 20). The simple addition of inefficient spatial data handling functions to devices which are designed to accomplish only some of the four minimal functions is not adequate. Also, some current systems, many of which qualify under this definition of a GIS, do not include an explicit linkage to spatial modeling activities. Soon this too will be included as a mandatory function of any true GIS (Marble, 1984b, p. 20).

The minimum criteria above are useful in identifying deficiencies in GIS's but they are less helpful in differentiating or evaluating geographic information systems which not only meet the minimal functional requirements, but also exceed or add to them in useful ways. It is helpful to understand that different GIS's can be complete according to the above criteria and can still exhibit variation in accessory features or in purpose, and that these differences may not be evident in the terminology used to describe the system as a whole. Complete geographic information systems might at the very least, consist of only the minimum functional components (computer technology). In expanded systems, GIS's might consist of not only the necessary functional components, but they might also include enhancements such as spatial modeling subsystems (computer technologies or sets of procedural logic). Finally, in systems which have already been implemented within the context of a particular set of spatial problems, GIS's may consist not only of computer technologies and their enhancements, they may also include one or more spatial data bases (digital map archive). The point is that in the case of an implemented system, a rudimentary GIS may not require "canned" spatial models or even modeling capability but it must include two fundamental parts; a data base or "data bank" and a data processing capability, typically a computer system. However, it is quite possible to have a GIS with full operating capability and have no data in the data bank, and thus, no application for which it has been prepared (Tomlinson, 1968, p. 201). It is also possible to have a geographic information system with full operating capability which is used to store numerous, independent data bases each identified in name as a different GIS (actually constituting different data bases) even though they depend for processing upon a common computer system and perhaps common modeling components.

Because all such variations are commonly referred to as GIS's, it can be difficult to know the precise kind of system which is meant. To better identify the special purpose GIS which this study has developed for use in gypsy moth management from the generic computer technologies upon which it depends (and from other data banks which depend upon the same computer systems), a naming convention has been adopted and will be used throughout the remainder of this study. Systems not used in this study will be referred to as "GIS's" in a generic sense unless their developers gave them a more specific label. The specific technology used in this study will be referred to by the trade names of the hardware and software components used. The system which this study has operationalized for management of gypsy moth and which includes a computer system, a specialized data base and a spatial (cartographic) model of gypsy moth risks, will be referred to as the Gypsy Moth Risk Information system or GMRIS.

Adaptations of GIS Technology to Forest Pest Management Needs

Among computer-based data processing technologies with applications to forest pest management problems, remote sensing (and allied technologies such as image processing) is probably the most familiar. The use of remote sensing technology has been well established since the early 1950s for purposes such as the classification of vegetation types and the detection of stress (Simonett, 1983, p. 3). Geographic information system technology, however, is a more recently developed capability and one to which remote sensing provides only one category of data input. Operational geographic information systems first came into being in the late 1960's as a means of facilitating the storage and analysis of large quantities of spatial data required for resource inventory, analysis and monitoring tasks. But only beginning in the late 1970s have efforts been identified which have undertaken to adapt geographic information systems to the objectives of forest pest management in the U.S. (Young, 1977).

During the past decade, as a result of a number of broad-ranging public mandates, important interdisciplinary planning was undertaken for the management of large heterogeneous tracts of national forest lands. This produced a great increase in data and data management efforts, forest-simulation capabilities, and multiple-objective decision-making systems. Quantitative computerized planning and management methods such as stand growth models, multiple-objective optimization programming, and pest management systems models have been useful in handling this burden but they are still incapable of including within their analytical framework a diversity of spatial data sets (such as wildlife, recreation of scenic quality components) or of responding accurately to projected changes in specific forest characteristics (Daniel, et al., 1983, p. 1-2).

Geographic information systems can be logically applied to these methodological deficiencies among forest management techniques. In fact, areas of potential pest hazard or actual pest damage are routinely identified by other means as units of land area (polygons) with a common attribute (value); similar levels of hazard or damage. These can be integrated with other resource data sets (themes or variables) as an initial step in estimating pest impacts or identifying areas of potential conflict (Pence, et al., 1983, p. 1). One such application would be the use of a GIS to integrate a data set containing information on the locations of pest activity with other data sets such as prime timber locations or recreational sites, to derive the juxtaposed locations where timber or recreation impacts might be expected. Similarly, data on alternate management strategies could be integrated with other data sets containing information on sensitive areas such as streams, lakes, and human habitations, to identify sites of potential conflict (Pence, et al., 1983, p. 1).

A literature search was begun at the start of this study to identify documented applications of geographic information system technologies to the achievement of forest management, and forest pest management (FPM) objectives. Few cases could be found in which GIS's had been designed or implemented for these specific purposes. Most of these cases represent initiatives of the U.S. Forest Service or other federal agencies although several state agencies have also undertaken cooperative state-federal, or independent GIS efforts. To date, most pertinent GIS development and applications activity has centered on the work of the U.S. Forest Service, Forest Insect and Disease Management, Methods Application Group (often in cooperation with the U.S. Fish and Wildlife Service) which has performed evaluations of commercial GIS's, participated in GIS development with other federal agencies, and sponsored pilot testing and implementation projects on various National Forests. One state has, however, also implemented a geographic information system for a forest pest management application; Pennsylvania has developed a unique GIS capability to manage its intensive, state-wide gypsy moth control program.

Although earlier GIS development by various field units has been cited, concerted action to organize data processing efforts appears to have been initiated in the U.S. Forest Service by establishment in 1975 of a special task force, the Systems Development Action Planning Team, formed to analyze and recommend ways to work with computers more effectively, and by Russell and others at the Pacific Southwest Forest and Range Experiment Station who designed the first in-house GIS, the Wildland Resource Information System (WRIS), since renamed the Resource Information Display System - Polygon Processor (RIDS*POLY) (Pelletier, 1979, p. 338 and Deschene, 1981, p. 1). Parallel but independent evaluation studies of commercial and governmental geographic information systems were begun by federal resource management agencies in the late 1970s. Some of the efforts of the two agencies principally involved, the Forest Service and the Fish and Wildlife Service, have since converged.

Benchmark studies evaluating the performance of GIS's for federal forest management purposes began in 1976 with evaluations done by Schwarzbart and others (Young, 1977, p.3-4). In 1977, Young (p. 1-4) reported on the first effort by the U.S. Forest Service, Forest Insect and Disease, Methods Application Group to compare the suitability of two commercial "computerized mapping systems" (PLOT and WRIS (now RIDS*POLY)) for processing forest insect and disease data by enabling mapping of chronic problem areas, and superimposition of related map data. Also in 1977, the U.S. Fish and Wildlife Service (USFWS), Western Energy and Land Use Team (WELUT) undertook an evaluation of existing GIS software with the objective of selecting the best available package for use in developing operational GIS capability within the Service (USFWS-WELUT, 1978, p. 105). The latter study, by far the more thorough of the two, found that none of the 52 systems evaluated met even half of the USFWS's requirements for a full GIS. Later, in 1979, Young (p. 1-2) evaluated, and found positive results with a single "state-of-the-art" commercial GIS within the context of a forest management demonstration project carried out on The Black Hills and Targhee National Forests.

In 1977 the U.S. Fish and Wildlife Service, presumably in response to their discouraging evaluation results, and by using some of the software thus acquired, initiated development of the Map Overlay and Statistical System (MOSS) which, after an early period of divergent growth under the support of several federal agencies, was later unified and widely adopted. The U.S. Geological Survey, which has been charged with responsibility for coordination of GIS activities among civil agencies, conducted an evaluation of vector-based GIS's in 1981-82 and found MOSS to be the best available system for public domain (non-proprietary) use (Thompson and Oleson, 1984, p. 75-76 and USFWS-WELUT, 1978, p. 105). MOSS offers a diverse array of data manipulation procedures and although existing versions contain features which were not designed to optimize their compatibility, proposals have recently been made for needed enhancements and standardizations (Lee et al., 1985, and Thompson and Oleson, 1984, p. 75-76). In 1975, to avoid further duplication of GIS development activities among a growing number of their field units, the USDA Forest Service developed a coordinated GIS capability now called RID*POLY (Pelletier, 1979, p. 337-338). This system meets the minimum functional criteria specified above but offers a data manipulation capability which is limited primarily to tabulation and overlay procedures (Deschene, 1981). Of the two GIS's, MOSS appears to have gained the wider base of user agencies which also includes units of the U.S. Forest Service.

In recent years numerous GIS demonstrations and field tests have been carried out by the Forest Service on the Nicolet and other National Forests and on test sites in Pennsylvania. Some of these projects have developed unique, general-purpose GIS capabilities but most have relied on RID*POLY and / or MOSS in some manner to address forest pest management and other planning needs (Martin, 1985, p. 1755). Projects implementing MOSS have been undertaken by the USFS Forest Pest Management, Methods Applications Group and the USFWS Western Energy and Land Use Team. These studies have typically concluded that GIS technology is useful, if not indispensable in achieving management objectives which are dependent upon complex spatial information analysis (White, 1985 and Morse, 1985, p. 1). Particularly noteworthy was a project carried out in 1983 in Mifflin County, Pennsylvania the purpose of which was to demonstrate the capabilities of MOSS to retrieve and analyze data on gypsy moth infestations. Mifflin County was selected because it was part of a 1981 test site for evaluation of high altitude panoramic aerial photography for mapping defoliation by gypsy moth. MOSS, coupled with a specially constructed county pest management data base, was used to measure net area of spray blocks, establish stream-side buffer zones, and evaluate foliage protection following treatment. The study found MOSS to work efficiently, to be sufficiently user-friendly, and to facilitate timely decision making (Pence et al., 1983, p. 1,3).

Federal development of forest resources data bases, GIS technology and methods for their further integration have continued in recent years. Every national forest in the U.S. now has a data base stored in the data base management system (DBMS) called System 2000 or S2K which is capable of data reduction and analyses and is designed to enable interactive queries in English-like language. In development since 1975, this DBMS has been used for timber management and sales purposes and is now being integrated into pest management applications (Daniel, et al., 1983, p. 4). Integrated remote sensing (image analysis) and geographic information system capabilities have recently been developed and are being tested by the Forest Service in Atlanta, Georgia for application to various inventory and assessment problems (Lachowski and Allison, 1985, pp. 10-6).

The principle Forest Service effort at integrating such technology is an on-going one undertaken by the Forest Pest Management, Methods Application Group called the Integrated Pest Impact Assessment System or IPIAS. Originally developed to assess impact of the Mountain Pine Beetle in Colorado, the project was expanded and has itself become the principal Forest Service model for GIS-based pest management technology. IPIAS grew out of efforts to develop and integrate models for pest and treatment effects on economic and amenity values of forests, and on stand growth and mortality. Damage and contagion models were later added. The objective of integrating models and related data bases in a management system was achieved by the assembly of three subsystems consisting of a textual/tabular data base management system (S2K), a set of socioeconomic and forest prediction models, and a geographic information system (MOSS). The modular format of IPIAS has been found to allow other models and data bases to be readily substituted for applications to other forest and pest types or any management problem where changes in forest characteristics can be described or modeled . The general framework of IPIAS has been found to provide a comprehensive model which can enhance the precision, reliability, and usefulness of socioeconomic variables in the forest planning and decision-making process (Daniel et al., 1983, pp. 2-5,18 and Hamilton et al., 1985, p. 1,3). Since its development and use in Colorado, the IPIAS "concept" has been used on the Nicolet National Forest in Wisconsin for management of Saratoga spittlebug, spruce budworm, and white trunk rot of aspen (FPM-MAG, 1984, p. 2). More recently, IPIAS has been implemented and demonstrated on the Red River Ranger District of central Idaho's Nezperce National Forest, again for management of the Mountain Pine Beetle (FPM-MAG, 1985, p. 1).

Several state-level projects have also been carried out which apply information systems technology to gypsy moth management needs. In 1982 the Renewable Resources Evaluation

Project of the U.S. Forest Service Southeastern Forest Experiment Station rated state-wide risk for gypsy moth in Virginia. This undertaking was a straight-forward attempt to select forest type and site condition inventory data which would approximate better indicators of susceptible forest stands for which no direct measures were available. Using a set of screening criteria based on four variables or data sets, queries were made of the Forest Information Retrieval (FIR) system, a customized tabular data base management system (DBMS), to identify combinations of variables which indicated likely susceptibility. A similar though slightly more ambitious approach was taken by the Illinois Natural History Survey, Economic Entomology Section, which has been working since 1983 to develop a risk assessment model to classify forested areas in Illinois as susceptible or resistant to gypsy moth defoliation. The Illinois model employs composition and tree growth form data, and software contained in the Illinois Forest Inventory Data Processing system (IFIDAP) (Jeffords, 1984a, p. 18 and Jeffords, 1984b). IFIDAP does not include location identifiers for stored data and while it is designed to perform calculations and summarizations (Pelz and Thom, 1977, p. 1), it does not perform spatial analyses and is thus not a geographic information system according to the definition stated earlier. The first information system to be used operationally for annual assessments of insect damage to forest canopies was begun in 1982 by Pennsylvania's Division of Forest Pest Management in cooperation with the NASA/Goddard Space Flight Center. The project was designed to overcome the limitations of manual processing of annual, state-wide gypsy moth defoliation data by developing a unified, rapid defoliation data retrieval and analysis capability. The system consists of a data base comprized of spatial forest resource, defoliation and administrative data; a data base management system; image processing software for LANDSAT data (from which most other data is derived); and a user-friendly "front end" system which integrates all features to form a geographic information system capable of manipulating the resulting LANDSAT-derived database. This system has been found to enable forest entomologists to prepare timely surveillance reports and pest management plans (Williams et al., 1982. p. 191,195-96 ; 1985, p. 648-49, 655).

Design Criteria for a Gypsy Moth Risk Information System

One of the principal objectives of this study has been to make maximum use of available computer resources and existing data sets. This precondition was imposed on the study in acknowledgement of the considerable difficulty, delay, and expense that accompanies development of computerized information systems. As a consequence, criteria for the operation and function of computer systems and for the acquisition and use of data, which normally would be established in the system design phase of a project, have been largely predetermined with respect to their use in gypsy moth risk assessment. This has allowed us to circumvent difficulties arising from the fact that relatively little has been written on the problems of initial design of GIS's and upon appropriate methods for selecting among existing systems (Marble, 1984c, p. (6-1)).

The design of geographic information systems has been found to consist of three major components: the functional design specifying what the system is to do, the design of the data base and its contents, and the detailed design of the entire system's operation (Calkins, 1983, p. (6-4)). It is not necessary to specify criteria for the functional or operational design of the system, since these have been accepted by default in choosing to employ several preexisting GIS's (computer hardware/software systems). It is, however necessary to document the operational and functional features of those systems we have adopted for use and this has been done in the remaining portions of this chapter. Design criteria for the multi-user data sets we have adapted for use in forest pest management, and for the custom software and data sets which are unique to our project, are provided in the subsequent chapters on model development and data base construction, respectively.

Although we did not have the option to substitute a preferred geographic information system for those immediately available for use at Michigan State University, we did have the option to procede or not based upon the ability of these available systems to meet, with minimal alteration, the objectives described at the beginning of this report. To the degree that design, in the narrow sense used here, can constitute adaptation of existing GIS components to a specific application, it is possible to specify one meaningful set of criteria. The criteria we used to accept or reject the available or achievable system configuration are essentially those variables which have been suggested to define system boundaries. System boundary refers to the definition of the system in terms of variables such as purpose, clientele, subject, geographical coverage, etc. (Marble et al., 1972, p. 1250-1252) . While parts of this definition have been determined in a de facto manner, the point of view taken in this study is that of the system user for whom the following are the nearest possible approximation of true design criteria.

1. Type of system (purpose)

The immediate purpose of a geographic information system for gypsy moth risk assessment was to determine the usefulness of local GIS capabilities and existing data to forest pest management, to demonstrate pertinent concepts to managers and policy makers, to improve upon decision making procedures used in pest management and related research, and to identify additional data and systems development needs.

2. Geographical area (areal coverage)

Full geographic representation was to be achieved for the entire state of Michigan including both the upper and lower penninsulas each at the same scale and spatial resolution. Islands were to be represented uniformly throughout all data sets. Detailed data for contacting states or water bodies was not to be included since a regional (multi-state) perspective was not intended. Regional coverage for multi-county areas within the state was to be evaluated and exploited where possible to test a hierarchical (higher resolution, windowing) approach.

3. Subject (data requirements)

A digital base map of land use/cover was required. This data must was to be available for the entire state, derived from a recent inventory, and collected and prepared by an external source without adverse impact on project resources or schedules. Other data requirements include: host type, major transportation corridors, climatic factors (precipitation, temperature, and wind), defoliation zones, insect population levels, soil water holding capacities, and land ownership/administrative units. In satisfying other data needs, maximum use was to be made of existing secondary data, preferably in digital form. Collection of primary data was to be limited, if possible, to annual pest surveys in which study members were already participants.

4. Object (functional requirements)

Execution of this study requires a GIS possessing only those capabilities which are currently typical of or nearly standard in complete systems. Features that will be of particular importance include: the ability to input data by manual digitization; the ability to process data in raster rather than polygon format; the ability to manipulate data to derive reclassifications, overlays, searches, and crosstabulations; the ability to interpolate a continuous surface from discontinuous (point) data; and the ability to output data to a high resolution color monitor in a grided or raster format. It is accepted that an interface will need to be created to link the DBMS in which tabular survey data are stored (CCMS, now MANRIS) and the GIS which is used for spatial analyses.

The evolution of geographic information systems technology is propelling change toward a design "environment" in which more emphasis will need to be placed on evaluating existing components and their ability to meet system requirements. To evaluate existing capabilities, functional requirements will need to be specified more precisely than in the past and related performance and testing criteria will have to be defined. This review and evaluation function is very important because it represents the beginning of the dialogue between users and the system designers which must continue throughout the design process (Calkins, 1983, p. (6-10),(6-12)). This study is intended to initiate practical evaluation of the system described below by applying it to a pest management problem to which it should be well suited, and evaluating its performance and impact within the context of that problem.

<u>Components of the Gypsy Moth Risk Information System</u>

The number and kind of components making up an information system can vary depending primarily upon whether one includes with the subsystems which handle spatial data, the management subsystem which must coordinate operations and the decision subsystem which is expected to benefit from information thus derived. Operationalizing and applying GIS technology to actual problems such as the management of gypsy moth, requires a broader perspective of the kind which introduces performance objectives concerning both GIS users and GIS managers which necessitates their inclusion too within the boundaries of a geographic information system (Myers and Shelton, 1980, p.12-17).

A generic, full potential geographic information system will typically consist of four data handling subsystems which provide capability for; data input, data storage and retrieval, data manipulation or analysis, and data output or display. These functions require devices such as computers (terminals and CPU's), magnetic and other storage units (tape, disc drives, etc.), digitizers (manual or automatic) or scanners, printers, and display screens (CRT's). In addition, the operation of the forementioned devices and their peripherals, and the execution of data analysis and other procedures require specialized software (usually programs). Taxonomies of hardware and software useful in the design or selection of GIS's have been prepared by Tomlinson (1972) and Dangermond (1984) respectively. The reader is referred to these authors for additional detail with the cautionary note that all of these technologies are now undergoing rapid change.

Following is a brief, introductory description of the subsystems and devices which, when integrated in accordance with our cartographic risk assessment model, form a unique configuration of GIS components known collectively as the Gypsy Moth Risk Information System (GMRIS). This is followed by a brief summary of the system's principle data manipulation and analysis capabilities. Additional information on hardware and software components can be obtained from subsystem manuals or from references cited below. Full descriptions of the GMRIS model, and the data base supporting it, are included in subsequent chapters. Detailed descriptions of specially developed software sets, which are discussed further in the chapter on the chapter on data base construction, are available from contacts listed at the end of that chapter.

Users and managers

The information use subsystem is usually external to the information system although it can be considered part of the system, particularly if there is only one user. However, even if this subsystem is not formally included, it is important to consider it because this is where the ultimate justifiction for the whole information system must be established (Tomlinson, 1972). Designers of information systems must consider their audience carefully from the beginning through every phase of construction and operation of the system (Myers and Shelton, 1980, p. 13).

Users and managers of GMRIS have some common members. The key agency with responsibility for gypsy moth management is Michigan's Department of Agriculture (MDA). However, several other agencies or programs, under the aegis of the Michigan Cooperative Forest Pest Management Program, and the Cooperative Crop Monitoring System (CCMS) have become cooperators with the MDA in gypsy moth-related activities. Also, GMRIS was intended to depend upon computing, and some data base resources maintained by MSU's Center for Remote Sensing (CRS). As a result, Michigan State University's Department of Entomology and CRS have, in effect, become co-managers of the system, the former contributing data base management and modeling needs, and the latter contributing computing facilities (GIS) and support for data base development. To a lesser extent, the Michigan Department of Natural Resources, Forestry Division, and the Michigan Department of Agriculture, Plant Industry Division have also become manager/users in so far as the former will continue to direct and contribute data from its annual pest surveys, and the latter will likely contribute equipment and personnel to annual monitoring activities. At this time all inter-agency relationships pivoting on the development, use and maintenance of GMRIS are purely informal. It is hoped that the co-management involvement of all groups will expand and perhaps become formalized in the future as each contributes additional data collection capabilities. All groups will use data from GMRIS, in different proportions and in different ways, to supply information useful for gypsy moth research, forest and forest pest management, gypsy moth control, and public education.

Computer systems

The Gypsy Moth Risk Assessment System actually consists of several independent computer systems which perform complimentary tasks. These computer systems are parts of separate facilities at Michigan State University which have GIS development and application as a common interest. Compatibility between these systems has been established by designing utility software that allows data files to be transported to support different functions at each of these facilities.

GIS data manipulation and analysis operations are currently carried out primarily on several turn-key GIS systems maintained by the Center for Remote Sensing (CRS) and the Comprehensive Resource Inventory and Evaluation System (CRIES) both at Michigan State University. CRS maintains a dedicated ERDAS 400 system and a PC-AT -based ERDAS system both supported by two microcomputer data input stations. Mass storage is provided by a Cipher tape drive and a 40 megabyte-capacity Bernoulli Box. CRIES maintains several similar ERDAS 400 systems, one coupled with a 96 megabyte removable hard-disc drive and a Cipher tape drive. CRIES also has designed, operates and distributes the CRIES-GIS, a PC-based GIS software package (Schultink and Zusmanis, 1985, p. (11-11)). All these systems are fully functional GIS's supported by various output devices and other peripherals except the CRIES-GIS which does not yet support a color user interface.

Graphic data for risk assessment are stored as GIS files or digital maps on the above systems or on appropriate magnetic media. Tabular data are stored on a minicomputer by arrangement with the Cooperative Crop Monitoring System (CCMS) a pest surveillance system developed and operated by MSU's Department of Entomology using INGRES, a large capacity DBMS (Gage and Russell, 1986, p. 5-6). The same minicomputer also supports any necessary preprocessing or complimentary statistical analysis. This system contributes substantial mathematical processing power and flexibility not offered by the GIS systems themselves.

Data acquisition and storage

Two kinds of risk assessment data can be identified based upon different temporal resolution requirements inherent in the variables being observed. Data on land use, forest type (host), climate, and other non-insect phenomena exhibit little change over relatively long periods of time as compared to data on insect populations and their impact. The reasonable "shelf-life" of non-pest data used by this project has been assumed to be about 5 years; about the period of time expected to elapse before technological advances will likely warrant re-evaluation, if not redesign or replacement, of the entire process outlined in this chapter. In contrast, insects generally, and gypsy moth in particular, have great capacity for rapid population change over a single year. Consequently, population monitoring data such as male moth trap catch and egg mass density, and larvae and pupae quality data must be collected yearly. Similarly, pest impact data on the extent and severity of defoliation must also be collected on an annual basis. Of course the analysis, or re-analysis of most data according to a model of gypsy moth risk must also be performed annually.

Data considered to have a useful 5-year life are considered within the planning horizon of this project, and are input to the system (GMRIS) once by digitizing analog maps and storing the resulting spatial data files on GIS systems and appropriate media. Pest data on gypsy moth populations or their impacts require both an on-going survey or field-inventory program for their collection and substantial preprocessing and analysis before they can be transported to the GIS described above.

Annual population data are provided to GMRIS by the gypsy moth survey conducted by the Michigan Department of Agriculture, Plant Industry Division in cooperation with the Michigan Agricultural and Natural Resources Information System (MANRIS) (formerly CCMS) (Gage and Russell, 1986, p. 6). This survey now provides base-line data from a grid system of permanent, uniformly distributed trapping sites deployed throughout Michigan's Lower Penninsula. In 1986, this system will be expanded to include the Upper Penninsula and perhaps to involve the collection of habitat data from a sample of these sites which will become permanent observation plots. Pest impact data on the extent and severity of defoliation are currently collected by means of aerial sketch mapping carried out by one or more state agencies. In 1986, the use of aerial reconnaisance using video cameras was evaluated for use in state wide detection and rating of forest defoliation. This, or some other more reliable, accurate, and economical means of collecting defoliation data for large areas of the state will likely be critical within several years. Annual impact monitoring activities are a cooperative effort of the Michigan Departments of Agriculture and Natural Resources.

In addition to the data referred to above which has a spatial resolution of 1 km^2. and a temporal resolution (after analysis) of one year, plans have been made to collect higher resolution pest population data on a number of variables which will allow the development of population dynamics models. Such models would likely allow much more precise prediction of changes in insect populations especially in assessments conducted for regions of the state or for separate forest stands. Population dynamics models and higher resolution data sets will likely need to be added to the current system design to further improve forecasting capability.

Models

Two types of models are needed to successfully integrate both the forecasting and decision-making activities involved in assessing gypsy moth risks. A model for inter-agency or inter-program cooperation or collaboration is necessary so that institutional needs can be accurately determined, complimentary objectives can be formulated, resource uses can be optimized, and resulting technologies and methods for their use can be "transferred" (installed and maintained among participating agencies). There is also need for a model of the GIS analysis process which charts the logic and organizes the procedures necessary to process data into risk assessments.

The first of these models, a decision-making model, is already in existence in the structure of a formally conceived, but informally operated interagency forest management team composed of representatives of several of Michigan's Universities, the Michigan Department of Natural Resources, the USDA Forest Service, and, more recently, the Michigan Department of Agriculture (Wilson et al., 1983, p. 109-110 and MCFPMP, 1986, p.1-2). Goals of these agencies are united under the Michigan Cooperative Forest Pest Management Program which forms an institutional framework which has guided the development, evaluation, and institutionalization of GMRIS.

The second model type, a cartographic risk assessment model, has been designed as a part of this study to match risk forecasting needs to currently available data and computing resources. This model, which is the subject of the following chapter, organizes spatial data analysis procedures into a logical sequence of actions which produces a hierarchy of risk assessment maps. Used in concert, these two models prescribe and document the processes that allow data to become information in a scheme to better manage gypsy moth and forest resources.

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DEVELOPMENT OF A GYPSY MOTH RISK PROJECTION MODEL FOR MICHIGAN

Risk Assessment Terminology

Considerable ambiguity exists among terms commonly used to express risk-related concepts as they apply to the impact of insect pests on forest resources. While some agreement does exist, acceptance of the meaning of many risk assessment terms is far from universal. In fact, few attempts have been made to define the meanings of key terms used by designers of risk models with the result that terminology has become confusing and often contradictory. This problem was acknowledged by Talerico (1980, p. 169) in a review of risk assessment systems developed for a broad array of forest pest combinations in the U.S. Imprecise terminology makes it difficult to build new risk rating schemes on standard concepts or to evaluate schemes employing different units of measurement, different thresholds of impact, or different variables.

Particularly problematic are the terms risk and hazard which often are used interchangeably. Witter and others tried to clarify these expressions for use in spruce budworm risk assessment by interrelating them with other imprecise terms which Talerico had earlier identified (Witter et al., 1984, p. 56). Risk-rating systems were defined as rankings of forest stands according to their susceptibility, or likelihood of attack by a particular pest. Hazard-rating systems were defined as rankings of forest stands according to their vulnerability, or likelihood of damage from a particular pest. These terms were found to be interrelated in the sense that susceptibility was construed to determine the severity of attack and, thus, the level of damage that is likely to occur (Witter et al., 1984, p. 56).

Another source of confusion arises from the paired usage of the terms susceptible and resistant to characterize, as a range, the likelihood that a particular forest stand will be attacked by gypsy moth. Most risk assessment systems for the gypsy moth make use of such a continuum extending from resistant to susceptible ratings to express the degree of likelihood or (nonstochastic) "probability" that a forest stand will be attacked by a particular forest pest. These terms were defined relative to each other by Painter who classified the degree of resistance of a plant to insect attack at levels ranging from immunity, through high, medium, and low resistance, to high susceptibility (Knight and Heikkenen, 1980, p. 65). Although different researchers have employed different terms to express intermediate levels along this continuum, the terms resistant and susceptible are nearly always retained as the extremes and connote in the former case, a positive immunity to infestation or absence of vulnerability to injury or damage, and in the latter case an absence of immunity or positive vulnerability. It is not assumed in this study that the relative invulnerability of a host to attack or injury by a specific pest can be equated with the presence of an immunity to that pest. Rather it is assumed that variation in the likelihood or consequences of attack by an insect pest represents only variation within a range of susceptibility to infestation, or within a range of vulnerability to injury or damage.

The preceding distinctions between hazard and risk and between susceptible and resistant forest stands have not been found to be useful ones in this study.Instead, a standard terminology has been redefined which is better adapted to the needs of a spatial or cartographic model of risk assessment. It is based on the observations that no singular and meaningful distinction exists between the concepts of hazard and risk; that of the two, risk is a more useful umbrella concept (the term "hazard" is hereafter excluded); and that all other related concepts should be logically nested within the central expression "risk". Morris has identified two additional risk concepts: the risk or likelihood of outbreak, and the risks associated with the selection of various control methods (Morris, 1980, p. 25). In the standard terminology proposed here, these concepts would simply represent differences in degree or definition within a hierarchy of five risk-initiation concepts: host capability, habitat suitability, habitat susceptibility (the term resistance is hereafter excluded), host vulnerability, and infestation acceptability. These five nested risk concepts can then each be further characterized by specific risk "ratings". These terms and their uses are fully defined later in this chapter.

The term risk "assessment" is reserved for a broader risk evaluation scheme involving several or all of these concepts in a collective sense. All risk evaluation or analysis schemes mentioned in this report are hereafter referred to as risk assessment systems. The execution of forecasts or other estimations of future events performed with risk assessment systems designed by others are hereafter termed predictions. Forecasts achieved with GMRIS are hereafter termed projections in recognition of their current reliance strictly upon extrapolation from known events and phenomena.

Purpose of Risk Assessment in Forest Pest Management

Risk assessment is a small, but essential part of forest pest management which in turn is but one component of a prevailing forest management regime. Forest pest management is a three-step process consisting of; quantification of pest impact; identification of when and where damage will occur; and determination if cost-effective, environmentally and socially acceptable methods of pest population management exist (Hedden, 1981, p. 9). Risk assessment is the practice concerned with the prediction of where damage or injury to forests is likely to occur. The prediction of when impacts on a forest will occur is normally reserved to the practice of population prediction, although many risk assessment systems are based upon a good understanding of pest population behavior (Hedden, 1981, p. 9).

The practical purposes of risk assessment systems have been characterized by Witter and others who reviewed systems used to assess spruce budworm risks in eastern North America and found that they varied according to the planning horizon and objectives of forest managers (Witter, et al., 1984, p. 56). Some systems were found to emphasize short-term objectives and to serve the purpose of helping managers determine which stands needed to be sprayed or salvaged during the next year or two. Other systems were found to emphasize long-term objectives for the purpose of helping managers reduce the vulnerability of the forest over time by facilitating selection of areas requiring protective spraying, scheduling of salvage operations, and selection of cutting areas.

Historically, most risk assessment efforts have been directed at the short-term, direct control of forest pests (Hertel, 1981, p. 13). Such systems emphasize remedial, rather than preventative methods. More recently, forest pest management systems which employ risk assessment practices have begun to emphasize the concept of damage prevention in which areas requiring intervention are identified and treated to minimize the chance of damage and to maximize control. However, the ability to predict where insect damage is likely to occur may also lead to a more efficient system of remedial control in which population monitoring and control efforts can be concentrated in accurately identified high-risk areas (Hedden, 1981, p. 9). This trend in management practice of deemphasizing pesticides and stressing integrated pest management (IPM), stimulated in part by reduction of federal support for large-scale spray projects, is expected to continue and to spur more intensive investigation of long-term, primarily silvicultural, means of reducing damage. Risk assessment is expected to be an important component of such work (Morris, 1981, p. 24).

Types of Risk Models Used in Forest Pest Management (FPM)

In the absence of a universally accepted terminology for risk assessment systems, it is impossible to differentiate risk modeling methods based upon their labels. And, although it should be possible to differentiate these models according to their structural, methodological, or performance characteristics, little has been written about the classification or evaluation of forest pest risk assessment schemes and, in fact, most are of relatively recent origin and many have not yet been tested (Morris, 1981, p. 23). Such systems may differ substantially with regard to the forest type which is at risk, the insect pest which is initiating risk, or the underlying site conditions.

In his review of risk assessment systems in the U.S., Talerico (1981, p. 169) found many to have common variables correlating risk with measurements such as tree age; basal area (growth rate, stand density); site (soil depth, aspect, topography); history (damage, ground cover, defoliation); crown characteristics (tree growth form); and insect counts. He also acknowledged variability among risk assessment systems noting that some models had to be calibrated for use in different regions, that many still required adequate validation or refinement, and that few addressed the socio-economic consequences of insect damage (Talerico, 1981, p. 169).

Hedden (1981, p. 9-10) has identified two fundamental kinds of risk assessment systems represented by what he terms either biological (or mechanistic) or empirical models. Biological models are based upon a good understanding of the relationships between the insect, the host tree, and the environment and they require a well-developed knowledge base. Actual design of a biological type risk model is preceded by the actions of identifying factors critical to the buildup of pest populations,and components of host resistance, and determining the influence of the environment on these factors. The advantages of this sort of model are that it can easily be evaluated for application in a region different from that in which it originated (because it is based upon a detailed understanding of the target system), and it may easily be modified if necessary (since it is based upon known biological linkages).

Empirical models are based upon the apparent or correlative relationships among insect, host, and the site. This type of model does not imply causation. Empirical models are typically designed when understanding of important underlying relationships is limited or when they are too complex to allow a biological model to be developed. They have the disadvantage of not being easily generalized to regions or conditions different from those in which they originated but they have the advantage of being more economical to develop. However, an empirical model can be used to suggest geographic or subject matter areas for further research and may ultimately lead to the development of a biological model. The reverse strategy can also occur in which researchers "compromise between biological realism and system complexity" by using biological relationships to develop an empirical model (Hedden, 1981, p. 9-10).

Conventional risk models for forest insect pests may also be distinguished on the basis of whether they are qualitative or quantitative. Although the form of a model depends upon its intended use, the complexity and understanding of the pest/host system, and the existing forest management regime, several tentative modeling prescriptions can be made (Hedden, 1981, p. 11). Qualitative models may suffice when assignment of broad categories of risk are all that is necessary. Quantitative models may be more appropriate to generate broad classes of risk which can, in turn, be used to determine treatment guidelines.

Of particular importance to this study is a method of modeling specifically adapted to the requirements of studies which employ geographic information systems for the analysis of data. Although risk assessment models, as distinguished from population prediction models, have a common, explicit concern with where risks may occur, a review of literature carried out during this study indicated that most risk models do not use spatial data as a direct input to the computations or judgements that may be required. It appears that most forest management systems use numerical or descriptive risk models which employ alpha-numeric, or tabular input data, irrespective of whether a mapped output is generated by some means. In contrast, risk models which perform computations on mapped data require both the capabilities of a geographic information system (GIS), and a modeling technique designed for the unique data analysis requirements of GIS's. Berry has described a method called cartographic modeling whereby the routine, primitive analytical operations of which a (full) GIS is capable can be organized in a logical manner best suited to a particular analytic task and, by treating entire mapped data sets as variables, manipulated in a kind of "map algebra" (Berry, 1981b, p. 414-415). In such a context, primitive map analysis operations can be considered analagous to traditional algebraic equations in which mathematical operations are sequentially ordered to solve complex expressions and to find unknowns. In this case, the unknowns represent entire mapped data sets which are derived according to relationships and procedures defined in the cartographic model (Berry, 1981a, p. 15-17).

Previous Methods Used to Model risks Due to Gypsy Moth

Most operational or applied risk assessment systems have been designed to predict impacts of insects such as bark beetles, weevils, and spittlebugs that kill trees outrightly by inflicting lethal damage (Talerico, 1981, p. 169). Systems designed to predict impacts of insects that defoliate and, thus, weaken trees are either still in development or require additional refinement. This difference in maturity between these two application areas may be attributable to the economic imperatives associated with rapid, directly induced mortality as contrasted with the complex and subtle biological and socioeconomic interactions associated with defoliation (Talerico, 1981, p. 169). Risk assessment efforts for the gypsy moth, a defoliating forest insect pest, fall into the latter category of systems which are in an earlier stage of development. Although a simple classification of forest stand susceptibility to gypsy moth, which was devised in 1947 (Bess et al. cited by Houston, 1981, p. 268), would qualify here as a risk assessment system, most such systems for this insect have been designed in about the last decade and are not in widespread use.

Risk assessment systems for gypsy moth can be classified according to their specific purpose and by the method each employs to establish levels of risk. The purposes of risk assessment systems examined for this study were found to be the determination of either the vulnerability or the susceptibility of forest stands although in some cases, partly because of ambiguous terminology, these purposes became less distinct and actually intergraded.

Susceptibility assessment systems

Valentine and Houston (1979, p. 468-469) have provided useful clarification of the terms forest "stands" and "susceptibility". They suggest that forest stands may be differentiated as potential hosts by consideration of whether they lie inside or outside the endemic range of gypsy moth and thus, whether they represent historically, newly, or never-infested stands. They divide "susceptibility" into two categories; resistant and susceptible which refer to the likelihood or frequency of defoliation (or indirectly, infestation), not the effects or consequences of defoliation. Relative to resistant stands, they define susceptible stands as those which contain abundant habitat for gypsy moth populations, and are apt to be defoliated often. They suggest that when populations increase to high densities, susceptible stands may serve as foci from which widespread infestations emanate. Resistant stands are those which provide scant habitat for gypsy moth populations and are defoliated only when large numbers of wind-dispersed larvae are blown into them. They find that in resistant stands, immigrant populations tend to be reduced quickly (within 2-3 years) by natural control agents, although subsequent defoliations may occur if more larvae are blown in.

The first effort to determine susceptibility to gypsy moth was made by Bess and others who, in 1947, initiated current terminology and established that ecological conditions may be of equal, if not greater importance than the presence of preferred food species (suitable hosts) (Houston, 1981, p. 267). This early study classified New England forest stands according to frequency of defoliation, as a function of species composition and history of disturbance.

Houston and Valentine (1977, p. 447) built upon Bess's early study in the attempt to predict, rather than simply characterize, forests which were likely to be defoliated often,and those where mortality was likely to be significant. They compared defoliation episodes and responses by the gypsy moth using data from 168 Northeastern forest stands and multivariate analysis methods. By means of principal-components analysis ordinations based on feeding preferences of the gypsy moth, and structural features of different hosts, they were able to separate stands into groups that were historically susceptible or resistant to prolonged infestation. Part of this procedure required subjective judgement made on the basis of criteria established in Bess's study. Later Valentine and Houston (1979, p. 468-469) compared resistant and susceptible stands using discriminant analysis in an attempt to provide a more objective measure of defoliation risk. Their discriminant function was based on structural features data from 121 northeastern mixed-oak forest stands. Because the structural feature variables used are not host-specific, it was thought this model would be useful in identifying potentially susceptible stands that had not previously been infested. However, the model had the disadvantage of not using site index or other standard inventory variables making it less useful in estimating the amount of susceptible forest in an area from existing inventory data (Valentine and Houston, 1981, p. 137). To make the model more practical, it was later modified to use less expensive and more easily measured habitat variables, and to include an additional discriminant function using standard inventory variables for contingency use when habitat measurements are not available (Valentine and Houston, 1984, p. 270-271).

Several risk assessment models have been designed which draw on previous work in separating susceptible and resistant stands and which also employ computerized information processing systems. The first of these is a risk assessment model for Illinois forests which uses variables from Valentine and Houston's model for which Illinois data are available, and which uses Valentine and Houston's original data from northeastern forest stands for partial validation. The Illinois model employs a classificatory discriminant analysis and a logistic multiple regression with stand composition, structural features, soil drainage, and topographical data which are handled by a tabular data management system, the Illinois Forest Inventory Data Processing System (IFADAP). The first two of these variables are obtained from Illinois forest inventories and the last two are interpreted from U.S. Geological Survey (USGS) map products sources. Computations are performed by IFADAP to predict the susceptibility or resistance of stands with known defoliation histories, and to estimate probabilities that given stands are susceptible (Jeffords, 1984a, p. 4; 1984b). The second of these risk models is one which makes subjective use of Valentine and Houston's variables to select "screening criteria" for use in querying a tabular data management system which provides forest statistics for geographic areas in the southeastern U.S. This data base management system, the Forest Information Retrieval system (FIR), is maintained by the Renewable Resources Evaluation (RRE) project at the Southeastern Forest Experiment Station. In order to identify the most susceptible of commercial forest lands in Virginia, data from a 1977 survey on forest type, site conditions, physiography, and stand size were used to approximate food preference and refuge variables used by Valentine and Houston. FIR is used to sort and exclude stands which do not meet screening criteria before assigning susceptibility ratings to those which remain (Huber et al., 1982, p. 2).

The final type of system for predicting susceptibility of forest stands is the index of feeding preference. The only identified example of this approach is a study by Lechowicz and Jobin (1983, p. 171-172) in which an Ivlev-type electivity index is used to quantify larval feeding preferences of gypsy moth. Data for this model were collected from a random sample of 922 trees and included; diameter at breast height (dbh), estimated foliage biomass, and number of feeding larvae. Deviations from a random case in which foliage of a tree species is assumed to be utilized relative to its abundance, are incorporated into algorithms which are then used to express the feeding preferences for each tree species evaluated.

Vulnerability assessment systems

The effects or consequences of infestation or defoliation by gypsy moth, provide the definition for the term "vulnerability". Although they do not use the term, Gansner and Herrick (1984, p. 21), have further clarified vulnerability as it was originally defined, via omission, from Valentine and Houston's earlier explanation of susceptibility. They suggest vulnerability to be an estimate of potential stand and tree mortality or change in timber value.

Houston (1981, p. 290) has cited a number of early attempts to model mortality of forest stands due to gypsy moth defoliation. He observes that nearly all such models are retrospective in that they attempt to predict future defoliation consequences on the basis of specific historical cases. The earliest of these models were simple tables and mortality curves based on data from the Melrose-Highlands study (the earliest, large U.S. data set available). Another model features regression equations developed from data on a two-year defoliation of the Newark Watershed in New Jersey. These early cases are not described further here.

More recent attempts to determine the vulnerability of forest stands are best represented in modeling efforts begun by Gansner, Herrick, and White in 1978 (p. 1-2). In their first effort they used stepwise multiple regression analysis techniques with data from 143 untreated sample plots in Pennsylvania to develop equations which estimate tree mortality based on simple stand condition characteristics. This model employs defoliation impact as the dependent variable, and pre-outbreak stand condition parameters as independent variables. Mortality is expressed as number of tree (timber) losses. This model was later refined by addition of the automatic interaction detection (AID) technique to separate mutually exclusive groups of stand conditions and to identify corresponding impact in each group (Gansner, 1981, p. 161-63 and Herrick, 1981, p. 165). Recently the model has been further expanded to include a simple equation for estimating the potential impact of defoliation on stand value which requires knowledge of only a few elements of stand condition (Gansner, 1984, p. 22).

Design of a Cartographic Model of Gypsy Moth risks in Michigan

Introduction

None of the models reviewed for the assessment of risks associated with gypsy moth are well adapted to current forest pest management circumstances in Michigan. Most of these models employ multi-variate statistical analyses of detailed forest inventory data on variables such as site condition and the structural features of trees to discriminate between susceptible and resistant stands. These detailed kinds of inventory data are not available on a state-wide basis in Michigan. Also, most of these models have been designed for use in the eastern hardwood forests of the ridge and valley physiographic province of the northeastern U.S. where mountainous terrain exerts a controlling influence on variables such as soils, drainage, and wind currents. Because such models are not adapted to the very dissimilar ecological conditions found in Michigan, they would require significant recalibration if they were accepted for use. None have yet been fully validated, so generalization from the conditions for which they were designed may be premature. They are also deficient with respect to the requirements of our study because the integration of socioeconomic variables into these models is not yet well developed and none have demonstrated a useful application of information systems technology beyond simple retrieval and processing of tabular data.

Entomological systems require that modelers consider: plant and animal behavior and physiology, including temperature and other weather-dependent developmental relationships; occurrences of time lags, if any, in development or other essential functions for each species; and populations age structure, host or prey specificity and preference, and the dispersion of the various life stages within the habitat (Gutierrez and Wang, 1984, p. 739). The difficulty of successfully constructing such a comprehensive model of the ecology of gypsy moth becomes apparent if one considers; that a state-wide analytic scope is required; that gypsy moth management poses inherently broad questions since it involves a wide range of biological, sociological, and economic impacts; and that bioecological understanding of Michigan gypsy moth populations is extremely limited. It is under these circumstances that empirical rather than biological models should be used, acknowledging the complexity of the problem, limited understanding of functional relationships, and the need to rely on expert judgement. Available modeling techniques range from scenario writing to mathematical forecasting models, but whatever technique is used, forecasts are always based on past and current data, observations, or measurements, plus assumptions about connections to the future (Findelsen and Quade, 1985, p. 134). For many broad problems and those requiring expert judgements (often made implicitly), forecasting can make very little use of quantitative models and for this reason forecasting techniques should be chosen that are not too sophisticated for the available data (Findelsen and Quade, 1985, p. 134). If data are scarce or inaccurate, simple judgemental forecasting models are often as good as very complex ones. It may, in fact, be inappropriate, in the early stages of analysis when more qualitative answers are sought, to attempt to use more complex forecasting models (Findelsen and Quade, 1985, p. 134). As previously stated, the geographic distributions of pests and hosts are fundamental to entomological models which are thus implicitly spatial in nature. Geographic information systems can provide an obvious solution to spatial analysis problems encountered by modelers who must forecast the geographic character of pest infestations. Marble has observed, however, that while complex spatial models require substantial data inputs on a detailed spatial and temporal level, few such models make use of the powerful capabilities of GIS's to provide these data (Marble et al. 1982, p. (1-1)).

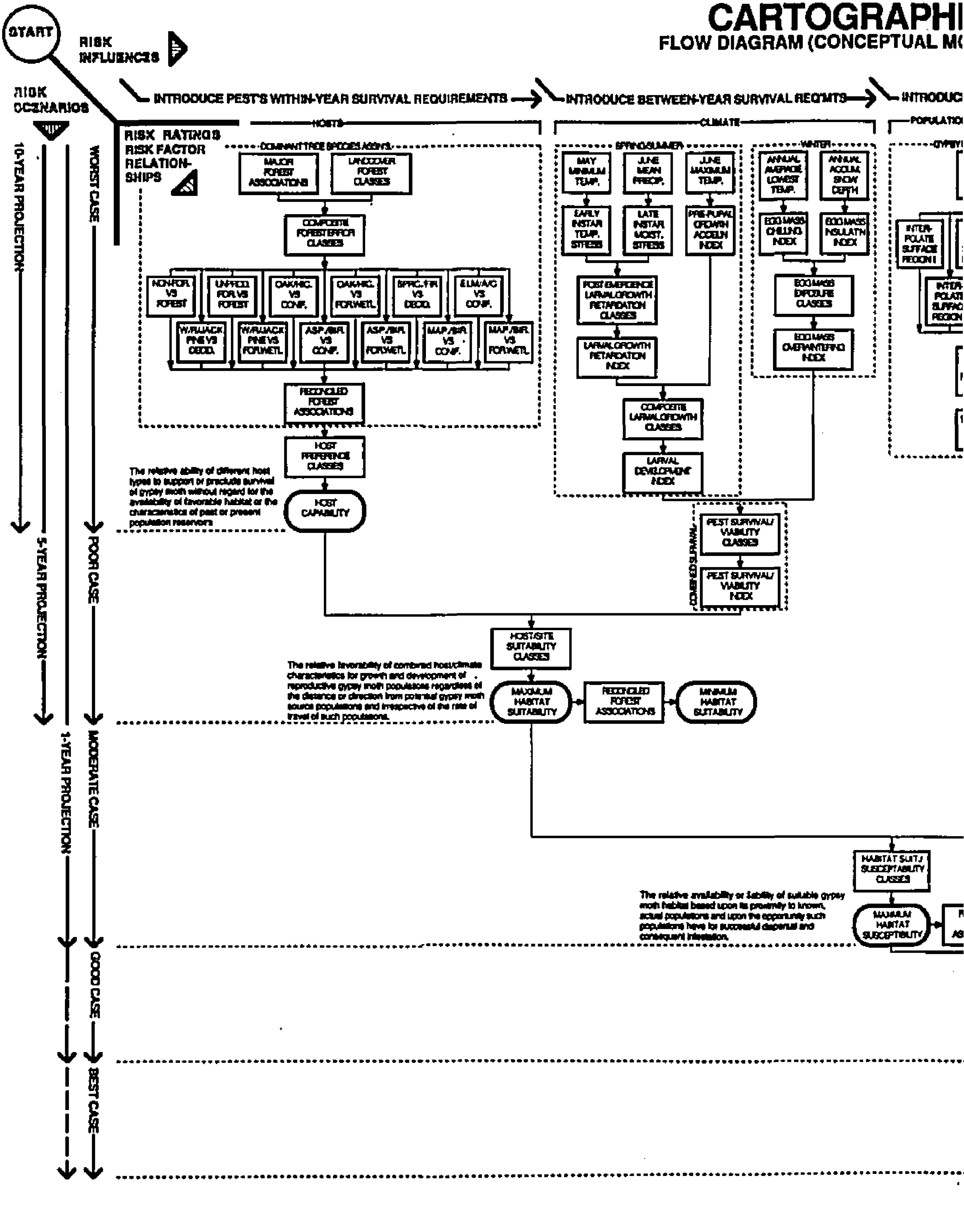
The kind of model selected for the Gypsy Moth Risk Assessment System (GMRIS) is a "conceptual" one which assumes all of the above mentioned limitations prescriptive of empirical models. Etter (1981, p. 708) defines conceptual models of such systems as predominantly verbal or diagrammatic descriptions; he defines a naturalistic description of the life system of the gypsy moth as a conceptual model. The modeling technique selected for use in this study is that of a flow diagram showing factors which initiate or influence risks due to gypsy moth, functional relationships between such factors, logical combinations of available data used to derive risk ratings, and scenarios which indicate the relative "gravity" and "longevity" of gypsy moth risk ratings produced (Figure 1). Crouch and Wilson (1982, p. 10) have suggested that to associate a risk with more complex events or actions, it is necessary to break those actions down into individual smaller actions, the summation of which is usually assumed to be possible. This assumption is reflected in the "modular" organization and "cumulative" process depicted in our diagrammatic (conceptual) model. It is worth noting that such models are no less useful than their bio-statistical or mathematical counterparts when applied appropriately. Etter (1981, p. 708) asserts that such models are essential in formulating a conceptual design for a humanly purposeful system, and that the conceptual design is itself a conceptual model of the proposed system. In many cases, he adds, successful implementation may proceed easily and directly from a largely conceptual model.

Our model is a cartographic one which organizes spatial data sets as variables within a pest management framework in which primitive mathematical operations are sequentially ordered for execution using a geographic information system to derive data display maps which characterize risks. The logic employed in this scheme systematizes various terminologies adapted from the fields of forest pest management, natural resources inventory and evaluation, and risk assessment and integrates them with fundamental properties of spatial distributions made explicit in cartographic models and in geographic information systems. It is helpful to remember that all data subjected to analysis in this risk assessment system are mapped data and because of this, the fundamental organizing principles of the scheme are the ecological and bio-geographical relationships of phenomena and objects represented in the data. Non-spatial ecological relationships are used in a preliminary sense to grasp, qualify, select, and prioritize bio-geographic

Figure 1. Cartographic model for gypsy moth risk assessments.

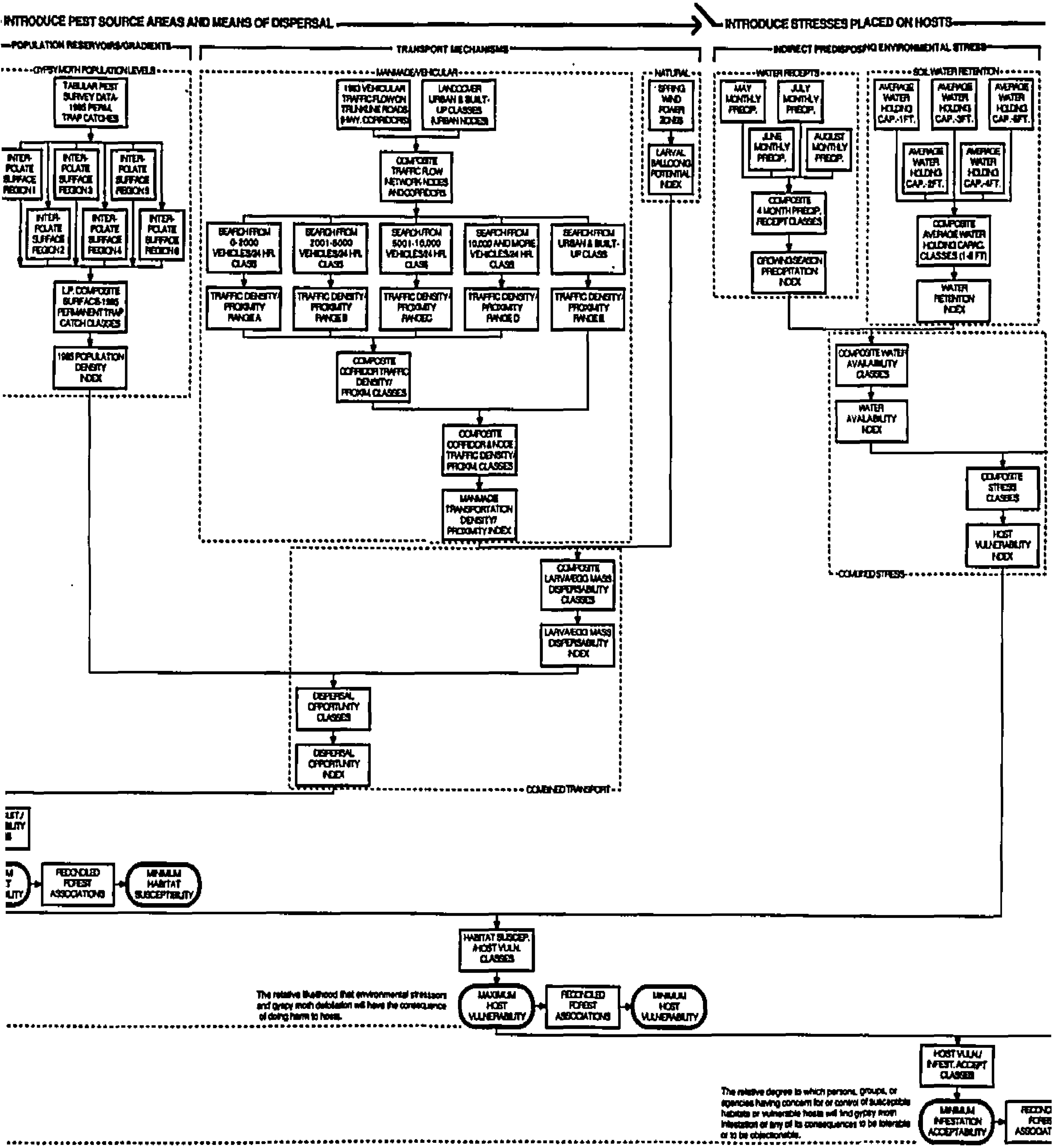
CARTOGRAPHI

FLOW DIAGRAM (CONCEPTUAL M



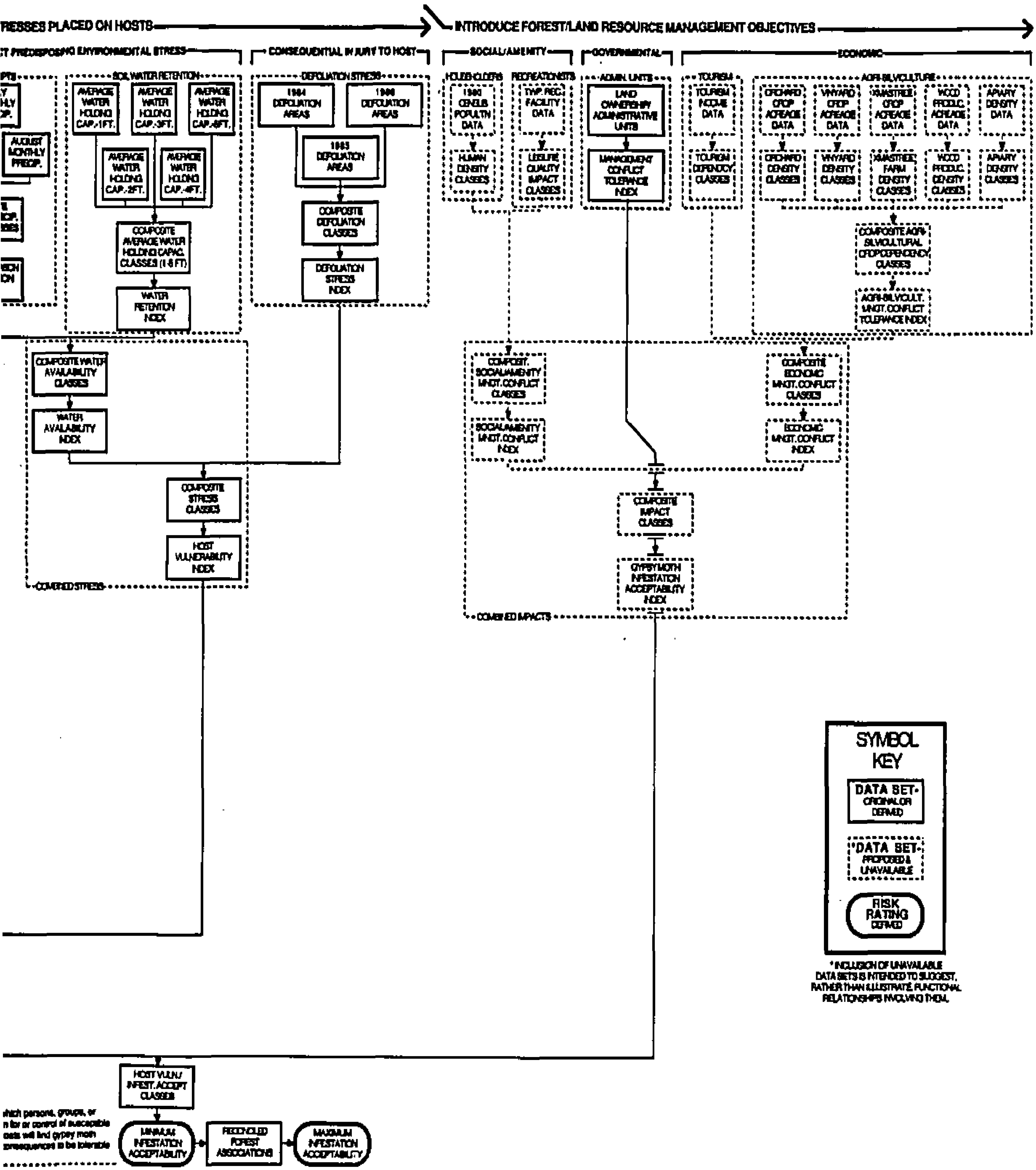
APHIC MODEL: STATE-WIDE GYPSY MOTH RISK ASSESSMENT-198

UAL MODEL) OF SPATIAL (GIS) ANALYSES TO PROJECT RISKS TO MICHIGAN FOREST LANDS DUE TO INFESTATION BY GYPSY



SESSMENT-1986

E TO INFESTATION BY GYPSY MOTH



relationships which are then examined in a direct rather than an inferential manner by using our spatial model to control data manipulations performed with the GIS.

An empirical rather than biological approach has been taken here in which model design is based on apparent insect/host/environment relationships. This is a reflection of the fact that gypsy moth ecology and population dynamics in Michigan are not yet well understood. It is likely that this model will lead to, and be capable of supporting development of biological models based on more detailed understanding of the target system. Although the current model was conceptualized as a hierarchical one in which localized (multi-county/township) risk assessment, and forest pest management research, could be supported at a higher resolution (grid cell size smaller that 1 km^2.), data limitations prevented this. The model is however, hierarchical with respect to the sequential, "cumulative" logic used to represent risk initiation and development.

The model is qualitative and deterministic. It is qualitative because; (1) the measurement scales used to represent variables are reduced to, or maintained as, nominal units (high-medium-low, severe-moderate-slight-negligible, etc.); (2) no complex arithmetic operations are performed on combinations of variables; and (3) no attempt is made to derive a numeric "grand index" of risk. The model is deterministic or non-stochastic in so far as no probabilities have been attached to estimates of risk.

The model has several strengths. First, it makes appropriate use of current knowledge by employing existing data and the advantages of geographic information systems to analyze large land areas using multiple spatial variables that are interrelated in complex and poorly understood ways. Second, it builds logically on existing technology and existing needs by integrating new demands for pest risk assessment with on-going resource management efforts in the areas of data base construction and computerized data processing. The model also addresses a number of objectives proposed for forest pest risk assessment systems by Talerico (1981, p. 169) by: fully defining terminology; including socioeconomic consequences of infestation; facilitating the use of remotely sensed data to locate, identify, and initially categorize management areas ; minimizing mathematical computation required to make risk estimates; and combining potential risk projection capability for several insect pests within one method.

Structure

The cartographic model for the gypsy moth risk assessment system is depicted as a flow diagram consisting of a number of submodels, identified along the horizontal axis, which are structured in a hierarchical framework (Figure 1). Each submodel represents a discrete risk "influence" and is comprised of a number of digital or map data sets, depicted as rectangularboxes which represent variables organized into a logical sequence of analytic procedures. Each of the original input variables is described in the following chapter both in terms of the character of the data and the method used for its preparation. Connecting lines indicate the order of integration of each of these variables or data sets using the fundamental data manipulation and analysis operations of the geographic information system. The broken lines of boxes denote variables for which data could not be obtained and the broken lines of connecting pathways represent analytic procedures that could thus not be used. The broken lines of very large boxes group closely related sets of variables within individual submodels.

The sequence in which submodels are employed and the "cumulative" method by which their results are integrated, define individual risk "factors" which are depicted by semi-elliptical symbols in the model positioned along a diagonal from upper left to lower right. Although each retains a distinct meaning, when viewed collectively, these risk factors define a more inclusive and multidimensional concept of risk in its entirety, as it is intended here. The flow of logic reflected in this model runs from the upper left to the right, and down. Beginning with the "start" point and with risk initiation via the host factor, the analysis of each submodel produces a range of outcomes expressed as an index which is then combined with its preceding risk factor, itself expressed as a range of risk ratings ordered by rank.

Along the vertical axis at the left of the diagram are four "scenarios". The first of these concerns the comparative severity of magnitude of risks and the other three concern the time frame within which risk ratings may be expected to be meaningful. These scenarios and other parts of the cartographic model are described in greater detail below.

Risk factors

The cartographic model designed for GMRIS is predicated on five components or risk factors as they are called here, which, taken collectively, define the overall concept of risk as it applies to potential incidences and consequences of gypsy moth infestation in Michigan. These five factors are described fully below.

1. Host Capability

The relative ability of different host types to support or preclude survival of gypsy moth without regard for the availability of favorable habitat or the characteristics of past or present pest population reservoirs. Host capability ratings suggest the potential which may exist for hypothetical gypsy moth life stages to survive solely as a function of the presence or absence of preferred kinds of food and shelter. No inference can be made regarding the prosperity or viability of gypsy moth populations that may survive (see 2).

2. Habitat Suitability

The relative favorability of combined host/climate characteristics for growth and development of reproductive gypsy moth populations regardless of the distance or direction from potential gypsy moth source populations and irrespective of the rate of movement of such populations. Habitat suitability ratings suggest the potential which may exist for hypothetical gypsy moth populations to prosper when the presence of capable host(s) is reinforced by advantageous environmental circumstances. No consideration is made of the characteristics of past or present gypsy moth population reservoirs (see 3).

3. Habitat Susceptibility

The relative availability or liability of suitable gypsy moth habitat based upon its proximity to known, actual populations and upon the opportunity such populations have for successful dispersal and consequent infestation. Habitat susceptibility ratings suggest the potential for gypsy moth infestations to occur or recur where existing source populations, and directed mobility are reinforced by hosts and habitats that meet or exceed survival requirements.

4. Host Vulnerability

The relative likelihood that environmental stressors and stresses induced by defoliation (by gypsy moth) will have the consequence of doing harm to hosts. Host vulnerability ratings suggest the potential for biological or physiological injury and tree mortality which may result from predisposing stressful conditions and gypsy moth attacks occurring in susceptible habitats. No inference can be made regarding "damage" or any other form of harm which is expressed through a socio-economic value system (see 5).

5. Infestation Acceptability

The relative degree to which persons, groups or agencies having concern for or control of susceptible habitats or vulnerable hosts will find gypsy moth infestation or its consequences to be tolerable or to be objectionable. Infestation acceptability suggests potential conflicts which may arise where the presence of gypsy moth life stages causes actual or perceived "damage" thereby reducing the utility or enjoyment of trees or other resources by commercial, recreational, and other user groups representing an array of socio-economic value systems and resource management objectives.

These five concepts form a hierarchical organization in which each is nested within those that precede it. They are arranged hierarchically in the sense that any consideration of risk must begin with the first (lower) of these factors which represents the initiation of risk due to potential gypsy moth infestation. They are nested because successively "higher" (rightward) factors are defined by and flow from preceding "lower" (leftward) factors and can not be considered without their prior examination. The notion of higher or lower positions in this hierarchically organized risk analysis scheme should not be confused with higher or lower levels of estimated risk due to gypsy moth infestation. Each of these risk factors is represented, when the model is operationalized, by a range of ratings which map its associated degree or severity by rank. Analytic combinations are made using the "maximum" representation of each derived risk factor in which the entire land area of Michigan is assigned some positive level of risk. This has been done in acknowledgement of the need to evaluate relative risks of areas whose land cover is not principally forest but whose (unknown) endowment of trees might nevertheless contribute in some degree to risk of gypsy moth infestation. After combinations are made to produce these "maximum" versions, each is altered by deleting nonforested lands to create areas of negative risk and to produce its "minimum" counterpart in which only predominantly forested lands are considered to be at significant risk. These paired ratings for each risk factor are designed to present approximated risks as a range between "maximum" and "minimum", and to provide more information to those who will interpret risks.

Risk Influences

Each of the model's risk factors as described above, is introduced by one of five sets of risk influences. The combination of these influences represents the totality of risk due to gypsy moth. Starting with host type, each successive set of influences contributes a complex of risk factors to the accumulative, final definition of risk. The purpose is to provide a more meaningful framework within which to integrate and align bio-ecological and socio-economic understanding of the gypsy moth with knowledge of its associated risks and its forest pest management requirements. The sequential method depicted in the model diagram is intended to simplify the logical progression of increasingly complex bio-geographic events by creating a sieve-like approach in which spatial data are subjected to progressively narrower criteria to screen out subsets of risk data that are conceptually more refined, and spatially more restrictive at each stage.

The result is a multi-dimensional model of risk in which each component is a successive redefinition of the meaning of risk but in which each retains distinct meaning and none is entirely redundant when combined to assess risk holistically. Examining the totality of risks due to gypsy moth requires the examination of each of five risk ratings and their relationships - the recombination of these within the model to calculate a singular "grand index" of risk has been purposefully avoided.

Each set of risk influences along the horizontal axis of the diagram is characterized by the introduction of an additional source of risk in the form of subgroups of variables selected from available data sets, on the basis of existing knowledge of gypsy moth biology and population dynamics. This has required that knowledge gained from study and modeling of gypsy moth, primarily in the northeastern U.S., be modified by the judgement of Michigan forest pest management experts to reflect Michigan's particular ecological conditions. The problem of selecting specific quantitative thresholds, whose appropriateness can only be verified by further research on Michigan gypsy moth populations has, for now, been simplified by using a strictly relative scheme to rank data for analysis and interpretation. In such a scheme all values of the variables are retained throughout spatial analyses but they are grouped or aggregated into rankings of severity or magnitude made on an equal or nearly equal proportion basis. Thus a variable described by a scale of values expressed in quantitative units (such as meters) or qualitative units (such as federal versus state or other lands) is classified or assigned to an ordinal scale (such as a scale ranging from high to low) that will reduce the original variable's range of values sufficiently to allow intuitive comparison without losing too much detail through aggregation. The reason for such reclassification is to make explicit the abscence of precise specific numeric thresholds and to avoid performing mathematical operations which are inappropriate to the measurement levels used to define a given variable. In cases having odd numbers of scale intervals or cases requiring relatively greater aggregation, the procedure has been to "split" very high (or extreme) values and to "lump" very low values. The logic in doing so is to retain the relatively more acute sensitivity these high or extreme values may provide as spatial indicators of risk. The same logic regarding the absence of reliable numeric thresholds has dictated that we avoid the use of weightings when using the combination functions of the geographic information system (two exceptions to this rule occurred in the cases of composite water holding capacity, and transportation corridor data sets, which required that weights be used. These weights were not explicitly reintroduced into subsequent analyses in any way). In all cases, the judgement of project investigators was the final arbiter for such reclassifications.

Following is a summary of the risk influences which have been built into the current model and the reasons for their use. Important risk influences which appear in the model diagram, but are not represented in the data base (denoted by broken lines), are also discussed below with the hope that their inclusion will clarify other concepts used here.

1. Introduction of Within-Year Survival Requirements

The introduction of the gypsy moth's short-term (within-year) life requirements in the form of host preferences provides the source of criteria by which host capability is projected.

Preferrence on the part of the gypsy moth for certain host types as sources of food and shelter is a risk assessment criterion common to all the rating systems previously reviewed. This is true despite early findings that it is not the presence or abundance of preferred host species that places a forest stand at risk of gypsy moth infestation, but rather ecological conditions such as those resulting from disturbance (Houston, 1981, p. 267). Houston and Valentine (1977, p. 459-60), upon whose model most later efforts have been based, acknowledge the subordinate role of host species, but address ecological conditions only indirectly as expressed through structural features of trees taken to be symptomatic of site conditions.

Forest inventory data on structural features of existing stands are not available for all of Michigan's forest lands. Data are available, however, for the alternate approach of attempting to identify potentially stressed sites where ecological conditions may place trees at risk. These data have been included in our model, but not as a substitute for host type as the initial influence in the risk process. We have retained host type in the position of risk initiating influence, and as an indicator of food and shelter preference, for two reasons. First, major (dominant) forest association data are the only forest inventory data available for the entire state. Second, of the fundamental influences on forest pest/stand relationships (host, pest, and environment), the mobility of pest populations suits their influence to a position in a spatial model of risks which is intermediate to the identification of potential hosts and the identification of potential consequences of infestation. Positioning pest population influences after host influences allows the concept of contagion to be applied on a geographic basis. Positioning population influences to logically precede site conditions, allows the concept of predisposing stress to be applied. Both of these concepts are described fully in 3 and 4 below.

One variable (spatial data set), major forest association or dominant forest type, is used in this model to represent the influence of the gypsy moth's within-year survival requirements.

2. Introduction of Between-Year (Reproductive) Survival Requirements

The introduction of gypsy moth's long-term survival requirements in the form of hospitable climatic conditions, in combination with host capability ratings, provides the source of criteria by which habitat suitability is projected.

Research has found the gypsy moth to be strongly affected by climate (Leonard, 1981, p. 22). Climatic influences which help to regulate gypsy moth populations can be separated into warm and cold weather periods each exhibiting countervailing effects. Cold weather carries the threat of mortality from freezing unless gypsy moth eggs successfully "over-winter". Exposure of egg masses to temperatures below -9 degrees C. for extended periods of time, or brief exposures to temperatures below -23 degrees C. can be lethal. Unusually deep snow cover or behavioral adaptations causing moths to lay eggs closer to the ground (below the average snow line) can increase the chances that eggs will survive cold temperatures as a result of the insulating properties of snow. Spring freezes that occur after hatch can also increase mortality by killing young larvae and/ or new leaves (Leonard, 1981, p. 22).

Temperature and moisture effects of warm weather periods can act to reinforce or retard development. Periods of high rainfall coinciding with gypsy moth hatch in late spring can increase mortality by washing-off and drowning young larvae. Periods of low populations have been correlated with high amounts of rainfall during early larval development. Exposure of larvae or pupae to consistently high temperatures in the 32 degree C. range can greatly accelerate their growth and development. Widescale outbreaks have been correlated with successive years of hot, dry weather during June (Leonard, 1981, p. 22).

Variables (spatial data sets) and their roles (indices) as used in this model to represent the influence of the gypsy moth's between-year survival requirements are: (a) mean maximum temperature in June (larval growth acceleration index), (b) mean minimum May temperature and mean precipitation in June (combined larval growth retardation index), (c) average annual lowest temperature and mean annual accumulated snow depth (combined egg mass overwintering index).

3. Introduction of Pest Source Areas and Means of Dispersal

The introduction of pest source areas and means of dispersal in the form of current population reservoirs and potential mobility patterns, in combination with habitat suitability ratings, provide the source of criteria by which habitat susceptibility is projected.

Known source areas or reservoirs of gypsy moth are generally determined from past population centers inferred from defoliation zones measured in the previous year or they are determined from egg mass or moth trapping surveys which can better indicate the concentration of individuals that may be expected to emerge in the future. High gypsy moth populations can easily be detected by obvious larval activity or by defoliation visible from aircraft or from the ground (Talerico, 1981, p. 31). Low density populations are more difficult to detect and require ground surveys to measure the units per acre of one or more life stages. Measurement of populations at low densities is more valuable because it permits concern with more confined unit areas, it allows managers lead time for planning, and it can provide trend data if superceded with annual observations on the rate and direction of population movement (Talerico, 1981, p. 31). The presence of man-made objects (MMO's) has been found to be a good indicator of potential source areas or reservoirs, particularly at low population densities, because of the additional refugia they provide (Campbell and Sloan, 1977, p. 323).

In its winged life stage, the gypsy moth is capable of only limited mobility in that the female is essentially flightless and the male's travel is consumed in searching flight usually directed by the female's sex attractant. However, the egg and larvae life stages of gypsy moth are more dispersible; the former by means of attachment to objects which then are transported by humans, the latter by means of wind currents which carry young larvae aloft and move them downwind moderate distances, sometimes in repeated episodes. Dispersal of egg masses attached to movable objects, particularly vehicles, can account for transport of the gypsy moth over great distances. Such "artificial" introductions of gypsy moth to remote locations was the basis for early quarantine of this insect (Talerico, 1981, p. 31). Dispersal of young larvae by wind generally results only in local spread of the insect (Talerico, 1981, p. 31). Conrad and others (1981, p. 177) have shown that although winds of only 2 miles per hour are sufficient to dislodge and transport larvae, and despite their capacity to repeatedly redisperse, the total distance covered by an individual is probably not substantial. Only larvae lifted above the canopy or those blown from the forest edge are likely to be carried by updrafts to heights where they can be dispersed for hundreds of meters or perhaps even kilometers, thus only a small proportion of the total larval population has the potential for long-range transport on wind currents. Efforts to model atmospheric dispersion of gypsy moth in flat terrain (typical of most of Michigan's Lower Penninsula) support this conclusion indicating that the probability is high that most larvae will be deposited within 1 kilometer of their origin (Conrad et al., 1981, p. 199). The concensus of opinion with regard to the importance of wind velocity to dispersal is that the greater the winds, the greater the amount and extent of dispersal that can be expected (Conrad et al., 1981, p. 200).

Although transport of gypsy moth on wind currents is regarded as a very limited dispersal mechanism, long range transport of gypsy moth life stages attached to man-made objects and commodities --particularly vehicles -- has no similar limitation. The importance of vehicular movement was acknowledged in the 1912 federal quarantine against gypsy moth which remains in effect for the purpose of reducing the accidental long-range transport of gypsy moth life stages on regulated commodities (McManus and McIntyre, 1981, p. 1). Highway corridors and areas of dense road networks are thus of obvious importance to the dispersal of gypsy moth.

Variables (spatial data sets) and their roles (indices) as used in this model to represent the influence of pest source areas and dispersal mechanisms are: (a) gypsy moth pheromone trap catch levels from the current or previous year (gypsy moth population density index or surface); (b) major roads and highway corridors differentiated by four levels of traffic density, and major urban areas representing a fifth density level as nodes within the road network (combined man-made transportation density/ proximity index); and (c) wind power zones (larval ballooning potential index).

4. Introduction of Stresses Placed on Host

The introduction of stresses placed on the host in the form of defoliation and soil moisture deficits, in combination with habitat susceptibility ratings, provide the source of criteria by which host vulnerability is projected.

When defoliation of trees occurs with sufficient severity or frequency, they dieback, decline or are killed. Studies of the consequences of gypsy moth defoliation have found that tree mortality begins to occur when defoliation exceeds 60-75 % of crown foliage. Such heavy defoliation for 2 or more successive years can trigger significant mortality. Defoliation below this level, even when repeated for as many as 5 years, results in relatively low mortality. But these lower levels of defoliation are sufficient to trigger refoliation initiating the trend toward dieback, decline, invasion by other organisms, and eventual death (Houston, 1981, p. 287-88).

Recent research has revealed that tree condition prior to defoliation is one of the most significant variables related to subsequent mortality (Gansner et al., 1978, p. 2). The presence of trees that are in poor condition before defoliation is a strong indicator of other adverse environmental stresses such as drought, frost, and other defoliators, working singly or in combination (Houston, 1981, p. 289). High mortality occurs on adverse sites with either poorly drained or excessively drained soils. In addition to droughty conditions, poor, dry sites are also the most likely to be defoliated repeatedly, and are often conducive to maintaining relatively high populations of mortality-causing agents such as the twolined chestnut borer. Severe, protracted droughts can compound the situation on excessively drained sites. Trees on poorly drained sites, such as those on wet bottoms and benches with perched water tables, may also suffer high mortality perhaps because trees in low-lying sites are often exposed to late spring frosts, they may suffer from even slight drops in water tables, and they often support tree species that seem to be vulnerable to defoliation (Houston, 1981, p. 289).

Variables (spatial data sets) and their roles (classes) as used in this model to represent the influence of stresses placed on hosts are: (a) Mean monthly precipitation for May-August (growing-season precipitation index), (b) average water holding capacity of each 1-foot increment of soil to a depth of 5 feet (water retention index), (c) 3-year defoliation record (defoliation stress index). No attempt has been made to accurately model water balance. This would require the addition of evapotranspiration data and would require further testing. Also, no adjustment has been made for the relative drought tolerance or drought intolerance of forest associations or for the predisposing stress which is thought to characterize wet sites and which may provide a high-moisture availability counterpart to the low-moisture availability stress factor used in this study. Additional work is warranted on the use of soil water availability data.

5. Introduction of Forest/Land Resource Management Objectives

The introduction of forest/land resource management objectives in the form of social/amenity, governmental, and economic land management objectives, in combination with host vulnerability ratings, provide the source of criteria by which infestation acceptability is projected.

The socioeconomic component of gypsy moth-caused impact (as contrasted with the ecological component represented in a vulnerability projection) considers how the effects of infestation and defoliation influence management objectives and forest resource values, including recreational and esthetic values (White and Schneeberger, 1981, p. 681). Impact, as an expression of the significance of damage (injury expressed through a value system) is a dynamic variable which is a function of insect-induced changes in forest stand conditions, and criteria established for particular management objectives. The meaning of impacts can vary with geographic region, ecological or economic conditions, current forest management practices, resource uses and potentials and the involvement of people (White and Schneeberger, 1981, p. 681). Gypsy moth nuisance and damage impacts are among the most important , the most difficult to measure, and certainly the most dynamic because public opinion and human tolerance for the insect are variable and highly subjective (White and Schneeberger, 1981, p. 681). Past state and federal efforts to estimate socioeconomic impacts have identified a number of important variables or"values at risk." These include impacts on: high-value forest or timber stands, real estate or residential property values, land ownership objectives, income from tourism, recreation opportunities, fire hazard, wildlife benefits, and watershed quality (White and Schneeberger, 1981, p. 681).

The variable (spatial data set) and its role (index) currently used in this model to represent the influence of forest/land resource management objectives is that of land ownership and administrative units (management conflict tolerance index). Other useful variables for which data are not now available have been included in the model diagram. The use of a single data set to represent land ownership and administrative units has had to be accepted as a surrogate for the purposes of this study. This data set best indicates governmental administrative units. It does not accurately represent private inholdings of land within administrative unit boundaries (which were below the resolving power of our 1 km^2. cell size), and in any case, it does not contain useful information concerning private (non-governmental) management objectives. Government representatives were asked to rank the tolerance of infestation and defoliation that would be indicated by typical management objectives for various administrative units (national forests, national parks, state wildlife areas, etc.). These rankings were then assigned to the appropriate spatial data. This procedure is not possible for the private land ownership class contained in this data set. Other data will be required to better represent private (social/amenity and economic) management objectives. Also, Indian reservations constitute a significant omission from federal administrative units in this data set.

Risk scenarios

The current version of the cartographic model presented in this report employs four sets of scenarios. The first three of these express the time-frames within which certain risk ratings and their associated data may be expected to be meaningful and useful. It is estimated that forest cover data and climate data will have "shelf-lives" of 10 years and 5 years respectively. This is based upon the expected real rate of change in forest cover and climatic phenomena in Michigan and upon the difficulty of obtaining new data to reflect such changes (the period of time for which existing data will likely have to suffice). These 10-year and 5-year periods also reflect the intervals at which the model must be used to project or re-project risks. Risk ratings for "host capability" need be projected only once in 10 years and ratings for "habitat suitability" need be projected only one in 5 years, unless changes are wanted in the decision criteria or thresholds used for either. However, risk ratings for "habitat susceptibility", "host vulnerability" and "infestation acceptability" must be re-projected every year, if for no other reason, because they depend upon yearly variations in phenomena monitored by annual gypsy moth trapping and defoliation surveys. Substitution of new data thus acquired, and re-projection of risks according to the model will also allow comparison of yearly projections to discover changes that occur over time and which may be studied to understand trends.

The fourth set of scenarios suggests a continuum between the extremes in which the "worst case" poses the prospect of all hosts becoming infested throughout their range, and the "best case" which poses the prospect of only some susceptible forest lands becoming sufficiently vulnerable for infestation to be considered unacceptable. These and other intermediate scenarios indicate a reduction in threat to pest management resources as one moves up the hierarchy of risks (leftward in the diagram) because each successively higher risk factor invokes an additional set of criteria, in effect reducing the amount of forest acreage which can qualify for each successive level of the risk hierarchy.

This sieve-like approach to cartographic modeling reflected in these scenarios serves to reduce the scope of the analytic problem at each step by imposing an ever "finer" screening procedure. The use of scenarios to further describe this procedure serves as a communications device to provide a simplified spatial conceptualization of the severity or magnitude of risk, and to inject an explicit dimension of uncertainty which is otherwise only implicit in this non-probabilistic model.

Limitations of the model

There are three principal limitations to the model proposed here.

1. The "infestation acceptability" factor is substantially incomplete because data are not yet available for variables representing human value systems. This is significant since it is these values which often exert a controlling influence on pest management.

2. No feedback components have been built into this model to reintroduce risk ratings projected in previous years or to introduce variables for which additional follow-up observations could be made. Examples might include collection of data on decline or mortality among infested forest stands, and the risk (injury, damage, impact) mitigating or enhancing effects of pest or forest management actions. This limitation is partly due to the unavailability of necessary data and partly due to the inability of GMRIS to facilitate trend analyses at this time. The current model depicts a "snap-shot" of risks as projected for a given year (actually for a given moment in time). Currently the power of this model to reveal spatial trends across time is dependent upon the user's willingness to re-run the model with each season's new data (pest population and defoliation

survey results) and refinements (improved decision criteria) and upon the user's ability to intuitively compare and integrate annual projections.

3. The current model limits the minimum unit area of forest land that a manager can "see" to the rectangular grid cell size of 1 km^2. This means that decisions requiring that managers be able to discriminate details within a 1 km^2 block of forest land cannot be supported.

4. The ability of the model to produce reasonable estimates of risks associated with gypsy moth has not been verified. The model should be validated and the data used with the model must be evaluated to determine their quality and suitability for the analyses specified in this model.

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CONSTRUCTION OF A STATE-WIDE DATA BASE FOR GYPSY MOTH RISK ASSESSMENT

Introduction

Construction of a geographic information system capable of assessing risks associated with gypsy moth has been dependent largely upon meeting data acquisition and preparation needs. Most hardware requirements were adequately met at the inception of the project and local system enhancements have since improved the convenience and speed with which data analyses can be carried out. Similarly, most software needs were well met by existing proprietary "canned" programs resident on the hardware systems used. An important exception occurred in the case of software needed to prepare gypsy moth trapping data for subsequent GIS analysis. Custom programs had to be prepared for these operations representing a significant investment of project resources.

For the purpose of planning data acquisitions, categories were established based on the level of effort and commitment of project resources which would be required to obtain or complete necessary data sets. These categories included: (1) digital data sets which were nearly fit for use and would require the commitment of modest additional effort; (2) data which were available in analog map form, which presumably could be digitized and completed with moderate additional effort; and (3) data which were not currently available, or satisfactory, in analog map form, or were available only in tabular form, and which would require maximum effort to prepare. Data were then classified accordingly and evaluated to determine if project resources could be allocated to meet both identified data needs and project objectives. It should be noted that the most obvious source of data of state-wide scope is the on-going resource inventory program of the Michigan Department of Natural Resources, Division of Land Resource Programs (DNR, 1985). Unfortunately, this program acquires and digitizes land use and other data as they become available from individual counties. As a result, scattered portions of both the upper and Lower Penninsulas remained incomplete at the time our study began.

Our project resources were found to be inadequate for the identified data preparation tasks. Consequently, in order not to overly compromise the quality of our data base, concerted efforts were made to secure additional funding and cooperation-in-kind to support a greater level of effort. Both the project's funding organizations and other research units at Michigan State University generously cooperated to achieve mutually beneficial results. Most data acquisition and preparation problems have now been overcome with the exception of the Upper Penninsula portion of each data set, the completion of which have had to be delayed. These data subsets have, however, been planned on a parallel basis with Lower Penninsula data and are expected to be completed within the year. Evaluations of accuracy and other measures of data quality have not been included with these descriptions because project resources have not permitted completion of that work element. This very important task is discussed in the chapter on implementation.

Following are descriptions intended as documentation for the data layers which have been completed for Michigan's Lower Penninsula. These have been organized according to the three level-of-effort categories described above. Each is labeled by risk influence category showing its position in the flow diagram of our risk model.

Data Preparation

The risk assessment data sets described below represent the individual, initial data "layers" or variables used to initiate what Berry (1982, p. 16-17) has termed "map algebra". This procedure uses a geographical information system to perform simple mathematical operations on what can be thought of as stacked or "layered" sets of digital mapped data, each representing components of a spatial problem. The purpose is to derive unique spatial solutions which are also expressed in the form of maps and which may be fed back into analytical operations through what Berry (1982, p. 16) calls "cyclical processing". Cyclical processing involves retrieving one or more maps from the data base which are then mathematically "combined" according to predetermined criteria ("map algebra") to create a new map. This new map then becomes part of the data base and is available for subsequent processing. This cyclical processing structure is analagous to the sequential evaluation of nested parentheticals used in conventional algebra.

The iterative nature of this kind of cyclical processing, as carried out in GIS analysis, begins with "original" digital maps or (initial data sets), and produces from them one or more "derived" maps or data sets. Unfortunately, these subsequent generations of mapped outputs often bear little resemblance to any one element of the original data (Vitek et al., 1984, p. 296). This issue of recognizing map "offspring" raises important questions concerning "lineage" and other indicators of the quality of data.

The National Committee for digital Cartographic Data Standards has recommended that any data base created by merging information obtained from distinct sources be described at sufficient detail to identify the actual source for each element in the file (Moellering, 1985, p. 18). They suggest that the basis of any quality report is a narrative of the lineage of the data which should include a description of the original source material from which the data are derived, and the methods of derivation, including all transformations involved in producing the final digital files. The committee recognizes that while recent interactive computer technology allows digital data bases to be easily modified, GIS's are not yet able to generate automated "versioning" analyses of modifications made to the data, requiring, for the time being, that less efficient practices be used to create a necessary audit trail of valuable information so that potential users can make their own informed decisions on the "fitness" of data for a given use (Moellering, 1985, 114-15). Experience during our study suggests that a lineage description should be part of mandatory data base or data file documentation whether or not the more difficult step is taken to quantitatively evaluate the quality of original or derived data.

The documentation which follows provides a partial lineage report, up to the point of digital file creation, for all the "original" data used to assess risks associated with gypsy moth. A full audit-trail or lineage of data derived from our analyses was not possible on an automated basis at the beginning of our study and, although new software with which some later analyses were done does support this function (the audit function of IBM-AT - basedERDAS software), it was not possible to work backwards to fully exploit this feature. Also, since we have deliberately made maximum use of existing data (prepared by others), it is often impossible to provide a good deductive estimate of the (often undocumented) errors encountered in the production process by those who actually prepared the original data. Neither data sets which have been documented in some degree by other preparers, or data sets which we have prepared have had their "quality" measured simply because project deadlines and funds have prohibited it.The documentation below is intended as a declaration of the data, criteria, and procedures used for spatial analysis. It is not intended as an adequate linneage statement or as an evaluation report on measures of accuracy, logical consistency, or completeness of the data . The level of detail in each of the following data set descriptions reflects, and varies with, the quality of documentation available from each original author. Additional information on data analyses can be obtained from contacts listed at the end of this chapter.

Digital data sources

Although it was not initially assumed that data already complete in digital form would be required to implement a GIS-based risk assessment method, it became obvious early in this study that land cover data would be necessary and that its creation would not be feasible with available project resources. The decision to use land cover data provided by Michigan State University's Center for Remote Sensing (CRS) was predicated on submodel data needs to represent host, and pest source area and disperal influences, and upon the need to establish a suitable base map or digital base file for the entire system. With regard to the submodels, some means had to be found to compensate for, or adjust deficiencies in both the forest cover type and highway corridor data then available. Accurate and current land cover data were thought to offer the best existing means of adapting available data and its deficiencies to the purposes depicted in the model. Urban or built up areas had to identified from some data source in order to adjust highway corridor data, which was incomplete in the form available, and forest cover data had to be merged or edited by some automated means in order to establish a reasonably accurate species map within a short time frame. While other sources of urban area data may have been acceptable, forest cover data needs could not be met in any way other than the CRS"S land cover file (these data are discussed individually later in this report). Equally important, was the need for a base file or digital map whose geometric properties could be adopted as a standard to which other data sets could be matched. The Center for Remote Sensing's graticule, which uses latitude/longitude and UTM georeferencing, has been described by Kroguleckl and Kimmel (1984, p. 11-13). It seemed most advantageous to maintain compatibility with other GIS-based studies by adopting this same base file. Specifically, this would allow conforming data to be exchanged among research projects thus conserving funds and optimizing the experience gained in developing and using a common base file.

1. Land Cover Data Set (digital base file)

The decision was made to adopt as our base file, the augmented level I land cover mapping data developed by Michigan State University's Center for Remote Sensing (CRS). This data set has been produced as part of a larger effort undertaken by CRS to develop a statewide data base of land-surface information using a raster (uniform grid) structure based on a 1square kilometer cell size, and containing 633 columns and 733 rows. Lusch and Enslin (1984, p. 40-42) have published a description of the land cover data set and other initial elements which were to be included in this state wide data base. Much of the following information on the establishment of an initial digital land cover file is taken from their description. More detail is available from interim documentation of the Lower Penninsula portion of the land cover mapping project prepared by Kroguleckl and Kimmel (1984).

In the abscence of complete state coverage among land cover/ use data compiled for Michigan by the U.S. Geodetic Survey, or by the Michigan Department of Natural Resources, original data had to be prepared to fill on-going research needs. The Center for Remote Sensing used visual interpretation of Landsat imagery to extract level 1 and some level 2 land cover categories according to the Michigan Land Cover/ Use Classification System (MDNR, 1979). Custom, enhanced 1:1 million-scale, false color composites (FCC's) were made using high density, color diazo transparency film to create 3-part, density-specified, contrast-stretched reproductions of the original black and white transparencies from Landsat Multispectral Sensor (MSS) bands 4,5, and 7 or Thematic Mapper (TM) bands 2,3 and 4. These standard false color composites were then magnified and registered to stable-base (film) copies of U.S. Geologic Survey 1 degree X 2 degree quadrangles using a rear-projector. Land cover entities were identified to a minimum mapping size of 16 square millimeters by using registered composites projected at 1: 250,000 scale and tracing polygons onto film overlays. Interpretation of land cover polygons was based on MSS imagery from 1979 and 1980 (June, July, and September), on TM imagery from 1982 (October) and on numerous kinds of ancillary data (B/W and CIR aerial photography at various scales, USGS Topographic quadrangles, and county soil surveys). The resulting 14 delineated land cover overlays were digitized using a Calcomp 9000 digitizer and either ERDAS 400 or in-house (CRS) software. Digital polygon files, which are unsupported by currently available ERDAS GIS capabilities, were converted to a grid format with a 333.333 meter square cell size using ERDAS 400 software. The resulting "high-resolution" grid file was then edited and subsequently aggregated to a final cell size of 1 square kilometer using in-house (CRS) software which employs a 3x3 pixel matrix to determine the dominant land cover category in each 1 square-kilometer neighborhood (in the case of co-dominance or ties, the lower numerical cover class was selected, thus biasing for "higher uses").

After evaluation of the digital land cover file for the Lower Penninsula, several omissions were identified and steps taken to remedy them. First, a small number of pixels were found to be missing from the file in scattered geographic locations. Coordinates for these were identified and given to the original interpretor who geo-coded their proper values into the digital file after consulting the source data. Second, some discrepancies were found between islands that were contained in the digital file and those which appeared in analog maps at a size which might have exceeded the minimum mapping unit of $16mm^2$. A list of islands routinely mapped was developed from other analog sources and was compared to Landsat imagery to determine the effects of fluctuating water levels on the inclusion or exclusion of islands. Some improperly omitted islands were thus identified and were also geo-coded into the final digital file. It is important to note that because islands are disconnected from the main land masses of both peninsulas of Michigan, they easily can be overlooked when constructing a data set. Or, if they are not overlooked it can be difficult to correctly associate them with the mainland political units which are their counterparts. Also, it is difficult to determine from analog maps of different scales whether an island will exceed the 16mm^2 minimum mapping size in Landsat composites projected at a scale of 1: 250,000. To standardize the inclusion or exclusion of islands from the base (land cover) file, and from conforming data files, we have developed a list of islands which should be included or acknowledged in a conforming data base. This list is expected to be included with land cover data documentation prepared by, and available from, the Center for Remote Sensing.

Analog map data sources (digitized data sets)

1. Precipitation and Temperature Data Sets

Numerous climatic data were needed for the climatic influence and environmental stress submodels of our cartographic risk model including: mean precipitation (water receipts during the larval life stage of the gypsy moth and the growing season of trees) (MDA, 1982a-d); average minimum and maximum, and average lowest temperature (extremes during the gypsy moth's life cycle) (MDA, 1980a,b and NOAA, 1950-77); and snowfall (winter protection). All climate data were originally compiled from observations made by the Volunteer Cooperative Weather Observers in the National Weather Service Climatological Network and from official National Weather Service observations. Of those data sets used for analysis, all but data on annual average lowest temperature were readily available in analog form. Data from those stations that had contributed to the original data set and which had observations over the period 1940-1969, were analyzed to generate 30-year summaries published in Climate of Michigan by Stations (MDA, 1974). (Snow depth data, for which the period of record is 1931-1960, were not included). These data were then manually plotted and hand contoured by the State Climatologist and subsequently published in the form of isopleth map sets as supplements to the aforementioned publication. These maps were drawn on standard 1: 3,839,616 scale NOAA paper base maps (routinely employed by the Michigan Weather Service) which use an Albers equal area projection with standard parallels at 45.5 degrees and 29.5 degrees.They are the only such map data sources known to be available for the state of Michigan. Contouring these data required the best judgement of the State Climatologist in positioning isolines to represent climatic gradients which might also accurately reflect the influence of factors such as topography and "lake effect", particularly as they operate along Michigan's shorelines. Automated models to generate a surface from these data were not then, and are not now, available for Michigan.

All of the climate map-supplements used in this study were digitized on a GTCO Digi-pad 5 digitizer coupled with an IBM-XT microcomputer and in-house software written at the Center for Remote Sensing. Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

2. Wind Power Data Set

Wind power data were necessary to introduce to the transport mechanism submodel the short-range, natural means of travel of which gypsy moth larvae are capable. Previous modeling efforts have found atmospheric dispersion of gypsy moth to be a very complex event involving many variables operating in flow regimes that differ with vicinity to terrain features such as ridges (ridge and valley turbulence of Pennsylvania) or coastlines (sea breeze effect of New Jersey) (Conrad et al., 1981, p. 200-201). Although useful models have resulted from such efforts, they have not been validated because, as is true of many states including Michigan, detailed empirical data with observations on proper variables over a sufficiently long period of record, are lacking. These and associated problems of wind flow modeling make it necessary at this time to substitute a surrogate measure or indicator in order to obtain seamless, state-wide data. The only existing state-wide, wind-related data which could be located is that contained in a study by Paton et al. (1981) of wind resources of the Great Lakes region performed as part of a National study for the U.S. Department of Energy. The following information is taken from their report.

The measure of geographical variation in the wind resource of Michigan was defined for mapping purposes to be wind power density rather than wind speed. The former measure has the advantage of combining in a single number the distribution of wind speeds and the dependence of the power density on air density and on (the cube of) the wind speed. Thus defined, the terms wind energy, wind power, and wind power density are regarded as synonymous. Original data were obtained from numerous sources including: the National Climatic Center (NCC), the U.S. Forest Service, university research programs, nuclear, fossil-fuel and wind power plants and studies for their siting, the Atmospheric Environment Service of Canada, and other state and local air pollution control and environmental impact monitoring agencies.

All data were subjected to screening criteria to determine those stations with the most useful observations based on: best exposure to wind, the greatest number of daily observations, the longest periods of record, the longest periods of unchanged anemometer height and location, and the greatest number of wind speed and direction classes. Data in summarized and digitized form were given preference to data in an unsummarized format, and data of very uncertain quality were omitted from the final analysis. Temporal resolution for mapped data was defined as seasonal and annual. Seasonal units were defined as 3-month increments with spring (relevant to gypsy moth risk assessment) consisting of the months of March, April, and May.

Quantitative estimates were then made by mathematically calculating separate average wind power densities for; three-hour digitized data, summarized data, and unsummarized data. These numerical estimates were subseguently adjusted for deviation of anemometer height from the selected 10 or 50 meter reference levels (using a power law), and for the lack of uniformity in distribution among data stations. Adjustment of estimates in areas of sparse data was accomplished by use of qualitative indicators of wind speed or power. These indicators consisted of topographical features (identified from topographic contour and shaded relief maps) and meteorological features (identified from synoptic and climatological maps or sea-level pressure patterns and air flow) whose combined influence was considered deterministic of high or low wind speeds. Wind power maps were produced by an unspecified, subjective, "synthesis" involving maps showing the location of stations, mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form. The purpose of this synthesis was to present wind power density values representative of sites well exposed to the prevailing winds. These sites would include hilltops, ridge crests, mountain summits, large clearings, and other locations free of local obstructions to wind as contrasted to poorly exposed sites such as narrow valleys and canyons, locations downwind of hills or obstructions, forested or urban areas. Areas with the appropriate combinations of topographical and meteorological features were identified giving great attention to the orientation of topographic features with the prevailing wind directions, and then mapped. These mapped wind power density classes represent the range of wind power densities likely to be encountered at exposed sites within an area designated as belonging to a particular wind power class. The resulting wind power density distributions depict lower limits of the wind power to be expected at exposed sites where local terrain features may enhance wind power considerably. They are are entirely unrepresentative of poorly exposed locations.

Since a direct, unique relationship does not exist between power density and mean wind speed, mathematical estimates were made of the mean wind speed corresponding to each wind power class. The range of wind power classes found in Michigan's Lower Penninsula and their associated wind speeds are as follows: wind power class 1 (wind speed 15.77 km/hr.), 2 (18.57 km/hr.), 3 (20.12 km/hr.), and 4 (21.57 km/hr.). Because wind power class ratings apply only to sites well exposed to wind, it was necessary to estimate the relative homogeneity of each unit area so rated. To do this, the "difficult-to -quantify relationship" among land surface-form classification, land-surface area, and wind power density was examined in an unspecified, subjective manner to produce additional grided maps showing the areal distribution of wind resources. In each cell of this 1/3 degree longitude by 1/4 degree latitude grid, the land-surface form was specified and the wind power class associated with a typical exposed site in that land-surface form was determined. By partitioning the area of the cell into four exposure categories, and by scaling the wind power class to each category, the contribution of that cell to the areal distribution was determined. Cell-by-cell representations of these areal distributions are given in maps that indicate the percentage land area in a cell over which the wind power class equals or exceeds a threshold value.

"Certainty ratings" were used to qualify the results achieved through analyses dependent on subjective integration of many factors. These ratings were based on the influence of: the abundance and quality of wind data used, the complexity of the terrain involved, and the geographical variability of the resource, on the certainty of the estimate of the wind power class for each cell. Final certainty ratings were then coded for each cell of the 1/3 X 1/4 degree grid.

The spring map of seasonal wind power, published with the study described here, was produced in paper form at a scale of 1/4 inch = 50 miles. The information on this map was magnified using a rear projector and transferred by tracing to a stable-base (film) overlay registered to latitude, longitude intersects of a standard USGS stable-base 1 : 1,000,000 scale map of Michigan. Control points were obtained from a table of UTM coordinates corresponding to the graticule developed by the Center for Remote Sensing (for use in registering spatial data sets to their 1 square kilometer grid, state-wide, land-surface data base).The overlay version of this map was then digitized using a Calcomp 9000 digitizer coupled with an IBM-XT microcomputer and the digitizing software module of the CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985). Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

3. Vehicular Traffic Flow Data Set

Data on the location and intensity of vehicle travel in Michigan provide a man-made, long-range transportation mechanism for egg masses that complements the natural, short-range transportation of gypsy moth larvae by wind currents. Together with data on urban areas(discussed below), these variables fill the data needs of the gypsy moth transport mechanism submodel. State-wide highway corridor data have been obtained from the 1983 average 24 hour traffic flow map prepared by the Michigan Department of Transportation (MDOT, 1986). Data for this map was collected by Michigan Department of Transportation field staff who station and tend trip counters along all of Michigan's trunk line roads (those with Interstate, Michigan, or National route number designations). Sampling of traffic flow is carried out in the period from April through November using 200 counting machines. Sampling is done on two levels; 400 locations throughout the state are selected to be sampled 3 times within the year's sample period for an interval of 6-7 days, and 3000 locations are selected to be sampled 1 time within the year's sample period, also for an interval of 6-7 days. Final traffic flow maps are compiled from these counts by plotting them on intermediate maps which are examined (in an unspecified manner) by departmental traffic planners who then average and estimate daily traffic volume. Traffic flow maps from such annual data are generated and published on an irregular basis.

Four classes of traffic flow vector data contained in the published 24-hour traffic flow map were digitized using control points for certain county boundary intersection points obtained from a table of UTM coordinates. These coordinates correspond to the graticule developed by the Center for Remote Sensing (for use in registering spatial data sets to their 1 square kilometer grid, state-wide, land-surface data base). An IBM-XT microcomputer was used with the digitizing software module of the CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985). Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

4. Urban Areas Data Set

A digital map of major urban areas was required to modifiy highway corridor data in order to assure fitness of data for the man-made vehicular transport submodel. This was made necessary because highway features on the map described above were differentiated into 4 classes based on the traffic volume borne by each highway route during a 24-hour period. As these corridors converged on mapped urban centers they became indistinguishable at the scale used for the original map. To remedy this problem the map's authors added detail maps depicting individual urban centers, each featuring the routes of major highways at a scale more suitable for detailed study. Although it was not possible to use these detail maps to digitize highway corridors where they extended into and merged in urban areas, inspection of these maps showed that many of the corridors which penetrated heavily populated areas carried the highest possible volume of traffic. Also, it seemed apparent that the influence of higher traffic volume roads within the same urban areas, particularly given the large scale of the original highway map, could be more than equaled within the confines of an urban area, by the influence of smaller, yet more densely spaced roadways. Assuming this is true, the result could be that the net traffic volume for entire urban areas, considering all roads within these incorporated units, could equal or exceed the heaviest traffic density classification. This conclusion seemed reasonable and handling urban areas as continuous zones of maximum traffic density suited many of the assumptions and limited knowledge upon which this study is based, so it was decide to merge the data sets for urban areas and highway corridors. The result of overlaying these data is a vector map of highways which traverse rural areas and which converge on what are represented as high traffic flow "nodes" in and near metropolitan and built-up areas.

Data on urban areas were acquired from the land cover data described above. Urban areas represent one of nine land cover categories mapped from landsat imagery. No further preparation of the original data was necessary beyond that already described.

5. Average Available Water Capacity (Soils) Data Sets

Water holding capacity data were required to meet needs of the soil moisture retention portion of our soil moisture submodel. Original data were obtained and prepared by the Center for Remote Sensing from the Soil Association Map of Michigan (MSU, 1981). This state-wide map was compiled from County Soil Surveys and shows the areal distribution of 78 soil associations separated into Fridgid and Mesic temperature regimes. It has been published in paper form at a scale of 1 : 1,004,000. Procedures used to create a digital file from this map and auxilliary data sources have been outlined by Lusch and Enslin (1984, p. 42) and it is from their description that the following information is taken.

The published Soil Association Map was digitized using a Calcomp 9000 digitizer and either ERDAS 400, or CRS software. Digital polygon files were then converted to a grid format with a 333.333 meter square cell size using ERDAS 400 software. The resulting "high-resolution" grid file was subsequently edited and aggregated to a final cell size of 1 square kilometer using in-house (CRS) software which employs a 3x3 pixel matrix to determine the dominant soil association category in each 1 square kilometer neighborhood (in the case of co-dominance or ties, the lower numerical cover class was selected).

Each digitized soil association was actually composed of data from 1 to 4 soil series which had been aggregated where necessary to produce map versions. Because the approximate proportion of each series in each association was known or could be estimated by Michigan State University soil scientists, these data could essentially be disaggregated using a decision rule which assigned percentage contributions (mixes) of soil series depending on their number within a given soil association. The digitized soil association map and corresponding decision rules were then used to derive data sets showing average available water capacity of the soil in one-foot increments, to a depth of five feet. To do this, available water capacity (AWC) data for each soil series were obtained from Soil Interpretation Records, published by the Soil Conservation Service, which list the AWC as a value range for each horizon in the pedon description. These value ranges were converted to one-foot incremental data by calculating the mean AWC for each horizon, multiplying the mean AWC by the percentage of the one-foot increment it occupied (using the decision rules), summing the products obtained for each one-foot increment, and then summing the individual series AWC data. All one-foot increment AWC files have been summed to produce a 5 foot depth measure for use in our study.

6. Gypsy Moth Defoliation Data Sets

Defoliation data have been obtained from aerial reconnaisance missions and are used in our study as an indicator of direct, gypsy moth-induced tree stress. These data are collected annually by Michigan Department of Natural Resources, Forestry Division personnel who have recently used sketch mapping and 35 mm vertical and oblique photography at low altitude from light aircraft, and more recently, vertical color infrared (CIR) videotaping to produce rough forest management and planning maps. Data used in this study are from flights made in late July and early August of 1984, 1985, and 1986. Maps from 1984 and 1985 are published only in a highly generalized form in an annual report of the Michigan Cooperative Forest Pest Management Program (Battenfield, 1984, p. 14). The 1986 sketch map is not yet published.

The original sketch maps (or copies) as modified after comparison to aerial photographs (1985) or video CIR imagery (1986), have been used in this study to maintain as much accuracy as possible. Details on defoliation sketch mapping, 35mm aerial photography, or videotaping procedures used to collect defoliation data are available from Michigan Cooperative Forest Pest Management Program (MCFPMP) members listed at the end of this chapter. Sketch maps have been produced directly on originals (1986) or on xerographic copies (1984 and 1985) of 3/8"= 1 mile scale county highway maps. 1984 and 1985 sketch maps do not rate the severity of defoliated areas. The 1986 sketch map rates defoliation in three severity classes. The information on these maps was magnified using a rear projector and transferred by tracing to polyester drafting film, 3/8" = 1 mile scale overlays registered to standard county highway maps of Michigan as published by the Michigan Department of Transportation. Control points for county boundary intersections were obtained from a table of UTM coordinates corresponding to the graticule developed by the Center for Remote Sensing to use in registering spatial data sets to their 1 square kilometer grid, state-wide, land-surface data base.The overlay versions of these maps were then digitized using a Calcomp 9000 digitizer coupled with an IBM-XT microcomputer and the digitizing software module of the CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985). Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using

ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

7. Administrative Units (Land Ownership/Administration) Data Set

Data on public land ownership and administrative units are currently the only data available to indicate influences which will need to be analyzed more fully in the amenity and economic impacts submodels. These data have been obtained from the Mapbook of Michigan Counties which contains individual county highway maps (as modified by the Michigan Department of Natural Resources) in paper form at a scale of 3/8" = 1 mile (MDNR, 1984). This mapbook was updated in 1983 by the DNR, Engineering Division to reflect changes in land ownership patterns.

To achieve somewhat greater accuracy, ownership data were transferred from county maps contained in the 1985 atlas to xerographically reduced copies of unpublished land ownership maps produced by the Michigan Department of Natural Resources, Land Use Programs Division. These maps were xerographically reproduced in paper form at a scale of 1 : 250,000 and display 1978-1979 state and national land ownership status patterns in nine categories. This transfer of data was done because the latter maps evidenced somewhat less cartographic generalization, thus providing a more detailed reference map. They also separated coverage of Michigan's Lower Penninsula into 5 map panels which suggesting they might provide a better "fit," when mosaicked together, than might be achieved with 68 separate county maps.

The information from the atlas was visually compared to that on each of the 5 xerographic copies and corrections/ modifications were then drawn manually on the copies using 1978-1979 land ownership patterns as reference points (a projector was not employed). Control points for county boundary intersections were obtained from a table of UTM coordinates corresponding to the graticule developed by the Center for Remote Sensing (for use in registering spatial data sets to their 1 square kilometer grid, state-wide, land-surface data base).The xerographic reductions were then digitized using a Calcomp 9000 digitizer coupled with an IBM-XT microcomputer and the digitizing software module of the CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985).

Digital polygon files were converted directly to a 1 kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

Tabular and other data sources (constructed data sets)

1. Annual Average Lowest Temperature Data Set

One of the data sets needed for the climatic influence component of our cartographic risk model was that characterizing annual extreme low temperatures. Available low temperature data summarized for Michigan included only daily low temperatures for each station which were averaged by month, and then across the period of record. These data were available as "average daily minimum temperatures" in the form of map supplements to the Climate of Michigan by Station but were not adequate for our purposes. Our recourse was to compile and map available tabular data from the Volunteer Cooperative Weather Observers in the National Weather Service Climatological Network (including official National Weather Service observations) in a manner that best approximated our needs. To do this, the lowest temperature observed at each station during the period of record 1950-1977 was divided by the number of observations actually made at those respective stations to derive the "average lowest annual temperature." Both the compiled tabular data and the derived average extreme temperatures were reviewed for consistency by the State Climatologist. All data were manually plotted on a standard 1: 3,839,616 scale NOAA paper base map (routinely employed by the Michigan Weather Service) which uses an Albers equal area projection with standard parallels at 45.5 degrees and 29.5 degrees. These data were then hand contoured by the State Climatologist using best judgement to position isolines to represent climatic gradients which might accurately reflect the influence of factors such as topography and the thermal ("lake effect") influences which operate along Michigan's shorelines. Automated models to generate a surface from such data were not then and are not now available for Michigan.

The resulting isopleth map of extreme low temperatures was digitized using a Calcomp 9000 digitizer coupled with an IBM-XT microcomputer and the digitizing software module of the

CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985). Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used.

2. Major Forest Associations Data Set

Acceptable forest association (host) data for Michigan had to be derived from 2 separate original sources because each of the available data sets exhibited significant deficiencies with respect to the assessment of gypsy moth host types. Fortunately, the deficiencies of each of these data sets were of a different sort. This made it possible to use a data transformation scheme which exploited the advantages inherent in each to derive a unique data set without the limitations of either of the originals.

One source of state-wide forest type data was the land cover inventory carried out by the Center for Remote Sensing. This project used visual interpretation of Landsat imagery to delineate 9 categories of land cover representing level 1 and some level 2 classes as specified in the Michigan Land Cover/Use Classification (MDNR, 1979). Of these 9 categories, those at level 2 identify forest types including; deciduous forest (41), coniferous forest (42), forested wetlands (61), and non-forested wetlands (62). Unfortunately, because identification of gypsy moth hosts requires that species type be known, these data alone were useless to our study. The only alternate source of state-wide forest type data was the map of Major Forest Types of Michigan - 1980 produced by the U.S. Forest Service as part of Michigan's fourth forest inventory (Spencer, 1983). This effort entailed sampling and photo-interpretation of aerial color infrared and other photography to classify the entire state into nonforested, or (7 categories of) forested land. The resulting map displays 6 distinct forest types: maple-birch, aspen-birch, white-red-jack pine, elm-ash-cottonwood, spruce-fir, and oak-hickory (the seventh category is unproductive forest land). These forest association data provided useful species differentiations for risk assessment purposes but inspection of the cartographic quality of the map suggested that the positional accuracy of map polygons was poor; exaggerating the extent of riparian forests, and mis-placing the boundaries of other forest lands. These limitations were assumed to be artifacts of the objectives and procedures used to generate the original map but they were unacceptable for our study. Because the first of these data sets was considered deficient in detail but positionally accurate, and the second was considered sufficiently detailed but positionally inaccurate, it was possible to use the capability of a geographic information system and the skills of a satellite imagery interpretation technician to merge these two data sets to produce a unique, derivative map which was sufficiently detailed and positionally accurate (effectively cancelling their individual limitations).

Data for Michigan's fourth forest inventory (and for the analog map described above) were obtained by the U.S. Forest Service from 1977-1978, 1: 24,000 scale aerial photographs (furnished by the Michigan DNR and the National Forests) and from ground plots visited between 1976 and 1980 as reported by Spencer (1983, p. 11 and map panel). The following information is taken from that report. Data were acquired using a sampling procedure designed to provide reliable statistics at the state and Survey Unit (regional) level. Survey procedures began by selecting a total of 176,976 1-acre sample points, systematically distributed across aerial photos of the entire state, except the National Forests. To make a preliminary estimate of forest area, these points were classified into 6 land classes: forest land; unproductive forest land; nonforest land with trees, without trees, with water; and questionable land. Next, 83,103 of these points were stereoclassified by forest type, stand class, and density. Finally 13,991 points were examined on the ground to correct the preliminary area estimate for errors in classification and for actual changes in land use since photography was acquired. At each forest ground plot location, variable-radius plots (basal area factor 37.5) were established at 10 points uniformly placed over the 1 acre sample unit. Data for National Forests were provided from 10-point variable radius plots established on the Hiawatha and Huron-Manistee National Forests in 1976, and on the Ottawa National Forest in 1980. Forest type information was recorded on Michigan Department of Natural Resources county (highway) maps and subsequently transferred to a 1: 1,000,000 scale base map in an unspecified manner. Since the tabular data were intended as estimates only, an assessment of their reliability was provided in the form of sampling error which was found to be + or - 33%, meaning that the chances are one in three that the true inventory value is within the limits described. No map accuracy evaluation was done. The procedures used by the Center for Remote Sensing to obtain data on forest cover categories from Landsat imagery were described in the earlier summary of their land cover mapping project.

The merging of forest information from these two data sets was accomplished by using data manipulation criteria ("map algebra") with GIS software. First the Forest Service analog map was digitized using control points for county boundary intersections obtained from a table of UTM coordinates corresponding to the graticule developed by the center for Remote Sensing (for use in registering spatial data sets to their 1 square kilometer grid, state-wide, land-surface data base). An IBM-XT microcomputer was used with the digitizing software module of the CRIES-GIS package (5.0) (Schultink and Zusmanis, 1985). Digital polygon files were converted directly to a 1 square kilometer cell-size grid format using ERDAS 400 software; no intermediate "high resolution" file or aggregation procedures were used. Although a "high resolution" file might have had some added utility, it was determined to be too costly to edit the digital file at that level of detail. After interactive editing to visually verify correspondence of the digital file with its paper map analog, a matrix operation was done using ERDAS 400 software to identify all logical and illogical combinations of the two data sets. Next, black and white "error" maps were produced at 1 : 1 scale on a dot-matrix printer to identify all pixels that represented illogical combinations such as the superimposition of deciduous forest cover on spruce-fir forest type, or forested wetland cover on white-red-jack pine forest type. These error maps provided a means of identifying those pixels for which classification was "confused" and for which new classification rules would be needed. Decision rules were devised based on the positional dominance of the forest cover data; thus the 6 forest types were imposed only on those pixels which were classed as being one of 4 forest cover classes, and therefore correctly positioned. Forest types which co-occurred with non-forest cover classes were consequently considered positionally incorrect and were reclassified as non forest land. Remaining illogical combinations were described in decision rules which were invoked based on reinterpretation of the original satellite imagery used to delineate land cover classes supplemented, for diagnostic purposes, by aerial photography, and forest inventory maps. "Confused" pixels which required reinterpretation were identified, and their corresponding remotely sensed image found, by reference to the "error" maps which had county boundaries superimposed on them as a visual referents. After reinterpretation, all illogical combinations were corrected interactively by editing into the digital file each pixel's correct forest type designation. The decision criteria and error maps used in this procedure can be obtained from the author or from the Center for Remote Sensing. Addresses are listed at the end of this chapter.

3. Gypsy Moth Trapping Survey Data Sets

Data representing source areas of gypsy moth populations are provided by annual gypsy moth trapping surveys conducted by the Michigan Department of Agriculture (MDA) with cooperation from other state and federal agencies. Previous survey procedures called for annual deployment of gypsy moth traps in designated portions of the state in a variety of sampling schemes varying in density, distribution, trap type, and sampling objectives. Gypsy moth traps of the milkcarton (manufactured from milkcarton designs with a protective "hood") or delta (similar waxed-paper container which is prism shaped) type are used to catch, kill and contain adult male moths (females do not fly). This is done by attaching such traps to trees or other suitable objects to which moths are drawn by a pheromone bait (female sex-attractant attached in the top of the trap) and killed by a pesticide strip at the bottom (milkcarton trap) or ensnared in an adhesive substance (delta trap). Although traps can be tended throughout a season, the large number of such observations for a state-wide survey requires that field inspectors return only at the end of the season to retrieve traps and count the number of dead moths they contain. Moore and Hanna (1984) have summarized earlier gypsy moth survey work conducted in Michigan. Data upon which our study were based, marked a departure from previous survey procedures. In 1985 the MDA began using a permanent plot or permanent trap-site system for their annual gypsy moth survey. In this new scheme, traps of a single kind (milkcarton) were deployed across the entire Lower

Penninsula in a uniform distribution targeting all sections numbered 8 and 26 (in Michigan's public land survey) as preferred sites (adjacent alternate or contingency sites were specified). This system of presumably static sample points provides approximately 2400 observations (for the Lower Penninsula) the locations of which are intended to remain stable across years allowing time series data to be obtained and used to further improve forecasting efforts. Permanent plots also facilitate the collection of auxilliary observations, such as habitat data, which can contribute to the additional refinement of predictive methods.

Once collected, field data on gypsy moth catch numbers are delivered to the Cooperative Crop Monitoring System (CCMS) of the Department of Entomology at Michigan State University for processing and reporting purposes. CCMS was developed to provide a standardized inter-agency information collection and retrieval system for agricultural pests, the crops they infest, and the actions taken to control such pests. Gypsy moth trapping data are also under the umbrella of CCMS which, since 1981, has had over 60,000 records of pheromone traps input. Using INGRES, a data base management system (DBMS), data are organized into tables or relations of similar data, which together make up the CCMS data base, now called the Michigan Agricultural and Natural Resources Information System (MANRIS) (Gage and Russell, 1986, p. 1,5-6). In addition to the aspatial attribute "trap catch" (number of male moths caught), each record of trap data also contains the spatial attributes or location coordinates for each observation. Geographic positions of gypsy moth traps are specified by using the public land survey or cadastral system of township and range designations within a standard coding scheme that was based on the U.S. DIME file codes for U.S. counties. As originally constructed for use with CCMS, this system of coding spatial and aspatial data attributes used multiple code designations for each unique record: an ascending, odd numbered, 3-digit code which corresponded to an alphabetic enumeration of county names; an ascending, odd and even numbered, 2-digit code which corresponded to an alphabetic enumeration of township names; township and range "coordinates" (36 1-mile square sections); section number (section = 1 square mile or 640 acres); and quarter section designation (160 acres). (Occasionally, special, smaller designators were also included for spatial units such as "quadrant" and "site"). Since CCMS was the repository of digital gypsy moth population data, it was necessary to retrieve data for use with our GIS in a manner that would assure that annual trap catches represented unique spatial values. Upon examination it was found that the CCMS coding system was not fully nested, with the result that the smallest standard spatial attribute (section number), would often not be unique. This occurred because "survey" townships (cadastral units of 36 1-mile square sections), as they will be called here, were omitted in confusion with "political" townships which have "English" names. Political townships can actually consist of as few as one (or a partial) survey township; the former being an historical, variably-sized, political subdivision of land and the latter a surveyors unit of (approximately) standard dimensions. However, political townships can also deviate in size and shape to include two or more survey townships (in whole or in part). Political townships that contain more than one (whole or partial) survey township may therefore, also contain an equal number of indistinguishable, identically numbered sections. This problem was remedied by inserting within the original coding scheme, an additional 2-digit numerical code for each "survey township" of a particular political township thus placing each section lower in a hierarchical, fully nested, system in which a section number is uniquely identified within one survey township, one political township, and one county. The resulting coding system which assigns unique spatial coordinates down to the section level, using the public land survey as its "grid" framework, has been documented and is stored in duplicate map sets available from MCFPMP members or from the Center for Remote Sensing. Addresses are listed at the end of this chapter.

Having satisfactorily overcome the problem of assuring unique spatial identification of all data, the problem remained of translating data stored in CCMS into the digital form required for analysis with a geographic information system. Other software resident on CCMS's host computer was capable of performing complex statistical analyses and many kinds of preprocessing functions, but was not adaptable to the task of geographically indexing trap data within the adopted 633 X 733 cell uniform grid for Michigan. Because preparation of gypsy moth trap data was expected to be required on at least an annual basis, it was desirable to automate this processes rather than repeatedly plotting and manually digitizing all such data. Unfortunately, cadastral (land ownership) systems (such as Michigan's public land survey) and cartographic systems, such as the 1 km^2 grid-based system used in our data base, are in different coordinate systems. Map data based on latitude-longitude provide the basic mechanism through which different spatial data sets can be brought together but cadastral data rarely include latitude and longitude coordinates. Until recently, there has been little demand for expressing Public Land Survey System units in the latitude longitude system or some other coordinate system. Not only are the two coordinate systems fundamentally different, but bridging the differences involves substantial cost and conflicts (Marble, 1984, p.1-5). Since software was not available, and manual methods were not acceptable, it was decided that the problem could be adequately solved by writing software which would employ a look-up table of grid cell locations to match tabular (trap catch) data coordinates obtained from CCMS, to corresponding cells within a 633 X 733 grid. This required digitizing the centroid of each section from the master CCMS code map, assigning its fully nested identification code, and assembling all resulting geographic coordinates into a look-up table. Software was then written which, by referencing this look-up table, essentially resamples all cadastral (1 square mile) data for input to a uniform grid for cartographic (1 square kilometer) data. Various kinds of output from this software can be specified in x-y coordinate form for 1 km^2 or 2 km^2 cell-size display of point data, or in x,y,z coordinate form for interpolation of a surface or contour map (continuous data) from point data. It is important to note that almost all data integration or analyses using multiple data sets with a GIS will require continuous data. Documentation for this software which converts tabular DBMS (1 $mi.^2$, "survey") data to spatial, GIS (1 km^2 cellular) data is available from contacts listed at the end of this chapter. No additional digital pre-processing of gypsy moth trap catch, or other data that is encoded in accordance with the prepared maps, is necessary beyond that achieved with CCMS (or other statistical analysis) programs and the custom software written for this project unless the user wishes to generate an interpolated, continuous surface from such point data.

Evaluation of Data Quality (Integrity) and Accuracy

Evaluating the quality, accuracy and other properties of data which may be added to an established data base, or of the outputs from analytical operations performed on such a data base, is an important part of the on-going process of data base construction, editing, and updating. Vitek (1984, p. 296) and others have proposed that the next step in the refinement of geographic information systems will be specifying the accuracy of the output products. McFarland (1981, 47-48) has suggested that data base development at any application level has to face several issues including, data integrity, data reliability, data base maintenance, and data privacy. Particularly important among these are concems with what McFarland has termed data integrity and data base maintenance. He asserts that the original creator of data should establish and underwrite the integrity of data by writing a defendable data accuracy statement, or what Vitek et al. would call an error statement. McFarland (1981, 49) also states that as data bases grow in complexity and size, the probability that the data they contain will be accurate, declines and that a large requirement of data base maintenance is discovering and correcting errors and flaws, and updating time-sensitive data at appropriate intervals. Accuracy appraisals must consider what Vitek et al. (1984, 296) have proposed are the two sources of error; inherent error,error introduced through the creation of the map by precision limits and poor cartographic practice; and operational error, error introduced or enhanced by successive transformations or manipulations of the data.

These and other aspects of the entire cycle of evaluation, correction and use of data, which by its repetition makes data and data bases dynamic, introduces the additional difficulty of "versioning" (Moellering, 1985, p. 115). Versioning is the process by which data sets change with time as deliberate and inadvertent changes are made creating uncertainty in the wary user as to the true status of the data in question. The speed and power of computerized GIS's only exacerbate the problem and make potentially unreliable, but visually appealing data all the more persuasive. The central problem, as Vitek (1984, p. 298) and others have pointed out, is that the problem of error is enhanced because only those users knowledgeable enough about maps (digital or analog) will question the accuracy of output products while most others will accept them as accurate because maps are finite and definite and do not ordinarily contain statements about quality. The best solution is the regular use of lineage records which provide users with an "audit trail" of all such changes as well as periodic and occasional evaluations of data quality.

Progress has been made with the issues of evaluating data quality. Mead (1982, p.51-59)has described a useful method of informally appraising candidate data sets before including them in a data base by using a rating system with which knowledgeable persons can evaluate 9 factors of data quality . Also, the National Committee for Digital Cartographic Standards has recently published Interim Proposed Standards which include recommendations for the procedures and tests to be used for formal, standardized data quality reports (Moellering, 1984). The committee has also produced a helpful bibliography of the literature concerning cartographic data standards (Moellering, 1984). Application of data quality assessment to GMRIS's data base is discussed further in the following chapter.

Data Storage

Data aquired during the course of this study have been preserved in floppy diskette, cartridge, or magnetic tape format. Analytic outputs have been stored as screen images on 35 mm color slides. These have been distributed or made accessible to other agencies and investigators. Documentation or additional information on custom software and data preparation and transformation procedures are also available. Readers may wish to consult the following sources to locate data files, software documentation, or data analysis information.

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IMPLEMENTATION OF THE GYPSY MOTH RISK INFORMATION SYSTEM (GMRIS)

Data Analysis

Results of risk ratings projected for 1986

Following is a description of the results obtained by performing a GIS-based gypsy moth risk assessment according to the Gypsy Moth Risk Information System (GMRIS) model, using data available for Michigan's Lower Penninsula as of August, 1986. Each of five risk factors and their ratings is described briefly, in sequence, using histograms and photographic reproductions of computer display images produced with ERDAS software. These results are intended chiefly as a demonstration of the spatial risk rating capability offered by GMRIS. No attempt is made here to interpret these results with respect to specific forest pest management objectives.

1. Host Capability

Host capability ratings have been derived by reclassifying dominant forest associations (Figure 2) into four classes thought to be indicative of the relative ability or inability of different host types, or groups of host types, to provide food and shelter conditions which may support or preclude survival of gypsy moth. These capability classes and their related host types are: (1) very high capability (oak/hickory association), (2) high capability (aspen/birch association), (3) moderate capability (spruce/fir and white/red/jack pine associations, and (4) low capability (maple/birch and elm/ash/cottonwood associations).

The spatial distributions of the above mentioned forest associations and host capability classes are illustrated in Figure 2 and Figure 3, respectively. The bulk of all forested lands can be seen to be located chiefly in the northern and west-central parts of the Lower Penninsula. The

Figure 2. Dominant forest associations in Michigan's Lower Pennninsula.

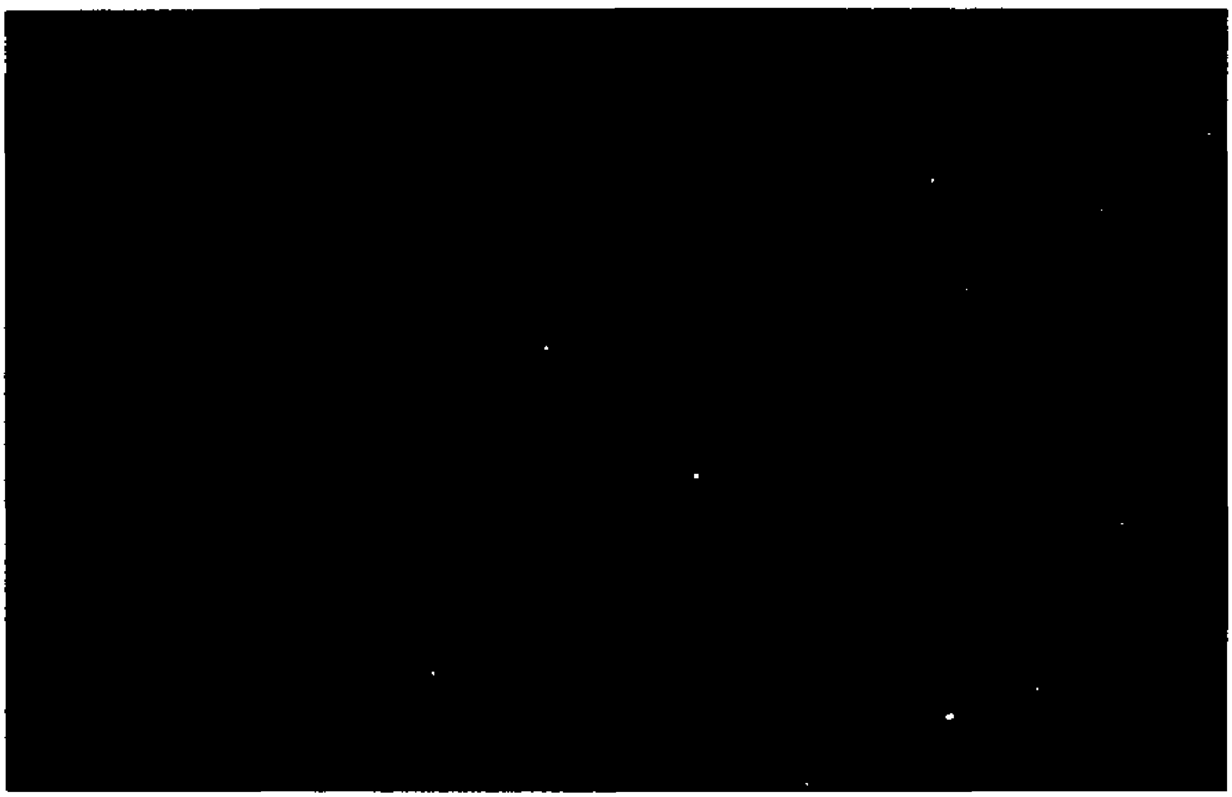

Figure 3. Host capability ratings projected for 1986.

Table 1. Land area tabulations of dominant forest associations.

Header listing for GIS file: FORESTLP.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 15-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 9
This file contains 8-bit data
The VARIABLE name is RECODE TO VALUES 0-8

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGROUND AND GREAT LAKES
1	10786.	2665366.250	10.13 %	OAK/HICKORY
2	6590.	1628477.870	6.19 %	MAPLE/BIRCH
3	9651.	2384892.250	9.06 %	ASPEN/BIRCH
4	3948.	975604.062	3.71 %	ELM/ASH/COTTON
5	4375.	1081121.500	4.11 %	SPRUCE/FIR
6	6442.	1591905.120	6.05 %	WHITE/RED/JACK PINE
7	62994.	15566667.000	59.16 %	NONFOREST LAND
8	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Table 2. Land area tabulations of 1986 host capability ratings.

```
Header listing for GIS file: HSTCAPLP.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 25-JUL-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 7
This file contains 4-bit data
The VARIABLE name is REC.HSTPRFLP.TO COLLAPSE TO HOST CAPABILITY
```

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	10786.	2665366.250	10.13 %	VERY HIGH CAPABILITY (O/H)
2	9651.	2384892.250	9.06 %	HIGH CAPABILITY (A/B)
3	10817.	2673026.750	10.16 %	MODERATE CAPABILITY (S/F,PINES)
4	10538.	2604082.000	9.90 %	LOW CAPABILITY (M/B,E/A/C)
5	62994.	15566667.000	59.16 %	NEGLIGIBLE CAP.(UNFAV'D.,NONFOR
6	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

high and very high capability classes, represented by oak/hickory and aspen/birch associations, are distributed most densely in the middle third of the Lower Penninsula but a good proportion of both classes is found dispersed throughout other forested lands, becoming scarce only in the uppermost few tiers of counties. Both classes also contribute significantly to the acreages of forested lands that extend into and through populated areas of the state.

Acreage tabulations for land areas represented by each of these host capability classes, and for the forest associations from which they are derived, are listed in Table 2 and Table 1, respectively. These figures show that each of the four capability classes just mentioned account for approximately 10 % of the land area of the Lower Penninsula of Michigan. Collectively they represent about forty percent of the land area with the remainder consisting of unforested lands. Approximately 60 % of Michigan, which is predominantly unforested, is rated as having a negligible, rather than null, host capability. This is because the negligible capability class was derived from data with a nominal resolution of 1 km^2 which does not allow extraction of information on stands smaller than about 1/2 km^2 although these may provide hosts of varying capability despite their limited size and their "invisibility".

Not evident in the tables of host capability ratings is a class considered to be unfavored by gypsy moth and thus rarely a host. The very low capability class contains no acreage for the Lower Penninsula and thus is absent from Table 2, but it is mentioned here because the relationships of dominant forest cover types to host capability classes will be seen to change later when they are used to rate Michigan's Upper Penninsula. This is because a discontinuity exists in the distribution and "capability" of forest associations within Michigan's considerable geographic area. In the Upper Penninsula oak/hickory will later be seen to be absent thus leaving the very high rating class empty for that portion of the state. Spruce, which is the dominant representative of the spruce/fir association in the Lower Penninsula, will be replaced in later analyses by fir, its dominant counterpart in the Upper Penninsula. Since fir is the less "preferred" of the two hosts, it will introduce a positive acreage tabulation for the very low capability class which now is negative (zero) in the Lower Penninsula tabulations.

Less than 2 % of Michigan's Lower Penninsula surface area is recognized in the GMRIS data base as inland water bodies. These areas naturally receive no capability rating, thus their contribution to land cover does not change throughout the risk assessment process.

2. Habitat Suitability

Habitat suitability ratings have been expressed in classes which reflect the relative favorability of combined host and climate characteristics for growth and development of reproductive gypsy moth populations, irrespective or direction from gypsy moth source populations. The distributions of these classes are approximated by mapping their minimum and maximum geographical extent. These extremes are meant to suggest the ends of a spatial continuum between which actual distributions are expected to lie.

The spatial distribution of habitat suitability classes can be seen in Figures 4 and 5 which show that very high suitability areas lie in two rather linear zones oriented from southwest to northeast and lying in the southwestern corner of the Lower Penninsula. The only exceptions are numerous small and rather isolated sites scattered in a narrow zone extending from the Flint area into the "thumb" of Michigan and showing the same southwest to northeast orientation. High suitability classes are much less confined and occur in comparatively large acreages in southwestern, westcentral, and northeastern parts of the state. A very large acreage of land classified as highly suitable can be seen to be located in the Midland area, the center of current gypsy moth activity. A prominent three-lobed region of relatively low suitability dominates the north central portion of the Lower Penninsula.

The extreme classes of very high, and negligible maximum suitabilities can be seen from the acreage tabulations in Table 3 to represent only .73 % and 3.68 % , respectively, of Michigan's land area. Nearly all of Michigan is comprised by the middle habitat classes with high and moderate suitabilities representing near equal land areas at approximately 15 %, and which, taken together, equal only about half of the 63 % acreage contribution of the low suitability class. Lands of negligible suitability contribute only about 4 % of all acreage. Acreage tabulations in

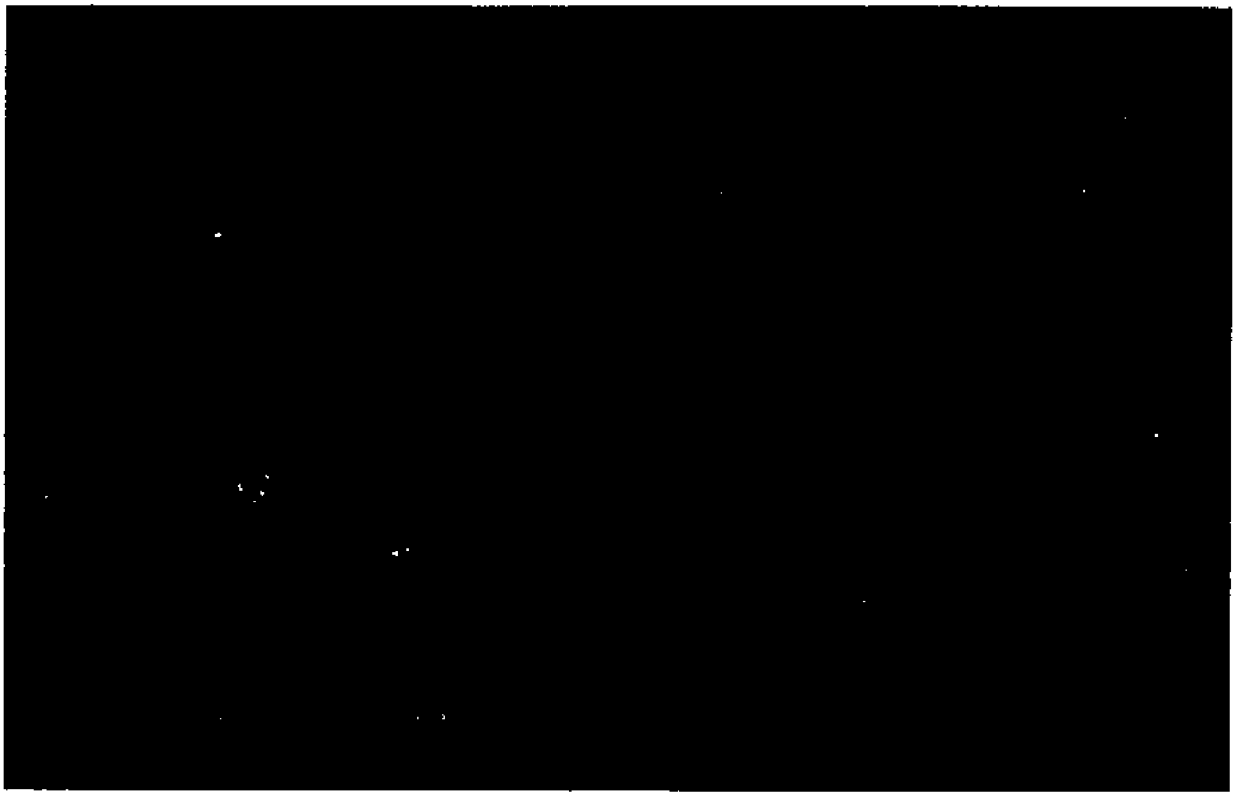

Figure 4. Maximum habitat suitability ratings projected for 1986.

Figure 5. Minimum habitat suitability ratings projected for 1986.

Table 3. Land area tabulations of 1986 maximum habitat suitability ratings.

Header listing for GIS file: HABSTLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 09-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 8
This file contains 4-bit data
The VARIABLE name is RECODE SUITINDX.FOR HABITAT SUITABIL.RATING

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	779.	192501.406	0.73 %	VERY HIGH SUITABILITY
2	16287.	4024737.500	15.29 %	HIGH SUITABILITY
3	16640.	4111968.500	15.63 %	MODERATE SUITABILITY
4	66775.	16501004.000	62.71 %	LOW SUITABILITY
5	3921.	968932.000	3.68 %	NEGLIGIBLE SUITABILITY
6	384.	94891.578	0.36 %	INSUFFICIENT DATA
7	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Table 4. Land area tabulations of 1986 minimum habitat suitability ratings.

Header listing for GIS file: MINSTLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 22-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 8
This file contains 4-bit data
The VARIABLE name is OVERLAY HABSTLP1. W/ FORESTLP.

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	779.	192501.406	0.73 %	VERY HIGH SUITABILITY
2	16287.	4024737.500	15.29 %	HIGH SUITABILITY
3	16640.	4111968.500	15.63 %	MODERATE SUITABILITY
4	7765.	1918836.250	7.29 %	LOW SUITABILITY
5	62931.	15551099.000	59.10 %	UNSUITABLE - NONFOREST LAND
6	384.	94891.578	0.36 %	INSUFFICIENT DATA
7	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Table 3 are quite comparable to those in Table 4 except that these minimum suitability tabulations find the low suitability class reduced to about 7 % and the negligible suitability class replaced by unsuitable or nonforested lands representing about 60 % of land area. A new data class representing .36 % of Michigan's land area has been introduced with the host suitability rating as a function of the distribution of available climate data. This class, insufficient data, and its associated acreage, will be carried through all subsequent analyses indicating that required climatic data were absent in a previous step, creating essentially un-rateable land areas. The acreage contribution by inland water bodies can be seen to be identical to that in Table 1 and Table 2. This figure (1.60% of land area) is also carried through all subsequent rating levels.

3. Habitat Susceptibility

Habitat susceptibility ratings have been expressed in classes which indicate the relative availability or liability of suitable gypsy moth habitat based upon its proximity to known gypsy moth populations and upon their opportunity for dispersal and subsequent infestation. The distributions of these classes are approximated by mapping their minimum and maximum geographical extent. These extremes are meant to suggest the ends of a spatial continuum between which actual distributions are expected to lie.

Maximum and minimum spatial distributions of host susceptibilities are illustrated in Figures 6 and 7. Both figures show broad linear features most of which appear to radiate from the Midland area. These represent lands classed as very highly susceptible and are primarily the result of introducing the effects of highway corridors into the analysis. Although lands classified into lower susceptibilities show less linear patterning, they tend to be clustered close-by these more linear features. This is the result of 1985 gypsy moth population data, the distribution of which, has introduced a somewhat concentric pattern centered on the midland area. Both Figures 6 and 7 also show high and moderate susceptibility classes to be distributed in a large arc around the Saginaw Bay region. Lower susceptibility classes are distributed widely throughout the Lower Penninsula.

Figure 6. Maximum habitat susceptibility ratings projected for 1986.

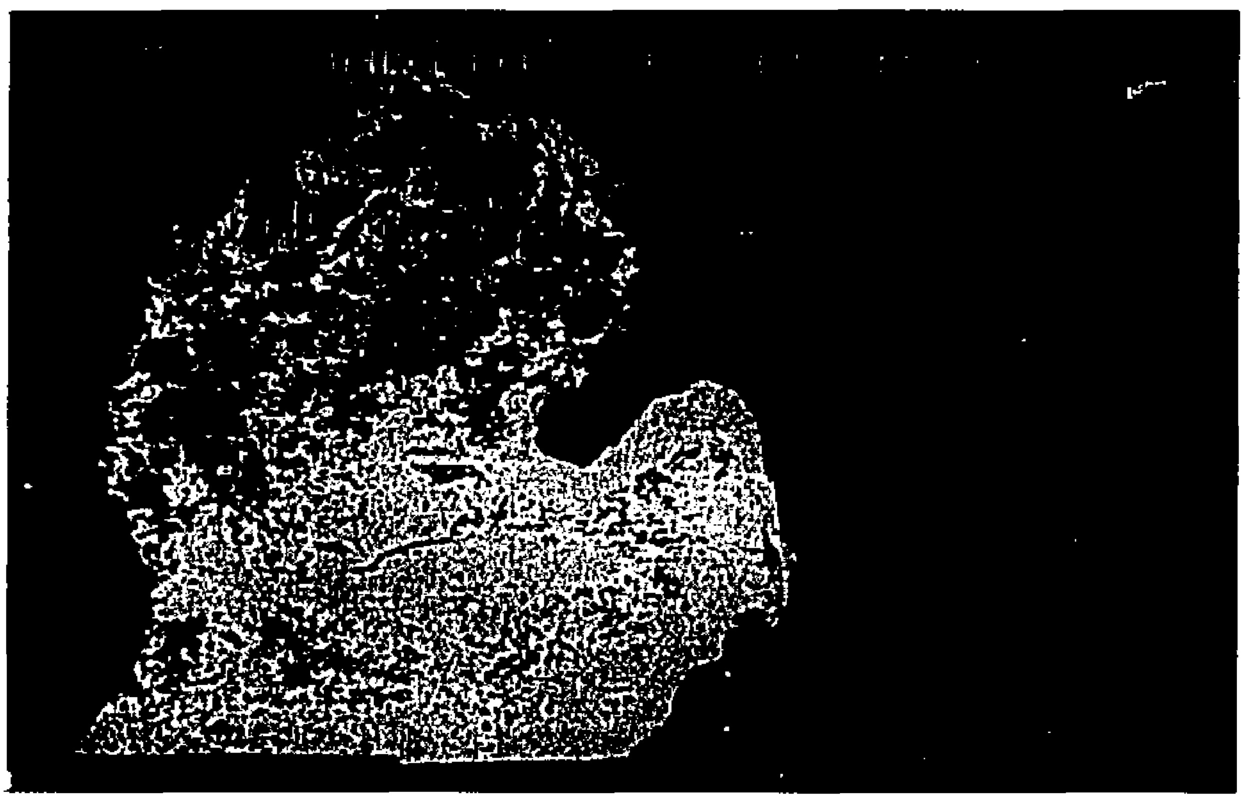

Figure 7. Minimum habitat susceptibility ratings projected for 1986.

Table 5. Land area tabulations of 1986 maximum habitat susceptability ratings.

Header listing for GIS file: HBSUSLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 23-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 8
This file contains 4-bit data
The VARIABLE name is RECODE HBSUSXLP.FOR HABITAT SUSCEPTIBIL.RAT

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	769.	190030.281	0.72 %	VERY HIGH SUSCEPTIBILITY
2	6158.	1521724.870	5.78 %	HIGH SUSCEPTIBILITY
3	36255.	8959100.000	34.05 %	MODERATE SUSCEPTIBILITY
4	53860.	13309533.000	50.58 %	LOW SUSCEPTIBILITY
5	7360.	1818755.370	6.91 %	NEGLIGIBLE SUSCEPTIBILITY
6	384.	94891.578	0.36 %	INSUFFICIENT DATA
7	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000	.	

Totals and Percentages are Based on Non-zero points

Table 6. Land area tabulations of 1986 minimum habitat susceptability ratings.

Header listing for GIS file: MINSCLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 23-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 9
This file contains 4-bit data
The VARIABLE name is OVERLAY HBSUSLP1. W/ FORESTLP.

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	769.	190030.281	0.72 %	VERY HIGH SUSCEPTIBILITY
2	6158.	1521724.870	5.78 %	HIGH SUSCEPTIBILITY
3	15882.	3924656.500	14.91 %	MODERATE SUSCEPTIBILITY
4	17268.	4267156.000	16.22 %	LOW SUSCEPTIBILITY
5	1394.	344476.219	1.31 %	NEGLIGIBLE SUSCEPTIBILITY
6	62931.	15551099.000	59.10 %	NON-SUSCEPTIBLE,NONFOREST LAND
7	384.	94891.578	0.36 %	INSUFFICIENT DATA
8	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Acreage tabulations in Tables 5 and 6 show (identically) that less than 1 % of land area lies in the very high susceptibility class and only about 6 % lies in the high susceptibility class. Michigan lands fall predominantly in the low and moderate susceptibility classes but a great disparity in acreage exists between the maximum and minimum distributions projected. Table 5 shows that together these classes constitute a maximum of approximately 85 % of all lands. Table 6 shows the sum for the two classes to be only about 31% of all lands. Lands of negligible host susceptibility (maximum distribution only) are shown in Table 5 to be almost equal in area to those of the high susceptibility class.

4. Host Vulnerability

Host vulnerability ratings have been expressed in classes which represent the relative likelihood that environmental stressors and gypsy moth defoliation will have the consequence of doing harm to hosts.The distributions of these classes are approximated by mapping their minimum and maximum geographical extent. These extremes are meant to suggest the ends of a spatial continuum between which actual distributions are expected to lie.

The spatial distribution of vulnerability classes is shown in Figures 8 and 9. The higher ratings show a very strong resemblence to the distribution of susceptibility ratings shown in Figures 6 and 7; making it difficult to discern significant differences in the images. Moderate and low ratings can be seen to be controlled, in part, by soil water holding capacity data which are recognizable by their many curvilinear features. Most apparent is the obvious contribution of water bodies and wet soils to these lower ratings. These soils data, combined with climate data, appear to reinforce the arcuate distribution of high vulnerability classes around the Saginaw Bay region.

As can be seen in the acreage tabulation in Tables 7 and 8, the extreme, very high and low classes, contribute less than 1 % in both the maximum and minimum vulnerability distributions. The preponderance of acreage is concentrated on the middle-most classes. Very high and high vulnerability ratings are identical at only .46 % and 3.38% of land area, respectively,

Figure 8. Maximum host vulnerability ratings projected for 1986.

Figure 9. Minimum host vulnerability ratings projected for 1986.

Table 7. Land area tabulations of 1986 maximum host vulnerability ratings.

Header listing for GIS file: HVULNLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 23-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 9
This file contains 4-bit data
The VARIABLE name is RECODE VULNDXLP. FOR HOST VULNERABILITY RAT

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	491.	121332.727	0.46 %	VERY HIGH VULNERABILITY
2	3603.	890349.937	3.38 %	HIGH VULNERABILITY
3	35561.	8787603.000	33.39 %	MODERATELY HIGH VULNERABILITY
4	49639.	12266467.000	46.62 %	MODERATE VULNERABILITY
5	14770.	3649866.250	13.87 %	MODERATELY LOW VULNERABILITY
6	338.	83524.359	0.32 %	LOW VULNERABILITY
7	384.	94891.578	0.36 %	INSUFFICIENT DATA
8	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Table 8. Land area tabulations of 1986 minimum host vulnerability ratings.

Header listing for GIS file: MINVULP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 23-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 10
This file contains 4-bit data
The VARIABLE name is OVERLAY HVULNLP1. W/ FORESTLP.

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	491.	121332.727	0.46 %	VERY HIGH VULNERABILITY
2	3597.	888867.250	3.38 %	HIGH VULNERABILITY
3	15798.	3903899.000	14.84 %	MODERATELY HIGH VULNERABILITY
4	17144.	4236514.000	16.10 %	MODERATE VULNERABILITY
5	4308.	1064564.870	4.05 %	MODERATELY LOW VULNERABILITY
6	133.	32866.094	0.12 %	LOW VULNERABILITY
7	62931.	15551099.000	59.10 %	NON-VULNERABLE,NONFORESTED L.
8	384.	94891.578	0.36 %	INSUFFICIENT DATA
9	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

for both the maximum and minimum distributions. Moderate vulnerability classes show great disparity between their maximum and minimum distributions, as they did in susceptibility ratings.

5. Infestation Acceptability

Infestation acceptability ratings have been expressed in classes extending from very high acceptability to very low acceptability. These represent the relative degree to which persons, groups, or agencies having concern for or control of susceptible habitats or vulnerable hosts will find gypsy moth infestation or any of its consequences to be tolerable or to be intolerable.The distributions of these classes are approximated by mapping their minimum and maximum geographical extent. These extremes are meant to suggest the ends of a spatial continuum between which actual distributions are expected to lie.

The spatial distributions of infestation acceptability classes are shown in Figures 10 and 11. Both of these show a moderate amount of dispersion among moderate and high acceptability ratings reflecting the reliance on administrative units whose locations are scattered throughout the state. Data for these areas are, in many places, recognizable as rectilinear features. As might be expected, the results achieved by introducing this data set do not differ substantially, for low and very low acceptability ratings, from those of the vulnerability classes previously discussed. This is largely due to the fact that available private land ownership data input to the model could not be subdivided and ranked and thus introduced almost no additional geographic variability in the derived risk data.

Acreage tabulations in Table 9 and 10 show that while percentages of land area differ between the maximum and minimum distributions of infestation acceptability, as would be expected, both show that Michigan lands fall primarily into the moderate acceptability classes. Little more should be concluded from current infestation acceptability ratings because the data used in this portion of the analysis were not available in sufficient quality or quantity to make possible reliable geographical projections.

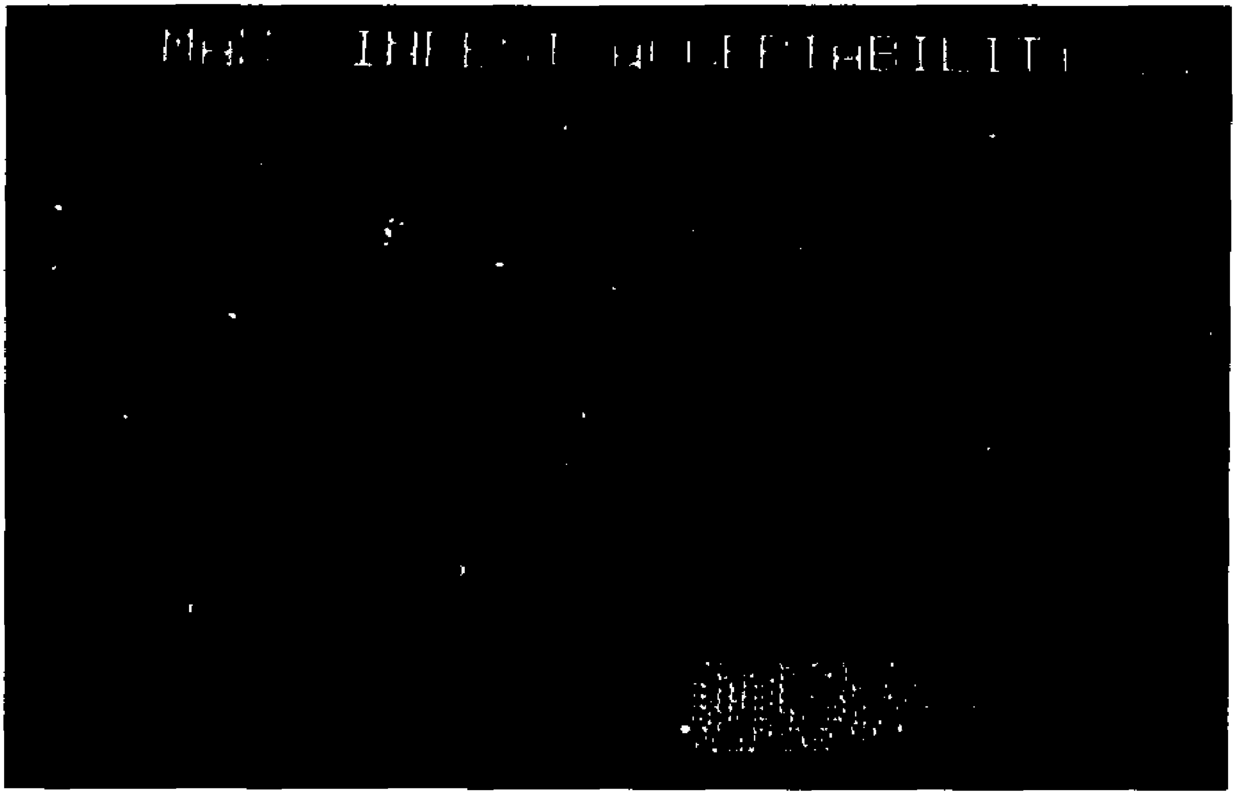

Figure 10. Maximum infestation acceptability ratings projected for 1986.

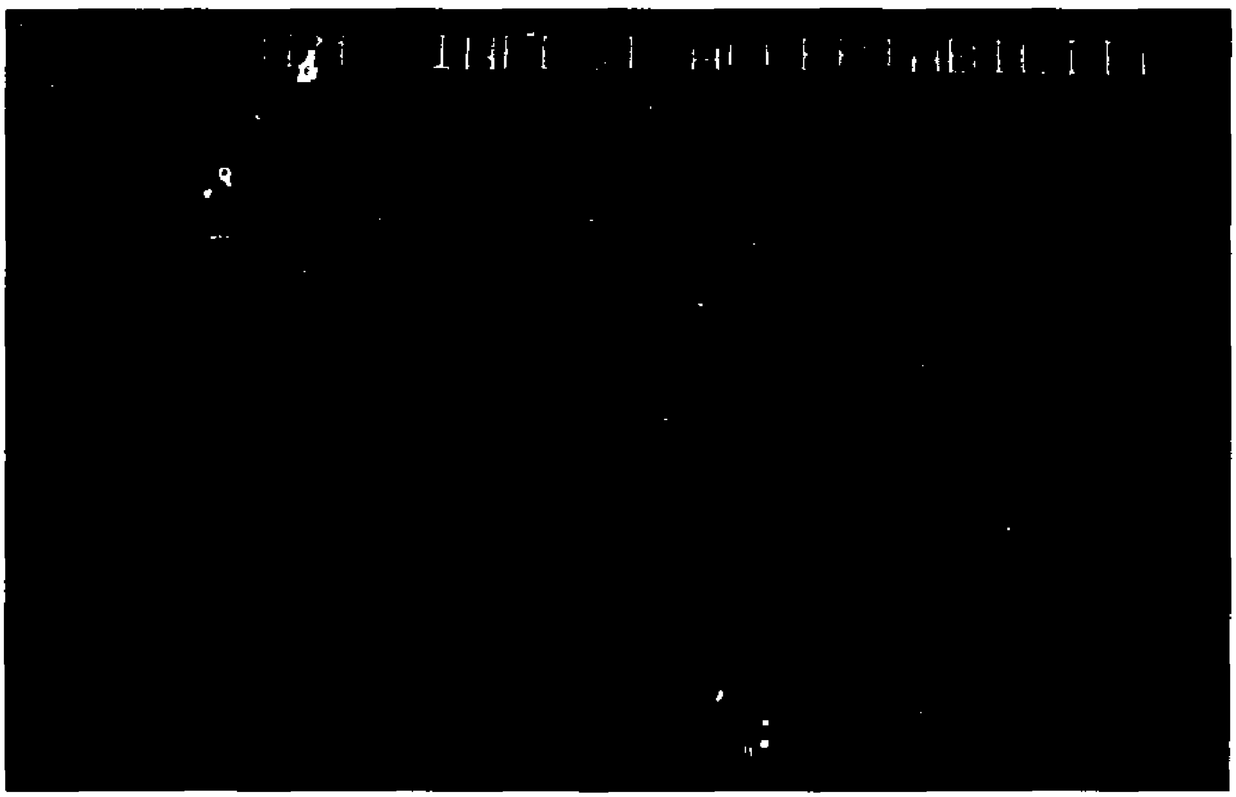

Figure 11. Minimum infestation acceptability ratings projected for 1986.

Table 9. Land area tabulations of 1986 maximum infestation acceptability ratings.

Header listing for GIS file: ACCPTLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 23-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 10
This file contains 4-bit data
The VARIABLE name is RECODE ACPTDXLP. FOR ACCEPTABILITY RATING

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	310.	76605.180	0.29 %	VERY LOW ACCEPTABILITY
2	2379.	587883.000	2.23 %	LOW ACCEPTABILITY
3	29314.	7243885.000	27.53 %	MODERATELY LOW ACCEPTABILITY
4	40861.	10097305.000	38.37 %	MODERATE ACCEPTABILITY
5	23040.	5693495.000	21.64 %	MODERATELY HIGH ACCEPTABILITY
6	8450.	2088109.000	7.94 %	HIGH ACCEPTABILITY
7	48.	11861.447	0.05 %	VERY HIGH ACCEPTABILITY
8	384.	94891.578	0.36 %	INSUFFICIENT DATA
9	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Table 10. Land area tabulations of 1986 minimum infestation acceptability ratings.

Header listing for GIS file: MINACLP1.GIS
Date statistics printed: 06-NOV-1986
Date statistics created: 24-AUG-1986

This file has 470 rows, and 361 columns

This image is geo-referenced to a UTM coordinate system
The upper left corner has coordinate: 290068.2, 557628

The cell size is (X, Y): 1000, 1000
The number of acres per cell is: 247.1135
Upper left corner data file coordinate (X,Y) is: 273, 264

Number of classes in this variable is: 11
This file contains 4-bit data
The VARIABLE name is OVERLAY ACCPTLP1. W/ FORESTLP.

VALUE	POINTS	Acres	%	DESCRIPTION
0	63183.	15613372.000	0.00 %	BACKGRND.(NON-MICH.& GREAT LKS)
1	310.	76605.180	0.29 %	VERY LOW ACCEPTABILITY
2	2375.	586894.562	2.23 %	LOW ACCEPTABILITY
3	10136.	2504742.500	9.52 %	MODERATELY LOW ACCEPTABILITY
4	11126.	2749384.750	10.45 %	MODERATE ACCEPTABILITY
5	11175.	2761493.250	10.49 %	MODERATELY HIGH ACCEPTABILITY
6	6344.	1567688.000	5.96 %	HIGH ACCEPTABILITY
7	5.	1235.568	0.00 %	VERY HIGH ACCEPTABILITY
8	62931.	15551099.000	59.10 %	ACCEPTABLE,NONFOREST LAND
9	384.	94891.578	0.36 %	INSUFFICIENT DATA
10	1701.	420340.062	1.60 %	INLAND WATERS
Totals:	106487.	26314374.000		

Totals and Percentages are Based on Non-zero points

Implications

Following is an interpretation of the results obtained from the GIS analysis, in so far as they have implications for further evaluation, development, or use of GMRIS. No attempt is made to interpret the significance of these results for forest pest management practice or policy in Michigan.

1. Performance of the GMRIS Risk Model

Results achieved with the gypsy moth risk assessment model, given current computing and data resources, are encouraging. A preliminary examination of results suggests a close correspondence between habitat susceptibility risk ratings projected for 1986 (using 1985 pest population data), and the results of the 1986 aerial defoliation survey. This close correspondence when overlaying projected and actual centers of defoliation suggests that the functional relationships expressed in the model may provide some predictive power and that further refinements of the model may be warranted. Such correspondence, or lack thereof, is the only immediate indication of the performance of the current GMRIS risk model since it relies on annual defoliation which is a relatively short term phenomenon and one for which monitoring is already being carried out. Risk projections for 1987 will facilitate further evaluation of the model's performance by allowing comparison of 1986 and 1987 projections, but these will require new defoliation data which will not become available until August, 1987.

Another potential problem remains for the evaluation of the GMRIS model. It appears, judging from the spatial distribution of susceptibility ratings projected for 1986, relative to the spatial distribution of 1986 defoliation, that patterns of defoliation change over the next few years may be confined to nearly the same portion of the Lower Penninsula and/ or may be dispersed in pockets smaller that about 500 m^2. If these events were to transpire, either would have the result of exceeding the resolution of our current information system with its 1 km^2 cell size by making it necessary to discriminate changes occurring largely within, rather than between, cells.Reaching reliable conclusions about the performance of the gypsy moth risk assessment model will require replicating procedures used in this study on higher resolution data sets developed for the current defoliation zone which is centered on Midland and Isabella counties.

If future defoliation becomes widely dispersed, it will also introduce important questions regarding the accuracy and speed with which defoliation maps can be produced for very large portions of the state, and the standards that should be used to assure their fitness for use with GMRIS. Prompt evaluation (before summer, 1987) of video, photographic or other sensing technology from air or space borne sensors will help prevent interruption of the flow of data critical to GMRIS and to later trend analysis efforts.

2. Adequacy of the Data Base

The salient problem with the current data base is its underrepresentation of important risk influences in the forest/land management objectives submodel. The single data set that is presently included, land ownership and administrative units, raises two important problems concerning data acquisition. First this data set represents primarily Michigan's governmental administrative units although private lands is included as the "remainder" management class. Since it is not divisible (as federal lands are, into forests, parks, and wildlife areas), and is little more than a default category, it neither contains useful information on private land management objectives nor offers any means of extracting such information from other sources, or attaching it to the digital data. Additional data must be acquired to increase the sensitivity of the forest/land management objectives submodel. At a minimum, human population density data should be obtained at a resolution as near as possible to the 1 km^2. resolution achieved with other variables. This would allow at least a very crude indicator of the number of persons who might be affected by various levels of risk.

The second problem raised by this data set is that of assuring that analog map data can be accurately input to GMRIS. Poor results were achieved in the digitization of this data with the result that they were poorly registered to other layers in the data base. This has now been rectified but it is obvious that additional data will often be available in analog map form which will have to be manually digitized using coordinates that correspond to the CRS Graticule adopted as our geo-referencing standard. Achieving co-registration in either latitude/longitude or UTM coordinate systems will continue to be difficult, at best, unless some analog base map is tested against, and matched to, the graticule so that subsequent analog map data (paper maps, for example) can first be checked for inaccuracies or distortions in the projections used or in their cartographic rendering. If the Center for Remote Sensing does not undertake this task in support of the state-wide 1 km^2 gis standard, then it should be done independently for GMRIS alone. Also, any future GIS data base development in support of risk assessment, or other research at higher resolutions, should begin with the selection of such a base map as a referent for all subsequent analog data.

3. Performance of Hardware/ Software Systems

Three deficiencies within the hardware and software subsystems used for GMRIS have been identified during the course of the 1986 risk assessment analyses. First, only one option currently exists to convert (interpolate) point data (such as trap catch data) to continuous data in the form of a "surface". This option exists in the form of proprietary software written by the CRIES Project. Use of this software module entails numerous problems for the user affecting both the efficiency and the quality of work done. These deficiencies could be remedied at very little additional cost to the sponsors of such improvements. None of the ERDAS hardware/software systems at MSU include ERDAS surfacing or related modeling software. If acquisition of the appropriate ERDAS software is not anticipated in the very immediate future, it is recommended that users negotiate or share the upgrading of the available CRIES-GIS surfacing module. Second, the ability of those GIS systems available to GMRIS to closely examine aspects of adjacency, contiguity, linear distance, directional trends, and other properties of spatial data, are severely limited. Unfortunately, these relationships are important to bio-ecological studies such as those required for gypsy moth risk assessment. These capabilities should be considered in light of this projects findings and numerous secondary analyses that may be required (such as the construction of higher resolution data sets to support more intensive study). Additional software or substitute geographical information systems may be required. Third, the greatest single impediment to conducting dependable, convenient, and truly useful GIS analyses is the "bottleneck" created by output devices which still are too expensive to be acquired locally (wide bed color printers), are inadequate for presentation purposes (line printers incapable of color output), are incompatible with raster images (plotting devices which function with vector data), or are undependable and/or offer the user little control or flexibility (ink-jet printers and color recorders). Marketplace conditions probably prohibit any near-term solution to this problem unless the costs of additional output devices can be shared among enough cooperators. Until this problem is solved data can not be returned to the analog form required after processing.

4. Resolution of Researchable Problems Posed by this Study

The three research questions posed at the outset of this study are addressed below based upon experience gained to date, results of the 1986 risk assessment, and expressed pest management objectives. The first of these questions asked whether a GIS-based gypsy moth risk assessment system could be made operational. The capability now exists to: draw upon a data base containing key risk-related variables; to update the contents of the data base by adding annual pest information in a dependable, reasonably convenient manner; and to perform the principal spatial analyses needed to establish broad, qualitative projections of annual risks at five different levels. Since no further large development efforts are required to derive such risk projections, and no additional system inputs are required beyond those which change with time, it is concluded that GMRIS is now a fully operationalized risk projection system.

The second research question asked how such a system, if operationalized, should be implemented. Experience gained with the technological subsystems of GMRIS and with the user/manager subsystem, indicate that coordination of GMRIS capabilities and operational requirements with other forest pest management activities, rather than the state of GIS technology, is and will continue to be the limiting factor in fully implementing this now operational system. The principal impediment to successfully implementing the system will be the difficulty of striking a balance between the independence which GMRIS can provide to users and the coordination that will be required to maintain its performance quality and to assure its survival. The portability and self-containment possible with the CRIES-GIS package installed on a micro-computer, serving as a remote work station compatible with central facilities on the MSU Campus, carries with it the potential for fragmentation of the institutional linkages and shared control which were required to operationalize the system. Further use and development of GMRIS should be predicated upon explicit agreements to formalize and share support of the system among members of the Cooperative Forest Pest Management Program. Such agreements should begin with an examination, by all members, of the utility GMRIS may have for continuing management efforts and of the best way to build it into the work agenda and perhaps the budget of each member agency. It should be remembered that the convenience with which data can be accessed and analyzed by users is not indicative of the time, expense, or difficulty with which data are prepared, and entered into the system. Unless sponsors of GMRIS recognize that it requires advance planning for a great many technical details and logistical problems, it will not continue to support the speedy querying that users will come to expect. To make GMRIS operational has required that institutional linkages be strengthened, and more importantly, that they be used. These linkages are informal and work well provided that all parties can recognize one party who operates as a liason on GIS matters, at least. Whether that role can be continued after the development stage ends, or whether members can formalize operations enough to maintain GMRIS's dependability without it, will depend upon decisions that will be made by its users.

The third research question asked whether GMRIS could help to better meet forest pest risk assessment objectives. This question remains largely unanswered because many management goals and objectives remain unexpressed, and therefore, unagreed upon or acquiesced to, making it difficult to establish a sound basis for evaluation. Also, and perhaps more important, agency representatives are not yet sufficiently familiar with the capabilities of GMRIS to judge its actual or potential contributions. Evaluation of GMRIS in several dimensions must be the very next step if GMRIS is to be fully implemented. Recommendations for evaluating GMRIS are made in the remainder of this chapter.

Evaluation of GMRIS

Evaluation of the Gypsy Moth Risk Information System is a critical step toward its effective utilization and refinement. However, its deletion from this study has been necessitated by the high level of effort and the great expense required to acquire and process data with state-wide coverage, design a model which makes thorough use of existing data and knowledge, and transfer an operational, understandable spatial analysis capability to agencies which can benefit from it. Based on the assertion that evaluation is an indispensable next-step in the continued use of state-wide GIS technology for forest insect pest management, and that more needs to be said about it than would constitute a simple recommendation, a brief description has been included of 3 distinct and very important aspects proposed for such an evaluation. GMRIS should be evaluated as an application of GIS technology to the partial solution of a specific set of forest resource management problems for which clear goals and objectives are stated. In particular, evaluation should include a quality report on system components, validation of the logic and performance of the conceptual model used, and a review of the system's contribution to meeting (or capability to meet) management objectives. These tasks represent largely independent evaluation "variables" and should thus be treated separately, as they are below.

1. Data base quality evaluation

A full quality report should be made of the integrity and fitness of the data assembled for use in GMRIS, with consideration of the software and hardware systems by which they are manipulated. The National Committee for Digital and Cartographic Standards (NCDCS) has proposed a kind of "truth-in-labeling" standard which avoids an unrealistic, fixed set of numerical thresholds (ill-suited to diverse applications of GIS technology), but does suggest useful alternate procedures which can make critical quality concerns explicit and accessible. They have recommended tests, standards of measurement, and reporting devices for evaluation of data quality. Following is a summary taken from the Committee's interim standards (Moellering, 1985, pp. 17-21, 113-120).

NCDCS has proposed a quality report be completed for all data, which recognizes the unique character of digital data and which, therefore, goes well beyond the inadequate practices originally prescribed for analog map products by the National Map Accuracy Standards. It is proposed that standards for digital data be executed in a report consisting 5 parts: an historical (on-going) report or "lineage" of the data set, and 4 accompanying measures or aspects of data integrity; positional accuracy, attribute accuracy, logical consistency, and completeness.

The lineage portion of a quality report should contain a detailed and accurate description of the original source material from which the digital data have been derived, all transformations performed on the data to date, and the methods used to accomplish all derivations and transformations. The report should also include sufficient reference to control information to allow data recovery (standards of the Federal Geodetic Control Committee (FGCC) are endorsed), and complete documentation of transformation algorithms used throughout the life of the data. In addition to a narrative report, the committee recommends use of reliability overlays or annotated data quality maps which can be used as overlays with other data sets to identify potential limitations to data use or problems which may arise from further transformations.

Measures of data integrity which should accompany, or contribute to a lineage statement address potential deficiencies in the forms of accuracy, consistency, and completeness. Four general types of tests have been identified by the committee for use in evaluating these aspects. These tests do not all apply equally well for the measurement of each aspect of data quality. Listed in order of preference and increasing rigor these test categories are: (1) deductive estimates, combined estimates based on knowledge of errors in each production step, (2) internal evidence, FGCC procedures carried out using repeated measures and redundancy in the data, (3) comparison to source, graphic inspection of results to determine the fidelity achieved by processes used, and (4) independent source of higher accuracy, comparison to measurements of identical entities in a more accurate source which are used as "true values" (definitions and standards are prescribed in the American Society of Photogrammetry's Accuracy Specifications for Large-scale Line Maps).

Provided that forest pest management objectives warrant continued use and development of GMRIS, it should be possible to match one or more data quality evaluation techniques to the precision demanded by, and the resources available to, the Michigan Cooperative Forest Pest Management Program. Data quality assessments should be coupled to complimentary research activities such as the development and evaluation of high resolution spatial data subsets for expanded gypsy moth management and research. Evaluation of current state-wide data sets should begin with the establishment of simple reliability overlays and with deductive estimates of accuracy.

2. Model validation

Little seems to have been written about the evaluation and refinement of conceptual models, the design category into which most cartographic models currently fall. This probably is due to their "lesser rigor" in comparison to other, more mathematically-oriented models. Perhaps because that they are often presumed less rigorous, and therefore less consequential, there is need to be certain that when conceptual models are employed, they are also fully evaluated. Unless this is done there is danger that such models will be employed uncritically in decision making. Unfortunately there are problems inherent in modeling and, thus, validating systems which are, in part, politically defined. Findheiser and Quade (1985, p. 136-137) suggest that confidence in models is particularly limited for questions of public policy, where social and political considerations dominate. In these cases, what are often regarded as "less satisfactory" judgemental models,those that depend more directly on expertise and intuition and are not as precise and manageable, may have to be used. Even in situations where the phenomena and relations required for prediction are quantifiable, the correctness (validity) of models used for prediction are limited by many factors including: restricted knowledge of the laws of system behavior, inadequate data, and inability to deal effectively with very complex relations (Findheiser and Quade, 1985, p. 137). All of these limits currently apply to the modeling of state-wide risks associated with gypsy moth.

Two important steps remain to be taken regarding the model developed in this study. The model should first be reviewed following its initial use here. There are two reasons for doing this. First, the forest/land management objectives submodel of GMRIS is largely incomplete, yet it is a very important component of overall risk. Second, the background context in which the model is to be used may have changed, reflecting personnel or goal changes among management agencies. In addition, the current risk model has not previously been subjected to satisfactory, multi-agency review, although this was attempted early in the project and found to be premature. Specifically, the model should be evaluated with respect to the logic it employs, the kind of data used, the decision criteria selected, and the potential effects of incomplete or unnecessary submodels on the level of effort required and the benefits derived. It would also be useful to attempt a quality evaluation using some more universal criteria of model quality such as those proposed by Holling as cited by Gutierrez and Wang (1984, p. 738-739). They suggest that the requisites of (good) models are that they have: (1) realism, they mimic the real world or nature, (2) wholeness, they contain enough detail to represent observed real-world behavior, (3) precision, they do so with a high degree of accuracy of detail, and (4) generality, they have general applicability beyond being a description of events proceeding from the specific data used in its construction.

The second important step assumes favorable post-study review and calls for formal validation of the model; the most important, and most often ignored phase in development of risk assessment systems (Hedden, 1981, p. 11). While validation of a model can occur before or after implementation, it is generally recommended that some form of validation should generally be done before the system is put into use (Hedden, 1981, p. 11). Improvements in a model can be made by testing it against another detailed model or against historic data and making adjustments accordingly (Quade, 1985, pp. 206-207). Hedden (1981, p. 11) describes a hierarchy of progressively rigorous tests for use in validation of models against data: (1) testing the model against the data from which it was developed, (2) testing it on a subset of the original data that were set aside for this purpose before the model was developed, and (3) testing the model on a completely independent set of new data . Good performance against data from which our model was developed is to be expected and, in any case, this has been done. Reserve data were not available for testing against a subset, and, in any case, a more rigorous test should be done with new data, at a higher resolution, and under ecological conditions which can be closely monitored over time. Validation by either means has not yet been possible because neither a more detailed model which has gained widespread confidence, nor sufficient historical data have been available for testing. Both more detailed models and comparable historical data should soon become available. Which ever option arises first should be exploited to validate the risk model used in this study.

3. Evaluation of GMRIS as a decision-support technology

The objective of measuring or estimating the effectiveness or efficiency of applied GIS-based decision-making systems is not well documented. Also, there appears to be an imbalance between the substantial efforts which are made to "benchmark" the problem-neutral performance of hardware/software, and rare efforts to evaluate the performance of "in-place", operationalized GIS-based decision support technologies. Tomlinson (1972) and others addressed the issues of GIS effectiveness and efficiency analyses in the early 1970's, as a few others have done since, but these treatments are usually design-stage considerations not well adapted to the kind of "post-hoc", or interim evaluation proposed here. Similarly, some attempts have been made at developing methods to make GIS's more responsive by ascertaining user opinion on such factors as the utility, cost, condition, and accessibility of data sets (Brooks, 1982, and Mead, 1981). But, while these methods might provide a data base content evaluation framework complimentary to the data base quality approach described above, they will likely contribute little to GIS evaluation beyond the data base design and construction stage.

None of these methods are suited to viewing and evaluating GMRIS as a whole system on a post- hoc basis. The difficulties, and perhaps the reasons for so little work having been done in this area, can be seen in observations on the value of information, and the results of better management decisions. Marble et al. (1972, p. 1205) state that the use of information from an information system begins with transfer of the final output to the user's decision system which in turn can only be understood in terms of the users goals and objectives, plans, and expectations. They then define the value or benefit of this information as the marginal improvement in the performance of the user's decision system that is achieved through the use of the information. Unfortunately, obtaining knowledge of marginal improvement in decision systems is extremely difficult, if not impossible. This value-of-information notion implies that the benefit or value of incremental additions to the stock of information can be quantified, but the marginal value of information is extremely difficult to determine because decisions may actually be made in the absence of information, or they may be deferred altogether (Marble et al., 1972, p. 1205). Wilson et al. (1983, p. 113) have characterized a similar problem in evaluating preventative (improved) forest pest management, a set of practices which are enabled, in part, by rapid delivery of information using technologies such as those developed for GMRIS. While traditional forest pest management programs are evaluated in terms of readily measured outputs such as acres treated, the activity that such figures indicate may not imply effectiveness. They point out that good management first stresses prevention, an approach that reduces the negative pest losses and inherent shortcomings of reaction, or control management. However, it is not easy to calculate the number of pest outbreaks avoided, or to measure the positive results of better management decisions.

Although little work appears to have been done in the area of evaluating implemented geographic information systems within a problem solving or applications context, some negative influences of GIS technology have been documented pointing up the need to identify implementation problems which may exist at a whole-systems level (Day, 1979). Based on the findings of this study, it appears that it will be necessary to turn to the non GIS-specific evaluation literature to begin developing appropriate methods to evaluate GMRIS provided that goals to support such work can be clearly articulated.

Technology Transfer

The gypsy moth risk information system was conceived, and has been developed, under the aegis of the Michigan Cooperative Forest Pest Management Program (MCFPMP), an interagency working group whose research goals include developing pest management schemes, developing techniques for monitoring, and devising impact models. MCFPMP is a cooperative, team approach to state-wide forest pest management formed in the late 1970's through joint effort by several of Michigan's universities, the Michigan Department of Natural Resources, and the U.S. Forest Service (Wilson et al., 1983, p. 109). These agencies have recently been joined by the Michigan Department of Agriculture which retains institutional responsibility for gypsy moth management in Michigan. The team's purpose is to devise new technologies, transfer available technology, and provide service and management alternatives. (Wilson et al., 1983, p. 110-111).

Technology transfer is a term commonly used to describe diffusion of useful innovations to practitioners; including in forestry, the owners and managers of land (Muth and Hendee, 1980, p. 141). From the perspective of the researcher, technology transfer is the process by which research results are communicated to practitioners for their use (Hertel, 1981, p. 13). Although not all methods, technologies, or results which one might wish to see implemented qualify as innovations, because they will not all be perceived as "new", it is assumed here that GMRIS does constitute a technological innovation whose diffusion is desirable. The term technology, as intended here, has been defined by Rogers (1983, p. 12) as a design for instrumental action that reduces the uncertainty in the cause-effect (sic.) relationships involved in achieving a desired outcome. They suggest that technology consists of two components: (1) a "hardware" aspect, consisting of the tool that embodies the technology as material or physical objects, and (2) a "software" aspect, consisting of the information base for the tool; and that the mix of these components, or the relative dominance of either, is dependent on the social system in which the technology is embedded. This is clearly analogous to the implementation of a geographic information system (as a risk assessment technology) within or among appropriate agencies.

These qualifications of technological concepts have significance for the utilization of research, the final issue facing the designers of any study. There is a general implication that a technological innovation has at least some degree of benefit or advantage for its potential adopters, but that this advantage may not be clear-cut in their eyes because they can seldom be certain that an innovation represents a superior alternative to practices it might replace. Thus, a technological innovation creates a kind of uncertainty in the minds of potential adopters (about its expected consequences), as well as an opportunity for reduced uncertainty (by virtue of what can be learned from the information base of the technology) (Rogers, 1983, p. 13). In a recent review of risk assessment systems, Hertel (1981, p. 16) found that a great deal of effort went into getting these systems near the implementation stage (through various combinations of need, people, and money) but that all too often, necessary staffing and money could not be found when they were most important: when the technology could be moved from the research and validation phase to the operational-use phase . Implementation, and therefore technology transfer, is important both for purposes of obtaining feedback from users that will be useful in its refinement, and for the purpose of achieving its eventual adoption (acceptance and use) by forest owners and managers. The usefulness of GMRIS as an innovation and the appropriateness of its diffusion are the subject of evaluation issues discussed earlier.

The Michigan Cooperative Forest Pest Management Program provides an ideal, preexisting vehicle for effective transfer of the various technologies that we have collectively termed GMRIS. Rogers (1983, p.10) has identified a chain of related elements which has become known as the classical diffusion -adoption model describing the factors which influence the speed of adoption, and thus the implementation, of presumably useful technologies such as GMRIS. These major factors, as paraphrased by Muth and Hendee (1980, p. 141), are: (1) the characteristics of the innovation itself, (2) the media used to communicate information about the innovation, (3) the individual and group processes required for adoption, and (4) the characteristics of the social system in which the innovation is diffused. The Michigan Cooperative Forest Pest Management Program has both a structure which formalizes and facilitates technology transfer, and experience with these influential factors (Wilson et al., 1983 and Montgomery et al., 1984). The MCFPMP has a three part structure which places an extension function between those of research and application and which assures appropriate feedback and interaction. The formal extension function provides for technology transfer through training sessions and use of communications media. More spontaneous, creative approaches to technology transfer are also facilitated by maintaining a flexible, rather than overly-rigid organizational structure (Wilson et al., 1983, p. 111,114). The Michigan Cooperative Forest Pest Management Program also has considerable experience with technology transfer, both on behalf of its individual participants and as a collective group. A recent technology transfer effort which involved MCFPMP through its members, was that undertaken for spruce budworm management in the Lake States Region (Montgomery et al., 1984). Also aimed at a defoliating forest pest with potentially wide-ranging impacts, this project executed a complete technology transfer program, including program evaluation, and has produced a lengthy set of recommendations and imparted many skills to MCFPMP members. The sum of these institutional arrangements and acquired skills should adequately equip The Michigan Cooperative Forest Pest Management Program to handle the important questions of how GMRIS technology and expertise is to be put in place, institutionalized, maintained.

Decision Support

The potential role of geographic information system-based risk assessment technologies can be better appreciated if placed within the context of other research, technology transfer ("extension") efforts, and forest management activities. The common thread running through each of these components of forest pest management is the need to better support decisions made by individuals at any point in this process. Of course, providing the informational or technical basis for better decision making does not necessarily require automation, or increased automation. However, computer-based technologies offer great advantages in their ability to perform complex calculations and data processing in a reasonably rapid manner. These advantages can be exploited on a stand-alone basis or they can be optimized by coupling complementary automated systems to gain advantages that neither alone can offer.

GIS technology can contribute to otherwise non-automated forest pest management activities throughout the management process. For example, research programs may be better able to make preliminary appraisals of the dimensions and significance of candidate problems by weighing their relative magnitude, their location, or their change with time using existing GIS capability. Or they may be better able to manage data or to monitor performance, allowing adjustments that minimize waste or disruption. Of course, new lines of research which explicitly address the spatial properties of pest problems will gain most, by fully integrating GIS capabilities into the fabric of inquiry. Technology transfer, which is largely dependent upon the amenability of a problem and its alternate solutions, to simplified and persuasive presentation, can be enhanced by drawing on the unique capabilities of GIS's to integrate large amounts of complex, dissimilar data and to present the results in a structured graphic form which can be easily understood by nearly everyone. Opportunities exist to explore creative uses of GIS technology to achieve technology transfer in an interactive context where forest owners and managers interact with the technology directly to explore the boundaries of a problem, or where specialists work with clients and public over time to structure a problem and the means of its solution in a participatory manner. Similarly, management, which can become reduced to simple execution of decisions made earlier in the management process, may begin to use GIS technology to compare alternate responses to problems or to validate judgements based on short-term "field" phenomena, and to feed information on the consequences of management interventions back into the information stream, allowing managers to become more adaptive to change and allowing more complete transfer of experience to their contemporaries.

GIS technology can also contribute significantly to forest pest management endeavors which are predicated on additional or enhanced automation. Members of the Michigan Cooperative Forest Pest Management Program have acknowledged the need to constantly be aware of new and improved information delivery systems. Accordingly, they intend to use more electronic information gathering, storage, and retrieval systems and eventually, through remote access terminals, to assist users to identify pests and seek sound pest management schemes (Wilson, et al. 1983, p. 114). A regional approach such as this might constitute what Coulson and Witter (1984, p. 296-297) describe as a computer-based, interactive decision support system (DSS) which uses data and models to help decision-makers solve unstructured problems in a manner offering sufficient flexibility to allow more spontaneous problem solving, and to produce results "tailored" to often unpredictable needs regarding detection, forecasting, evaluation, suppression, prevention, or utilization decisions. The modeling and data retrieval capabilities of such a decision support systems would be greatly enhanced by the integration of cartographic modeling and spatial data handling capabilities of a geographic information system.

Recommendations

Need for change and refinement of the Gypsy Moth Risk Information System will arise from the "trial" nature of this study, and from the dynamic nature of spatial studies in general and of GIS-based data analyses in particular. Some tasks begun in this project have had to be left partially completed and will need to be finalized. Some tasks will need to be repeated as additional data become available or as old data are replaced. New tasks will need to be added, and other tasks terminated or modified as the model proposed here, or the procedures for its use, become better understood. The specific objectives of those who continue to use GMRIS, or those who adapt it to other pest management problems, may also require that changes be made to some part of the system. Portions of the system will also become technologically obsolete (particularly hardware and software) requiring their replacement, in whole or in part.

In the interest of creating a useful linkage between what has been accomplished and learned during this study, and what may yet need to be done or understood, a full list of recommendations has been included. These are separated into subject matter areas which correspond to the components of the information system described in this report. It is our hope that any further development or use of GMRIS or other GIS technologies will involve consideration of these observations relative to forest pest management applications in Michigan.

1. Data base

A. Document Implementation of Permanent Gypsy Moth Trapping Scheme

The system of permanent gypsy moth trapping sites (begun in the Lower Penninsula in 1985 and in the Upper Penninsula in 1986) should be documented in a manner that differentiates treatment of the Lower and Upper Penninsulas (since there will inevitably be at least minor differences), and in a manner that compares the ideal and the actual condition of the system on an on-going basis. Specifically, the system of permanent trap sites needs to be fully described as it was conceived, as it was first implemented, and as it is modified each year on a separate basis for the Upper and Lower Penninsulas. This documentation should include the criteria used for selection of sites, designation of sites in list and map form, characterization of omissions from the scheme (when, where, and why they occurred, and when they are implemented, if this occurs at a later time), and arguments for adding previously omitted sites to achieve an acceptable spatial array. Omissions should not be allowed to cluster, creating large openings in the resulting spatial distribution of trap catch data. Omissions that are spatially dispersed will be less detrimental to data analysis and interpretation efforts. It may be necessary to negotiate implementation of some percentage of the hard-to-reach sites. All of these aspects should be documented.

B. Evaluate Defoliation Monitoring by Means of Aerial, Video Imagery

Aerial sketch mapping has been proven inadequate as the sole, or principal means of monitoring and recording annual defoliation by gypsy moth. Although sketch mapping alone can play an important role in reconnaisance work, it has been found to be relatively inaccurate, and to lack detail, unless done in a painstaking manner (the expense of which would negate its inherent advantages and likely justify substitution with a better technology). Also, the image collected (a sketch map) cannot be reanalyzed to extract new data as need arises (photographs can be reprocessed and reanalyzed with different criteria or methods to achieve different results). Better monitoring data are necessary to improve the predictive capability of our model and to enable full use of GMRIS in support of other gypsy moth management decisions. Video imagery offers several advantages; it is an "intermediate" technology capable of complete user control, the media (magnetic tape) are inexpensive and reusable, photographic development costs are eliminated, imagery is collected in "real time" (images can be monitored as they are collected), and the continuous nature of the tape media allow still images to be extracted at an infinite number of points along the flight path. Video tape also offers educational and communications advantages in that it allows "simulated" presentation of aerial views to decision-makers, forest managers and others. Plans made during this project to test video technology for these purposes should be carried through and, if results are encouraging, its use should be carefully integrated with GIS data acquisition efforts and with other forest pest management technologies.

C. Design and Adopt a Hierarchical Scheme for Temporary Trap Site Placement

Temporary trap sites will likely continue to be relied upon by Michigan Department of Agriculture staff for the identification and delimitation of gypsy moth infestations. The adoption of a permanent trap site system has not, and likely will not, displace temporary trapping schemes, the expense and level of effort of which should invite constant scrutiny. Temporary data collection points can offer a valuable source of data for regional or multi-county analyses of gypsy moth populations which in turn can be enhanced if organized around the spatial capabilities of GMRIS, and common management objectives. However, the current placement of temporary traps is largely unsystematic and poorly suited to produce data which can help to answer research or management questions. These trapping efforts should be regularized in a nested scheme of progressively greater densities of trap deployments reflecting a pre-specified sequence of management regimes (detection, delimitation, etc.). Such a scheme should call for deployment of traps (1) at density intervals (for instance: 4 traps / survey township, 36 traps/ survey township(1 trap/sec.), 72 traps / survey township(2 traps/sec.)); (2) in specific, uniformly spaced arrangement (sections 8,11, 26, and 29; sections 1-36, etc.); and (3) for specific, progressively more demanding purposes (localized detection, delimitation of infestation boundaries, delimitation of infestation loci, detailed population monitoring for research work, etc.). Potentially useful temporary trapping schemes include those which the MDA uses over fairly large areas and those which call for trap tending throughout the season (the latter offers the possibility of acquiring within-year time series data). Schemes involving small areas or widely scattered and isolated traps should be considered relevant only in so far as the data may need to be displayed, but not necessarily analyzed, with the aid of GMRIS.

D. Automate Data Encoding Operations with Machine Readable Forms

Mark-sense forms for collection of trap data should be designed for the 1987 field season unless 1986 "handwritten" data sheets are found to be complete, accurate, and legible. If 1986 data collection sheets are found to be deficient, the added difficulty, expense and inflexibility of mark-sense forms will be justified by their circumvention of legibility problems, the ease with which omissions can be found, and the speed with which data can be encoded. Mark-sense forms will not increase data recording accuracy; they may actually make it more difficult to detect carelessness on the part of observers. Additional problems in the form of data "clean-up" can be avoided only by such preventative or error detecting measures as: designing a data collection form which is well organized and easy to understand, persuading MDA field personnel that attention to detail is important, having trap setters record only observation data while actually in the field (other information can be pre-entered without error-see 5 and 6 below), and having MDA personnel proof-read and correct all data collection forms before delivery for processing. If mark-sense forms are used, consideration should be made of using a card rather than a sheet format. Regardless of all else, proof-reading guidelines should be written and used for internal review of data collection sheets by MDA.

E. Encourage Data Input Via Microcomputer and Substitute Computer Printout Form for Data Sheets

Delivery of gypsy moth trap data to CCMS in digital form is preferred to the delivery of raw data on field sheets which must be reviewed, occasionally corrected, and then digitized. The MDA is now equipped with IBM-compatible micro computers in both their main offices and in their field offices. This agency also has a mandate to make such equipment operational, a step which could reduce problems with survey data acquisition which have been identified by this study. An agreement should be made with MDA to assist the development of micro-based data base management capability featuring "templates" designed for ease of use and compatibility with CCMS file structures. Procedures should also be developed which will ensure dependable data input at field offices and subsequent quality checking of the data before delivery to CCMS on magnetic media. This will have the effect of transferring a larger portion of the responsibility for data preparation to the MDA freeing CCMS for the analytical and data reporting tasks for which it is adapted. Whether or not data entry via micro computer becomes feasible, it should be possible to pre-print data sheets as complete records for permanent trap sites provided complete location descriptions can be produced for each. These printout sheets could be requested from CCMS via MSU's high-speed printer and could contain all permanent site-related data requiring that field workers enter only catch-related values for the season, or specifications for those sites which may need to be relocated. This method will make complete annual revision of blank data sheets (usually done while in the field) unnecessary, thereby simplifying and speeding survey work, perhaps compensating for the additional time required to collect of useful habitat, and other ancillary data (discussed below).

F. Formalize Modified CCMS Coding Scheme and Verify Associated State-Wide Look-up Table

Final changes to the modified version of the CCMS location codes should be verified for complete and accurate correspondence to the associated county code maps produced for this study. Specifically, the correspondence of political units (county and "political township" names and code numbers) and survey units ("survey township" and section code numbers), as well as special cases (islands and major cities) should be examined to assure that the map and tabular codes are identical. After this step is complete, the new, verified list of the tabular codes should be distributed to users with a caution that all previous versions should be destroyed by those who intend to employ the code for spatial analyses (other versions exist and may be useful for projects which predate our modifications and which do not require spatial analyses using our DBMS-GIS translation software). Two related activities also require completion. First, any remaining coding or digitizing errors in the look-up table for the Lower Penninsula should be corrected before it is released for use by others. Second, the look-up table for the Upper Penninsula must either be corrected or redigitized. The Upper Penninsula portion of the table is incorrect due to an error in the state-wide graticule upon which it was based. Mathematical transformations are currently being used in an attempt to rectify the image achieved with this version, but this procedure is not a promising one. The Upper Penninsula portion of the statewide look-up table should be redigitized as soon as possible, in case corrective actions do not remedy the problem. It is also recommended that the locations of permanent trap sites for both the Upper and Lower Penninsulas be plotted on specially prepared field maps and used to assess the conformity of actual trap deployments with survey objectives and instructions, and to track "movement" of what are intended to be permanent (static) data collection points.

G. Identify Additional Data Needs and Establish Data Reporting Specifications

Experience in this study points out that there have been many changes in the gypsy moth trapping survey and a good number in the data processing and reporting procedures. Recently changes have also been made in the administration of gypsy moth control programs and in the participation of agencies in those programs. It has been established during the course of this study that the MDA has relatively simple (known) data needs but strong preferences regarding the format and scheduling of data summaries. Other agencies now involved in management efforts will undoubtedly have different or additional data needs which may be expected to impinge on standing arrangements between the MDA and CCMS. In order to identify undiscovered data needs and to improve the likelihood of complimentary data collection and reporting activities, it is recommended that a cooperative, structured attempt soon be made to specify which data will be required for particular research and management needs, and how and when such data will be acquired and paid for. Particular importance should be paid to considering the acquisition of habitat data from a sample of permanent trap sites designated as permanent plots, and to the desirability and requirements of regional or sub-state data bases to support model validation and more detailed research and risk prediction and management prescription needs. The importance of these steps can not be overstated.

H. Adopt Quality Testing and Reporting Procedures

Specific and detailed quality testing measures need to be selected which are appropriate for the particular data and analysis needs of GIS-based risk assessment studies. Such measures should adhere closely to the standards proposed by the National Committee for Digital Cartographic Standards. When several testing procedures of variable rigor can be considered, the most stringent feasible test should be used. In addition, the requirements of data quality evaluation should become known, and should be considered early in planning further GIS development so that the benefit of such practices can be maximized. In a similar vein, the results of such tests should be considered as changes and updates to data become possible so that an effort may be made over time to increase the quality of data used and of the analytic results obtained. It is also recommended that forms, logs, and other standardized conveniences (such as ERDAS's "audit" feature) be developed and used to simplify and regularize recording activities necessary for lineage statements and other reports.

I. Determine Locations of Permanent Sites in Alternate Coordinate System

On the assumption that a different geo-referencing system will eventually be needed or wanted to replace or supplement that used with the CRS's land-surface data base, it is recommended that an alternative be identified. If undertaken early, this will allow for a smooth transition from one system to its successor and will preserve the value of historical data by making them comparable with new data registered to a new locational system. It is recommended that close attention be paid to standards and practices recommended by the Federal Geodetic Control Committee (FGCC).

2. Hardware / software

A. Adapt DBMS-to-GIS Software to Operate on an IBM Microcomputer

Custom software has been produced to automate the process of registering pest (or other) data, geo-referenced to the Public Land Survey System, with the state-wide, land-surface information system begun by MSU's Center for Remote Sensing and geo-referenced to a 1-km^2 uniform grid. This software was written in Fortran to run on an ERDAS 400 computer because the storage capacity of the CRIES (operator agency) hard disc was required, and because accessory programming modules written in Fortran could then be used. With more local GIS work being performed on IBM compatible microcomputers, and in view of the recommendation (below) that the Michigan Forest Pest Management Program implement a micro-based GIS, it is desirable, if not imperative, that this software be re-compiled or re-written to run on non-ERDAS (IBM compatible) micro computers. This has been estimated to be a very reasonable task and is expected to greatly increase the utility of this translation software to a diversity of other users. Making this software operational on an IBM micro computer is critical for GIS applications in the area of forest pest management.

B. Evaluate Utility of Designing a Township-Range Coordinate Look-up Table for Data Encoding

The DBMS-GIS software mentioned above functions with a look-up table of section centroid coordinates referenced to the 1-km^2 land-surface information system. Correspondence is established using the CCMS location codes as modified for this study. This coding system is based on the system of townships and range lines but does not make direct use of township-range coordinates. The MDA has proposed that location identification of observations in the field might be made simpler by using a list of township-range coordinates rather than the field maps prepared for this purpose, which display the modified CCMS code. This matter should be examined and a decision made. The position advocated here holds that the original reasons for avoiding such a list, and the reasons for producing 4 sets of coding maps instead, still apply. It was concluded early in this study that the chances for error are greatly increased by data being encoded from tables (potentially confusing column by row numeric listings), from unverified master sources (such as customized, incomplete, or degenerate copies of such tables), or from township-range coordinates (which carry east-west and north-south designations that can easily be interposed). Master coding maps were produced in color and individually verified in an attempt to minimize reading, interpretation and fatigue errors anticipated with tabular codes. Unless overriding circumstances are identified or limited use of such coding tables is planned, with quality check procedures, experience from this study would suggest that the prepared code maps should remain the preferred, and exclusive means of determining data location codes.

3. Catrographic risk model

A. Carry out Pre-Validation Critical Review Before Expanding or Refining the Risk Model

The gypsy moth risk model presented in this study has passed a cursory review by a panel of experts knowledgeable of gypsy moth management in Michigan and by Dr. Robert Campbell who has had extensive experience with gypsy moth research and management in the eastern U.S. It has not been validated to determine whether it can predict with any reliability, the location of infestations and their consequences. A more intensive review of the structure of this model and of the results achieved in its first implementation should be made as soon as possible. This sort of review is important because validation will not be possible against another model or with historical data for at least one year. Firm assessment of the model's worth must be made before it is used to make projections for 1987, and before further development is begun on the Upper Penninsula component. It is also recommended that as mathematical models become available for gypsy moth forecasting, they should be used to refine and complement, rather than replace the cartographic model described here.

4. GMRIS users/ managers

A. Implement Limited Micro Computer-Based GIS Capability for Forest Pest Management

Based on information available at the close of this study, it appears that the greatest long-range benefit of GIS capability may be gained by implementation of the CRIES-GIS version 6.0 (or later) for forest management purposes. This software package could be purchased by the Michigan Cooperative Forest Pest Management Program (MCFPMP), installed on any IBM XT or AT model micro computer, and used on a cooperative basis. The software has full GIS capabilities and processes large geographic data bases quickly. It is relatively inexpensive and is currently being enhanced to support color graphic displays. This software package is fully compatible with the ERDAS systems at MSU with which operations could be integrated. For routine spatial analyses and data management, the CRIES-GIS would offer: portability of hardware and operations (making use possible in remote locations); fast, and simple GIS operations (it is very fast and has a well designed user interface making it easy to learn and run); it is inexpensive compared to other GIS packages, and well executed (making it both affordable and a better long-term investment); and it is fully compatible (can interchange data) with existing, local GIS systems (making pre-processing operations independent of other agencies and making final processing capable of the additional features offered by ERDAS systems). Purchase of the CRIES-GIS software is recommended, providing a favorable review is made of this study and its products, and of other decision criteria such as the objectives of MCFPMP, and their future data acquisition needs and capabilities. Other very important considerations include: the availability of personnel to learn and operate the system, the willingness of members to engage in planning required for implementation, and the ability of members to exchange information concerning spatial analysis.

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