Project Status Report: Ecology and Environment Project

Holling, C.S., Bell, D.E., Clark, W.C., Dantzig, G.B., Fiering, M.B., Jones, D.D., Rashid, Z., Velimirovic, H., Walters, C.J. and Winkler, C.

IIASA Collaborative Paper
June 1974

Holling, C.S., Bell, D.E., Clark, W.C., Dantzig, G.B., Fiering, M.B., Jones, D.D., Rashid, Z., Velimirovic, H., Walters, C.J. and Winkler, C. (1974) Project Status Report: Ecology and Environment Project. IIASA Collaborative Paper.

SR-74-2-EC

PROJECT STATUS REPORT:
ECOLOGY AND ENVIRONMENT PROJECT

June 21, 1974

STATUS REPORT FOR ECOLOGY & ENVIRONMENT PROJECT

We present here the extended outline and copies of the illustrations used in the Status Report of the IIASA Ecology and Environment Project, presented at Schloss Laxenburg on 21 June 1974.

Section 1., "General Review", is covered in the outline.

Section 2., "A Case Study of Ecosystem Management", is the subject of a major monograph now in preparation.

Section 3., on Selected Conceptual Developments, is in part documented in IIASA Research Reports RR-73-3 and RR-74-3.

- - - -

C.S. Holling - Project Leader

D.E. Bell
W.C. Clark
G.B. Dantzig
M.B. Fiering
D.D. Jones
Z. Rashid
H. Velimirovic
C.J. Walters
C. Winkler

NOTES FOR
IIASA STATUS REPORT
ECOLOGY AND ENVIRONMENT PROJECT

Presented 21 June 1974

1. General Review of Ecology/Environment Project
    1.1 Background
    1.2 Strategy
    1.3 Tactics
    1.4 Tasks Chosen in the First Year
2. A Case Study of Ecosystem Management
    2.1 The Budworm Problem, the Setting, the Goal
    2.2 Bounding the Problem
    2.3 Budworm Ecosystem Model
        2.3.1 Stochastic model of the weather
    2.4 Model Analysis
        2.4.1 The site model
        2.4.2 States of the system
        2.4.3 Validation of multi-site model
    2.5 Policy Analysis
        2.5.1 Introduction
        2.5.2 Indicators
        2.5.3 Preferences
        2.5.4 Budworm-forest optimization model
        2.5.5 Compressed policy analysis
        2.5.6 Generating policy alternatives

IIASA STATUS REPORT

Ecology/Environment Project
21 June 1974

EXTENDED OUTLINE

1. GENERAL REVIEW

1.1 BACKGROUND

- The alternate approaches to innovation at IIASA:
  - global problems -- e.g., energy, food, population, resources and their interaction; global climatic change; Law of the Sea,

or

universal problems -- e.g., new universal concepts and methods for regional problems occurring in all countries.

- we have chosen to focus on the latter regional problems.

- Rationale: The past management of ecological systems (e.g., agricultural, forest, fish, water) has been a successful application of the trial-and-error approach of dealing with ignorance -- interventions are incremental and if problems arise, then a revised incremental action can be made.
  - The result has been phenomenal increases in production of food and fibre.
  - But now incremental acts produce more extensive and intensive consequences (witness the unexpected results of some insecticide pest control experience; the scale of unexpected consequences of some large hydroelectric developments; the possible scale of some man-induced climatic shifts)
  - And other consequences are emerging from accumulation of past incremental decisions (witness resistance to insecticide; sudden pollution "episodes," emergence of "new" pest species)

  - Present remedial responses to these "emergencies" are as ad hoc as their original cause (witness restrictions on DDT use)

  - Conclusion: Trial-and-error seems to be an increasingly dangerous strategy for dealing with the unknown. We need a new strategy for dealing with ignorance.

1.2 STRATEGY

Goal: To develop, test, and transfer the interrelated concepts and techniques needed for a new science of ecosystem management/engineering.

Aims:

1. Conceptual:

   to represent and categorize the resilience and stability behavior of ecological systems (how do such systems absorb the "unexpected"? What structures result in highly resilient systems, i.e., ones capable of absorbing large shocks?)

2. Methodological:

   to link and apply the existing set of systems analytic techniques (modelling, mathematical analysis, policy analysis, decision theory)

   to develop and apply new techniques to cope with the unknown (qualitative modelling and analysis, resilience indicators, generation of strategic alternates (from fail-safe to safe-failure))

   to develop communication formats that can link the analyst, decision-maker, and constituents.

1.3 TACTICS

The above goals and aims are the long term necessities if IIASA is to make a significant and lasting contribution. But there are short term needs -- immediate problems, immediate demands.

Hence, a tactic is needed

- to assure short term results within the framework of the long term objective,
- to maintain realism re sources of data, validation, testing and policy relevance,
- to maintain an applied and not abstract focus,
- to assure generality and transferability of results of short term applied subprojects.

Figure 1: Matrix Organization of Ecology and Environment Project,

showing the interrelationship between applied problems and the fundamental conceptual and methodological areas.

Applied Areas	Conceptual Methodological Areas			
	Behavior of ecol. systems	Indicators	Standards	Methodology
Single Species Management				
Eco-system Management				
Environmental Management				

The solution is a matrix organization (Figure 1) which relates applied problems with fundamental issues, so that each applied problem can contribute to the fundamental issues and still provide a specific case study of linking ecology/economics, modelling, policy analysis, and decision theory.

- Each case study must have the following ingredients:

  (1) A regional problem of:

  single species management: pest, disease, fish, wildlife
  ecosystem management: multiple land and resource use in a region (hydroelectric, fisheries, hunting, mining, forestry, tourism)
  environmental management: industrial pollution

  (2) Good data -- both extensive and intensive

  (3) Universal, i.e., shared by a number of nations

  (4) Client(s) with management experience and interest

  (5) Intersects the interests of at least one other IIASA project.

1.4 TASKS CHOSEN IN THE FIRST YEAR

(the ones starred are selected for detailed discussion in our status report)

FUNDAMENTAL

(1) Resilience and Stability Behavior of Resource Systems

*-- theoretical analyses of multi-equilibria ecological models,

- retrospective studies demonstrating response to stress of ecological, anthropological, and resource systems,

-- measures of resilience (ecological "Reynolds" numbers)

-- a framework for generating resilience indicators.

(2)* Environmental Standards and Management for Resilient Systems

APPLICATION

(1) Modelling and Simulation for Environmental Impact Assessment (with SCOPE, UNEP)

(2) Development and Use of Ecological Modules for Resource Development Simulation ("A Module Library")

CASE STUDIES

(1)* Regional Ecosystem Management: A Case Study of Forest and Pest Mangement (with Canada Department of the Environment)

(2) Regional Ecosystem Analysis and Policy Options: A Case Study of Human Impact on High Mountain Areas (with MAB)

2. A CASE STUDY OF ECOSYSTEM MANAGEMENT

2.1 THE BUDWORM PROBLEM, THE SETTING, THE GOAL

Universality

- the budworm-pest complex is a classic example of pest management within an ecosystem, whether the pest is one of agricultural or forest crops
- budworm species present significant economic problems throughout the whole of the northeastern part of North America (Fig. 2), the Pacific region, the U.S.S.R., forested regions of Europe (e.g. Poland) and Japan

Data:

- a group of 25 entomologists, foresters, economists have been exhaustively studying this problem in Canada for the past 30 years - the first significant example of interdisciplinary research in ecology
- the best of sampling procedures and statistical analysis; detailed understanding of many causative links
- extensive and intensive validation data: a 14,310 sq. mile area (approximately the size of the Republic of Moldavia (USSR) or of the Netherlands)was divided into 265 subregions each of 54 sq. miles; key variables (pest densities, forest condition, harvesting and spraying activity) were measured in each subregion, every year for the past 30 years.

Clients and Collaborators:

Scientific: Canada Dept. of the Environment research team; Institute of Resource Ecology,University of British Columbia modelling team.

Management and Policy: Canada Dept. of the Environment Policy Branch; Province of New Brunswick, Forest Industry.

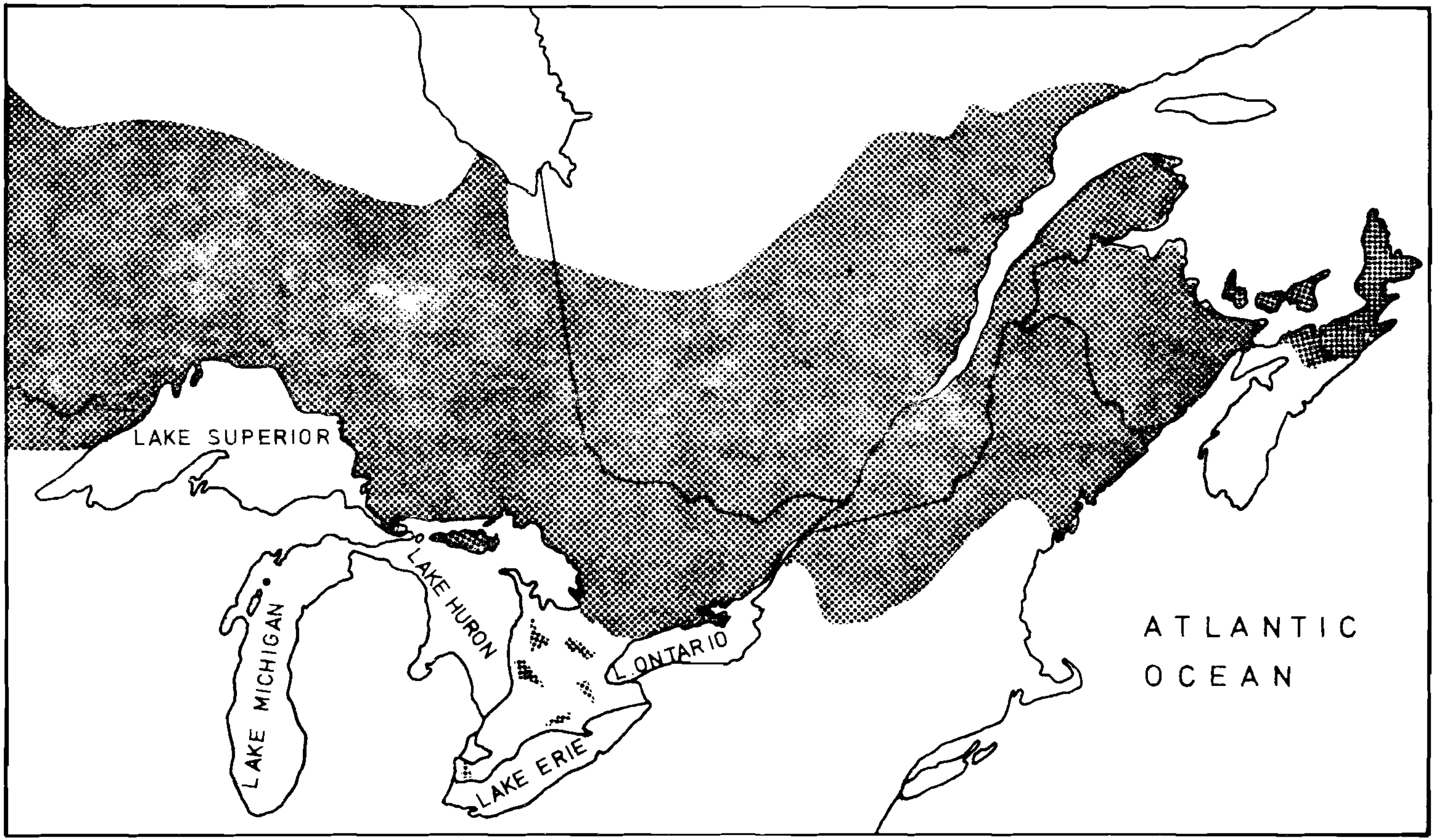


Figure 2: Map of Eastern North America
showing the area of spruce budworm infestations since 1909.

Interest for Other IIASA Projects

Methodology - provides a test bed for

a) developing optimization techniques for more complex systems

b) interfacing utility theory with a complex simulation model

c) developing compressed policy analytic techniques for more complex systems.

Conclusion: An admirable case study for demonstrating the way to combine the best of ecology/economics, modelling, policy analysis and decision theory.

2.2. BOUNDING THE PROBLEM

- It is essential to bound the problem in space, time and key species and still retain the key properties of behavior and the key needs for management.

Time:

The pattern in time has been traced back to 1770 - typical pattern in Fig. 3

i.e.

- 34-72 years periodicity of outbreaks
- between outbreaks the pest is extremely rare
- outbreak densities increase by 2-3 orders of magnitude
- outbreaks last 6-17 years.

Bounding time:

We need a (1) time horizon which can contain two outbreaks, i.e. 150-200 years

(2) time resolution of one year with seasonal events represented.

The Pattern in Time

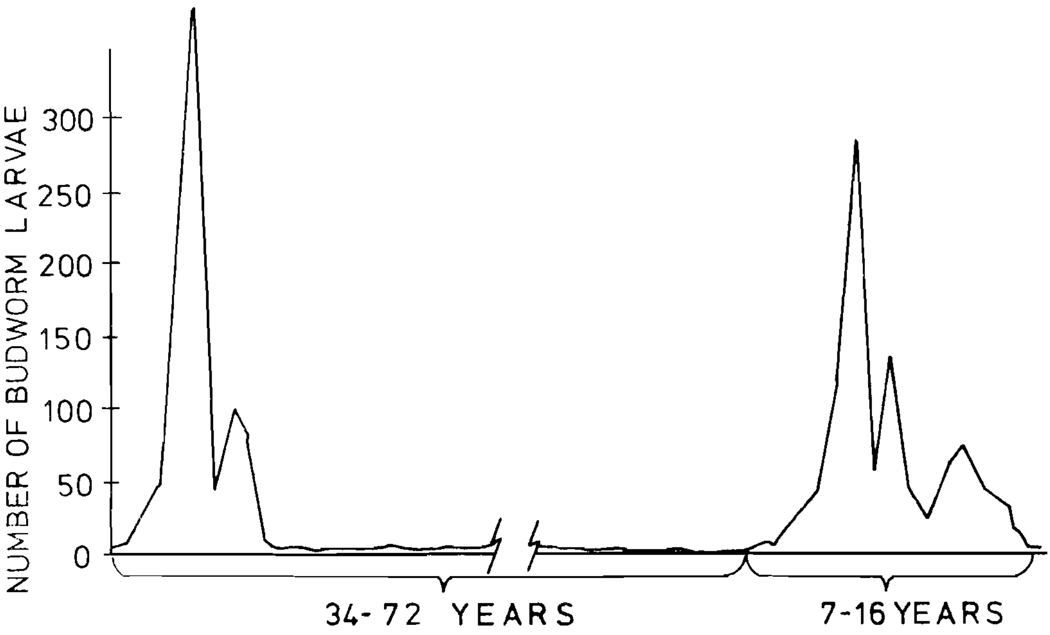


Figure 3: Representative historical pattern of spruce budworm outbreak. There have been four major outbreaks since 1770.

Space:

- As in many pest species, the budworm disperses over long distances: a modal distance of 50 miles from one site;
- therefore, it is essential to have a minimum area at least twice that radius, i.e., 14,000 - 15,000 sq. miles;
- the area chosen is therefore a 14,310 sq. mile area which contains most of the Canadian Province of New Brunswick (Fig. 4).

Spatial Resolution:

Behavior of the system is highly heterogeneous in space and in time (Fig. 5). Therefore, spatial disaggregation is essential.

All elements of the system are similarly heterogeneous:

- distribution of primary host species; balsam fir (Fig. 6),
- distribution of harvesting activities is heterogeneous (Fig. 7),
- distribution of recreational potential is heterogeneous (Fig. 8).

Figure 4: Study area within the Province of New Brunswick used in the current study. The hatched area includes the primary forested regions of New Brunswick.

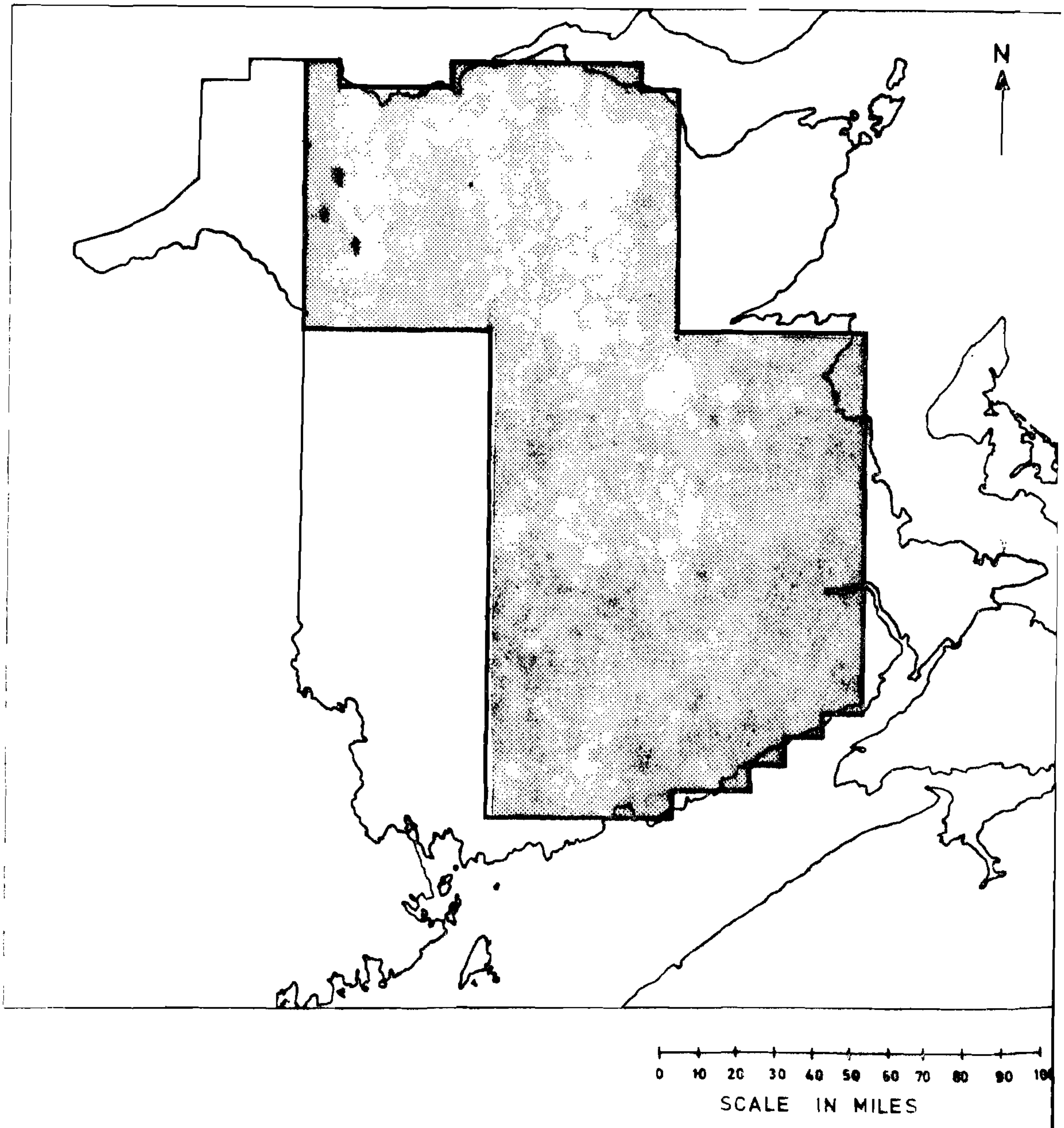


FIGURE 5a: THIS FIGURE SHOWS A TYPICAL OUTBREAK IN A SEQUENCE OF COMPUTER-DRAWN MAPS OF BUDWORM DENSITY AS GENERATED WITH THE SIMULATION MODEL. EACH SQUARE REPRESENTS ONE OF THE 265 SITES. THE VERTICAL DIMENSION IS THE LOGARITHM OF BUDWORM EGG DENSITY FOR THAT SIMULATED YEAR. IN THIS SEQUENCE NO SPRAYING OCCURS BUT LOGGING FOLLOWS THE HISTORICAL PATTERN NOTE THE GROWTH, SPREAD, AND COLLAPSE DURING THE SIX YEARS SHOWN.

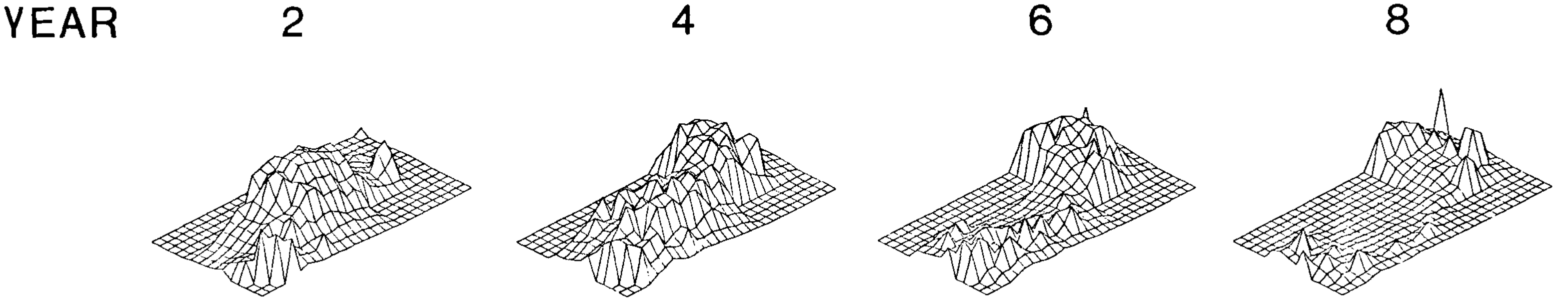
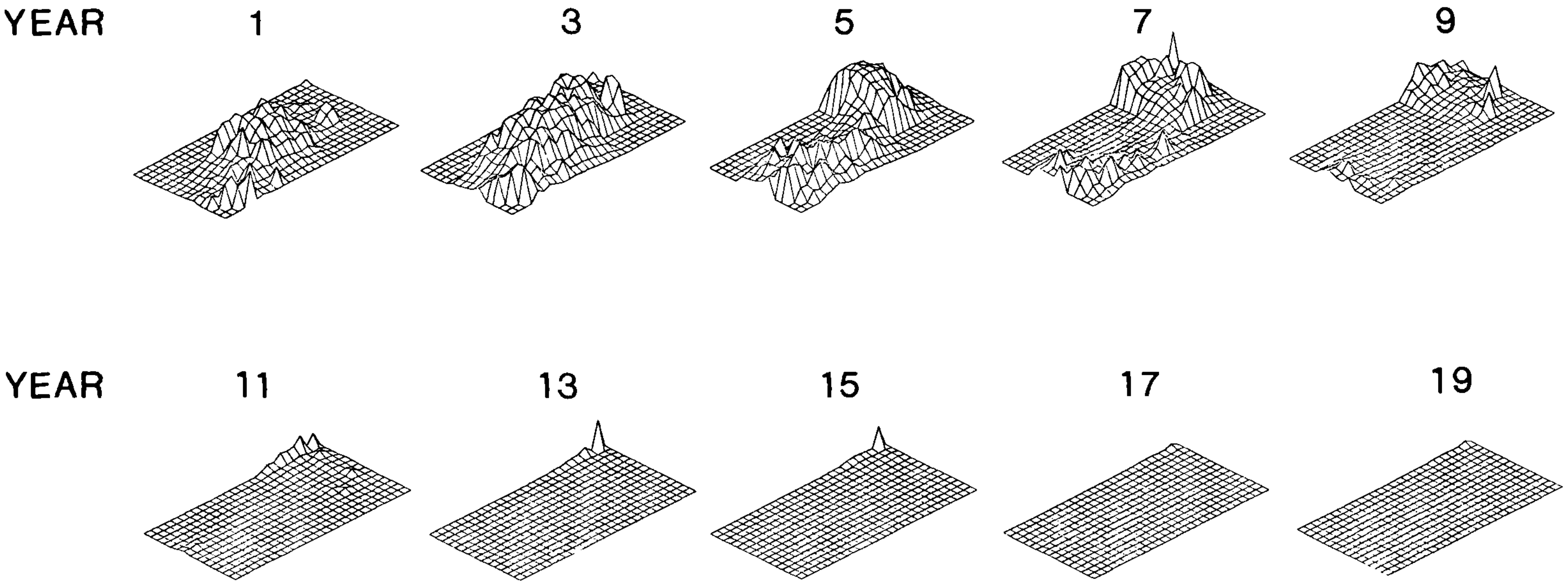


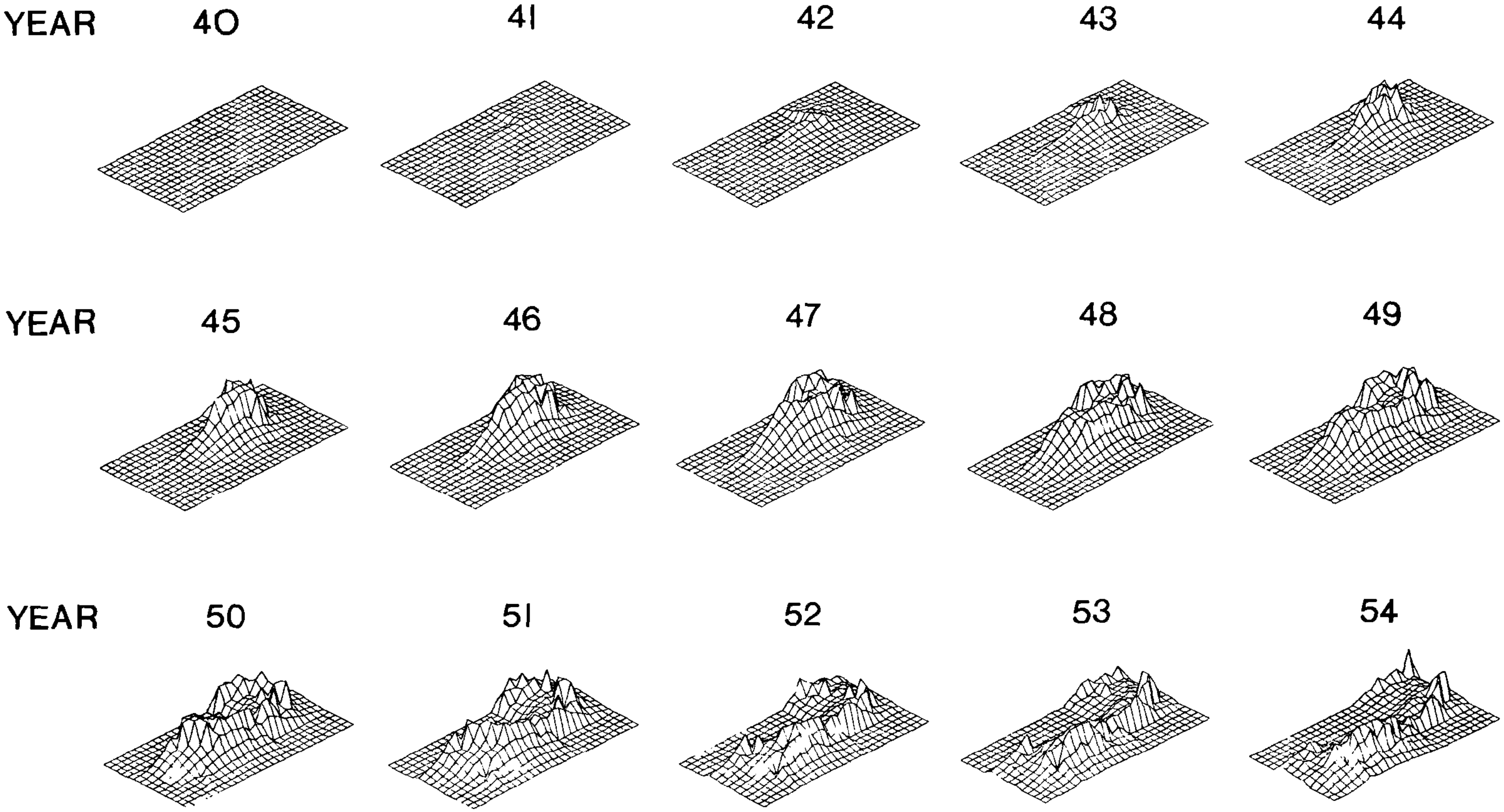
FIGURE 5b: FIGURES 5b AND 5c SHOW A LONGER SIMULATION SEQUENCE. THE OUTBREAK IN THE FIRST DECADE IS THE SAME AS THAT OF FIGURE 5a. A SECOND OUTBREAK BEGINS IN THE FOURTH DECADE AND FOLLOWS A SIMILAR PATTERN.



NO SPRAYING

FIGURE 5c

NO SPRAYING



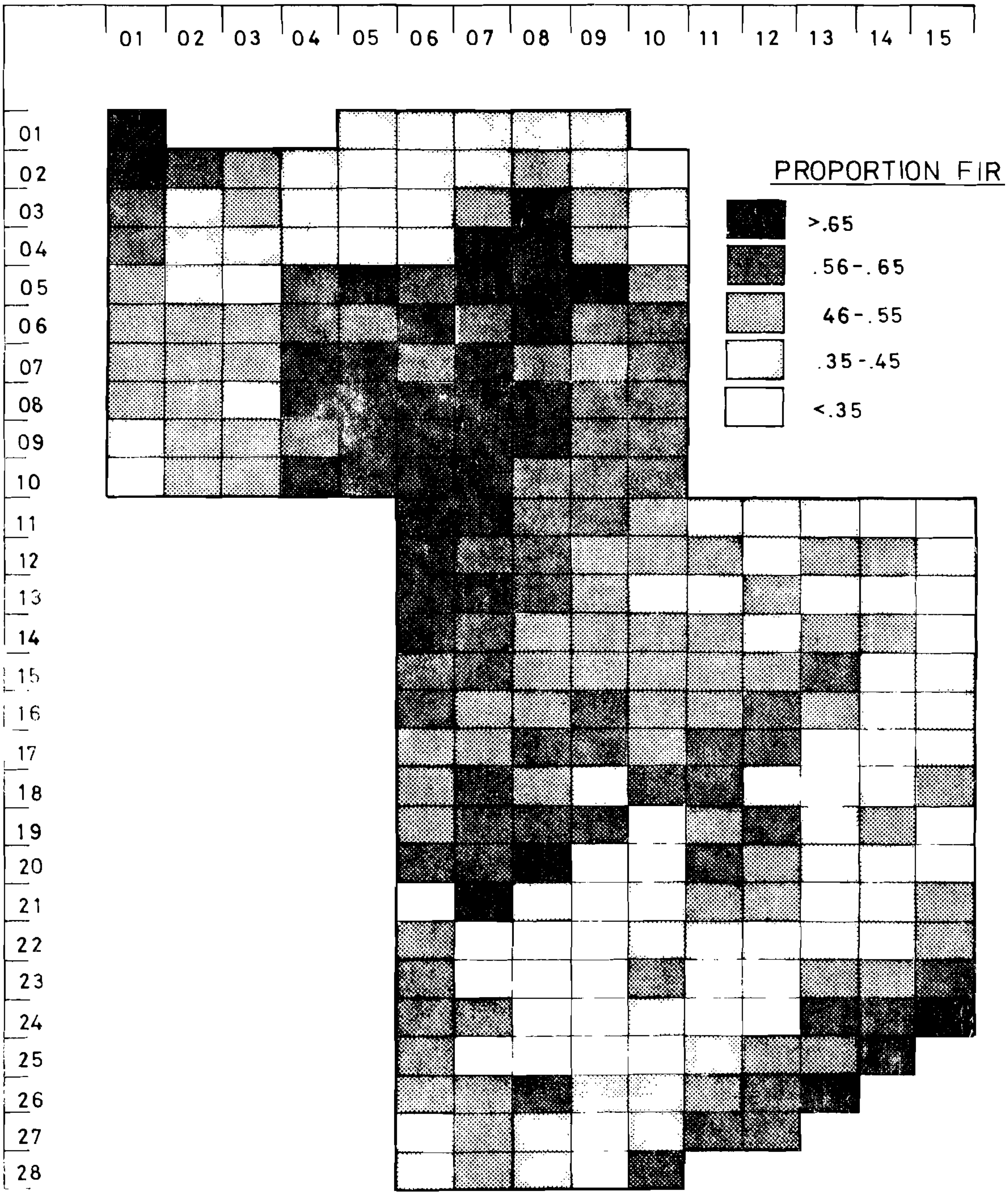


Figure 6: Map of study area showing the initial proportion of land in fir, the host tree species of the budworm. This complex spatial mosaic strongly influences the system dynamics.

Figure 7: The logging intensity is also spatially heterogeneous. This map shows the mileage from each site to the nearest processing mill.

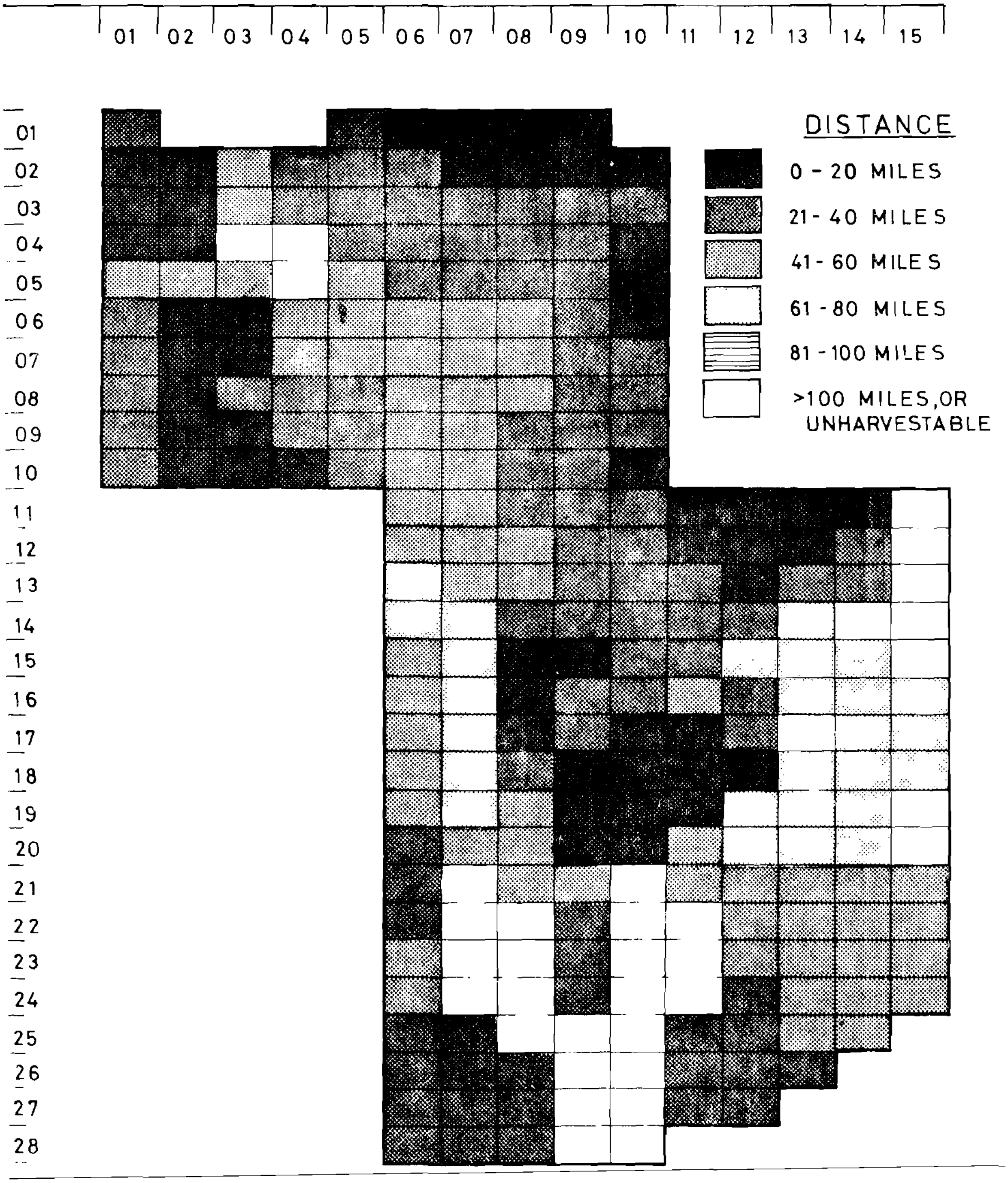
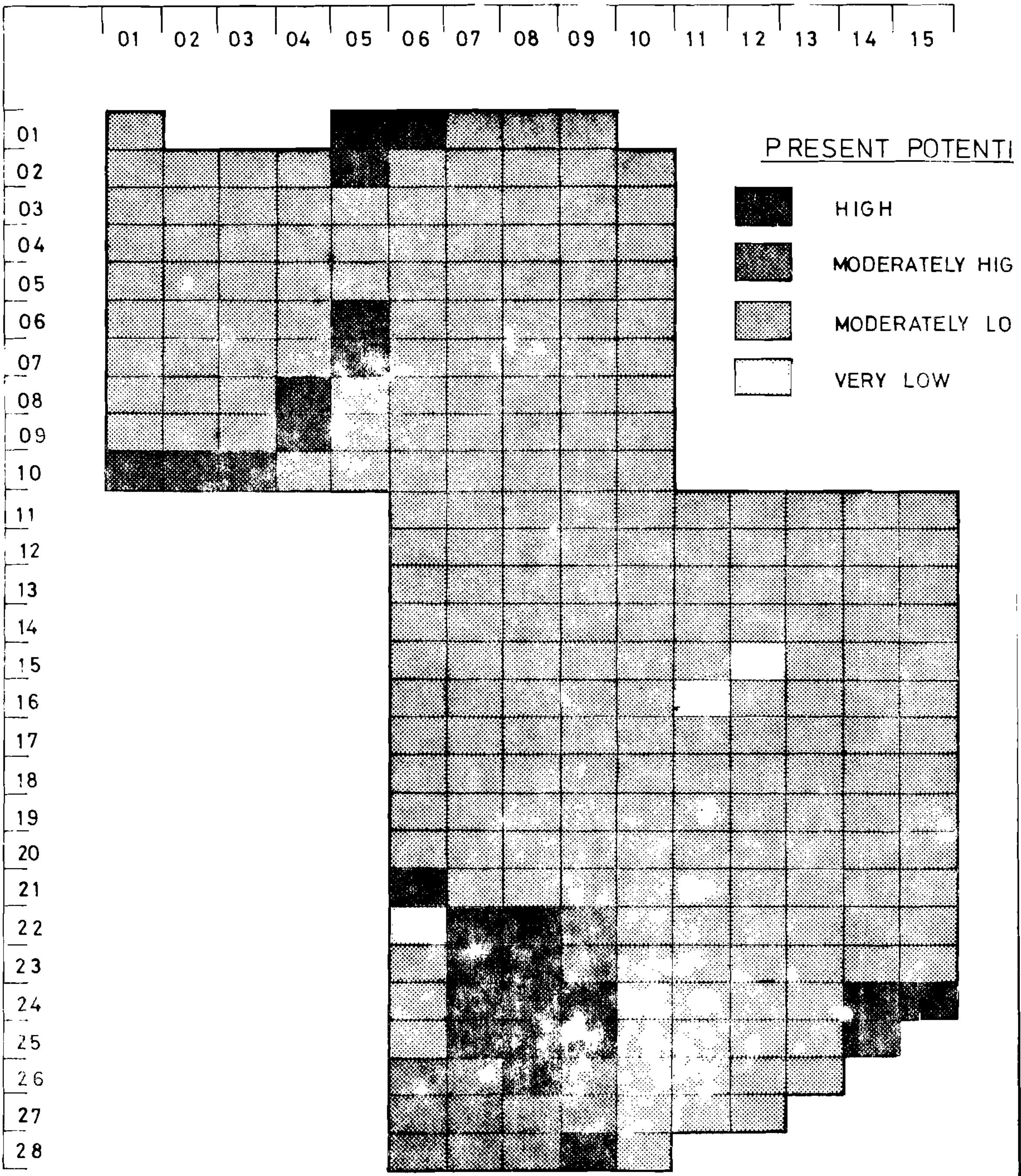


Figure 8: This map shows the spatial distribution of the present recreation potential for each site. Current preferences strongly favor the areas with coastal or lake recreation opportunities.



These heterogeneities have emerged from the dynamic historic interplay between the forest and the budworm as a consequence of the dispersal powers of the pest. The 50 mile modal probability of dispersal suggests a minimum resolution of about 1/5 - 1/10 that distance.

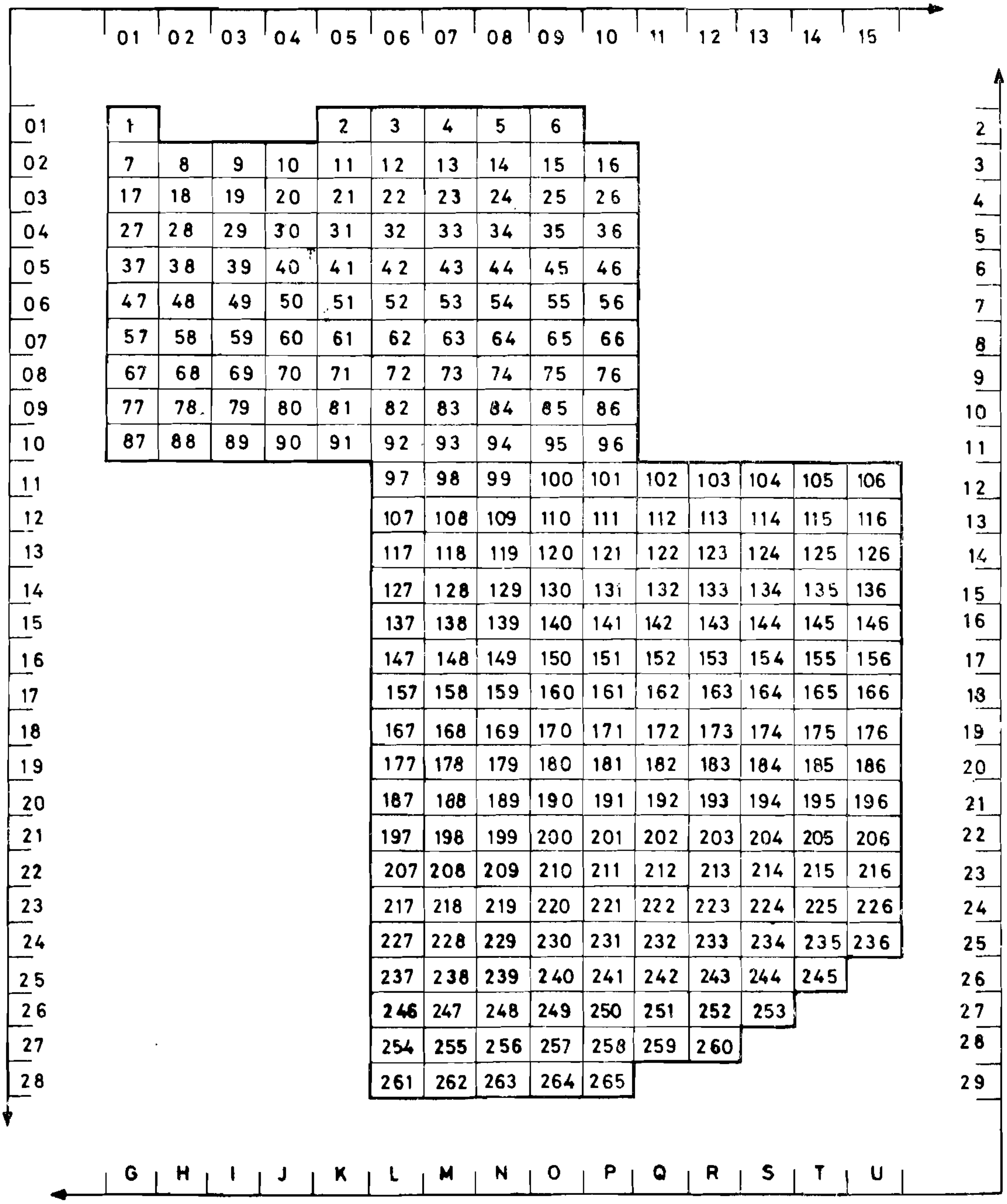
Hence the area is divided into 265 6x9 mile areas. (Fig. 9)

Species

An ecosystem of this extent has hundreds of thousands of species. The understanding of the dynamics is so detailed, however, that the essential behavior can be captured by the interrelation between 5 sets of species, each of which represent the key species (roles) that determine the major dynamics of the forest ecosystem and its resulting diversity, species mixture and structure.

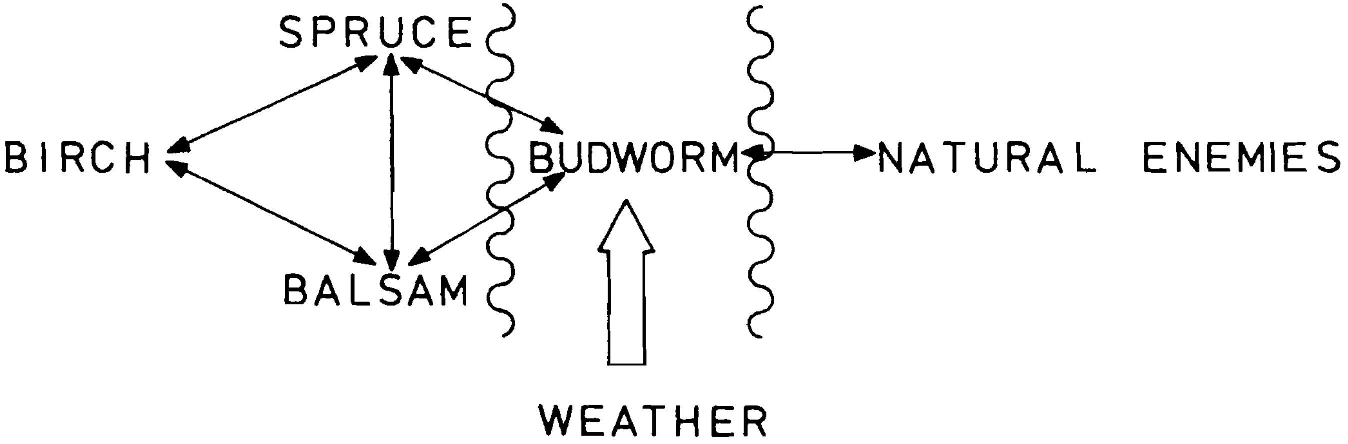
- The principal tree species are birch, spruce and balsam (Fig. 10);
- in the absence of budworm and its associated natural enemies balsam outcompetes spruce and birch and so would tend to result in a monoculture of low spatial diversity;
- budworm shifts that competitive edge since balsam is most susceptible, spruce less so and birch not at all. Thus there is a dynamic rhythm with balsam having the advantage between outbreaks and spruce and birch during outbreaks - this produces a diverse species mix and great spatial and temporal variability;
- between outbreaks the budworm is rare but not extinct - its numbers are controlled by natural enemies (insectivorous birds, parasites) - but the key characteristic of this control is that there is an upper threshold of budworm numbers, which, if exceeded, allows the budworm to "escape", i.e. there is a distinct but limited stability region at low budworm densities;

Figure 9: This figure shows the numbering and indexing system for the 265 subregions, or "sites," in the study area.



	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	
01	1				2	3	4	5	6							2
02	7	8	9	10	11	12	13	14	15	16						3
03	17	18	19	20	21	22	23	24	25	26						4
04	27	28	29	30	31	32	33	34	35	36						5
05	37	38	39	40	41	42	43	44	45	46						6
06	47	48	49	50	51	52	53	54	55	56						7
07	57	58	59	60	61	62	63	64	65	66						8
08	67	68	69	70	71	72	73	74	75	76						9
09	77	78	79	80	81	82	83	84	85	86						10
10	87	88	89	90	91	92	93	94	95	96						11
11						97	98	99	100	101	102	103	104	105	106	12
12						107	108	109	110	111	112	113	114	115	116	13
13						117	118	119	120	121	122	123	124	125	126	14
14						127	128	129	130	131	132	133	134	135	136	15
15						137	138	139	140	141	142	143	144	145	146	16
16						147	148	149	150	151	152	153	154	155	156	17
17						157	158	159	160	161	162	163	164	165	166	18
18						167	168	169	170	171	172	173	174	175	176	19
19						177	178	179	180	181	182	183	184	185	186	20
20						187	188	189	190	191	192	193	194	195	196	21
21						197	198	199	200	201	202	203	204	205	206	22
22						207	208	209	210	211	212	213	214	215	216	23
23						217	218	219	220	221	222	223	224	225	226	24
24						227	228	229	230	231	232	233	234	235	236	25
25						237	238	239	240	241	242	243	244	245		26
26						246	247	248	249	250	251	252	253			27
27						254	255	256	257	258	259	260				28
28						261	262	263	264	265						29
	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	

Figure 10: The key roles or variables and their interrelations in the natural ecosystem. The principal tree species (birch, spruce and balsam fir) have a dynamic interaction of their own. This interaction is altered by the presence of budworm which consumes some spruce but primarily balsam. The budworm is in turn affected by a complex of natural enemies and the random effects of weather.



- in a deterministic world, the budworm would never escape. But there is a stochastic driving variable, weather, which can flip the budworm out of this stability region.

  Outbreaks cannot occur unless the forest has partially recovered from the previous outbreak (enough food, therefore). When that happens, the budworm then remains in control by natural enemies until the weather shifts to years with warm dry summers. In those conditions, the larvae develop so rapidly they reduce the period of vulnerability to predation and can achieve densities above the escape threshold.

  At that point, an outbreak is inevitable irrespective of weather.

Conclusion:

1. Time horizon = 150 - 200 years
2. Time resolution = 1 year with seasonal causation
3. Spatial area = 14,000+ sq. miles
4. Spatial resolution = 265 5x9 mile subregions
5. Key variables to capture the behavior: ideally three tree species, budworm, natural enemies, and weather.

How many state variables emerge from this bounding of the problem?

IDEAL NUMBER OF STATE VARIABLES

In one subregion	1	
Birch	1	
Spruce by age	30	
Balsam by age	70	
Budworm	1	
Natural enemies	1	
Weather	1)	) retains memory
Tree stress	1)	
Foliage new	1	
Foliage old	1	
Number of state variables per subregion	107	
Total number of state variables in all 265 subregions	107 x 265 = 28,355	

Therefore, even this drastic simplification generates an impossible number of state variables -- further simplification is necessary.

SIMPLIFIED NUMBER OF STATE VARIABLES

THE GOAL: A Well Tested Model of the System for Testing of Behavior and of Policy Alternates

(a) Full Simulation Model

	Subregion	Full Region
Balsam	25	
Budworm	1	
Weather	1	
Foliage New	1	
Foliage Old	1	
	29	7,685

The rest of the state variables represented implicitly rather than explicitly.

(b) Simplified Simulation Model

	Subregion	Full Region
Balsam	2	
Budworm	1	
Weather	1	
Stress	1	
	5	1,325

- Any further simplification destroys the behavior in space and time, and eliminates management options.

Conclusion:

(1) Spatial heterogeneity produces this curse of dimensionality.

(2) Spatial heterogeneity is an essential property here and in all ecological systems management problems.

(3) Therefore, this represents a major methodological issue.

2.3 BUDWORM ECOSYSTEM MODEL

An early, first-cut simulation model of the spruce budworm/balsam fir ecosystem demonstrated the feasibility of modelling that system with a high degree of realism (Stander, 1973). However, before that model could be used for serious management planning, some major revisions and refinements were required. Many important features were only implicit in the first version and had to become explicit before the model could be a proper vehicle for policy analysis. In early 1973, the first iteration of a more precise and explicit model was designed (Jones, 1974). This document served as the basis for a workshop sponsored by Environment Canada held in Fredericton, New Brunswick, in May 1974. The refined model of that workshop became the basis for the IIASA budworm project and is described briefly in this section. Full documentation and detailed analyses of the budworm model will be prepared for publication in a subsequent IIASA research report.

The general features of the natural budworm/forest system have been described in previous sections. The model used here only incorporates the two major species -- spruce budworm and balsam fir. The normal life history events occurring in New Brunswick are illustrated in Figure 11. This figure shows the approximate time for various life stages throughout the year. In reality, of course, there is some variation in the dates for each event as well as some overlap between the various events among the tree and budworm populations. In the model, we take the sequence of events to be that as shown in Figure 11. The budworm generation time is one year, making that a convenient iteration time for the model.

The basic structure of the model is illustrated in Figure 12. For each of the 265 sites there is a budworm survival model and a forest response model which run in parallel. These models compute for each site the various effects of the budworm upon the forest and the forest upon the budworm. These computations are repeated for all sites. Once each iteration, dispersal occurs between all sites and the model advances one time step. The various possible policies are arbitrarily designated as budworm control policy or forest management policy. These are distinguished as to where the policy levers are attached in the model algorithms.

The fine structure of the budworm and forest models is illustrated in Figure 13. The yearly sequence of computation for the forest is shown as the inner cycle and that for the budworm as the outer cycle. The format of Figure 13 is meant to illustrate the continuity of the process. There is no one unique starting point in this system, but for purposes of model construction, and comparison with field data, the simulation model starts its yearly iteration in the fall, i.e., with the initial egg density for each site. The computational sequence is based on the concept of survivals. The functions which relate the survival from one stage to another appear in the small circles of the budworm cycle. Weather, of course, affects all stages of the budworm and many aspects of forest growth. However, it has been determined by field experiment that 86% of the variance in the total generation survival can be explained by the variation in large larval survival (S_L). It is at this stage that weather has its most pronounced effect. Milder climate affects survival by shortening the development time and thus reducing parasite and predator attack. Warm-dry weather at this time of year promotes survival while cool-damp weather retards it. It is at this point that weather, and thereby stochastic variation, enters the model.

The propensity to disperse from one site to another increases when conditions on the native site deteriorate. Additionally, successful egg laying in a new home site depends upon the local conditions there. The budworm can disperse for long distances; some reports indicate over 100 miles. The probability function used in this model has a maximum distance of 75 miles and an average distance of approximately 50 miles.

There is a separate but equivalent forest response model for each of the 265 sites. On each site the proportion of land in fir is fixed. Trees on each site are subdivided into 25 different age classes and a simple bookkeeping algorithm maintains an updated inventory of the amount in each class. Mortality to balsam fir is considered to be both "natural" and budworm induced. An empirical relationship is used to translate the amount of accumulated stress from previous defoliation to actual tree mortality. This is an age specific response. Forest acreage upon which the balsam fir have died reverts back to the first age class.

Let us now refer again to Figure 13 and review the major budworm-fir interactions. At (a) we have the effect of branch surface area and foliage quantity upon the survival of small larvae. At (b) the large larvae remove foliage. The amount available affects the large larval survival and subsequent adult fecundity. At (c) the amount of forest available and the level of defoliation affect adult egg laying success.

The policy models are flexible, limited only by the imagination of the model user. The essential policy attachment points can be manipulated in any way desired. For instance, the policy can change the survival of the budworm at any stage to depict such things as spraying, introduction of parasites and manipulation of the micro-climate. The age structure of the forest can be changed to depict logging or burning. The amount of forest cover on any site can be changed by clearing or cultivation of alternate species. The density of foliage in a stand could be reduced by thinning. Traditionally, the policies used in New Brunswick have been spraying and logging. Some spraying has been tried on adults but most has been directed against large larvae. Spraying is employed at a level to kill between 80 and 90% of the large larvae. But even at this high mortality level, they can still eat a considerable amount of foliage. Logging and other silva culture tactics have been used, but the reality of the situation is that the logging capacity is too small to affect much of the province in any year.

Policies which are not in the traditional repertoire can, of course, be included in the simulation model. All that we require is some knowledge or estimation of the relationship between the action proposed and its subsequent effect on the elements of the simulation model.

References

Jones, D.D., 1974. "Biology of the Budworm Model". IIASA RM-74-3, IIASA, Laxenburg, Austria

Stander, J.M., 1973. "A Simulation Model of the Spruce Budworm and the Forest in New Brunswick". MS, Inst. Res. Ecol., University of British Columbia.

CALENDAR OF EVENTS

15 August	Eggs hatch into instar I First dispersal
1 September	Overwintering hibernacula formed
1 May	Emergence as instar II Second dispersal
1 June	Trees begin development of spring foliage and flowers Transformation to instar III
	Development to instars IV V VI Destructive defoliation
15 July	Pupation
25 July	Adult moth emergence Mating Dispersal
1 August	Egg laying complete

Figure 11: Sequence of life history events for the spruce budworm and balsam fir forest in New Brunswick.

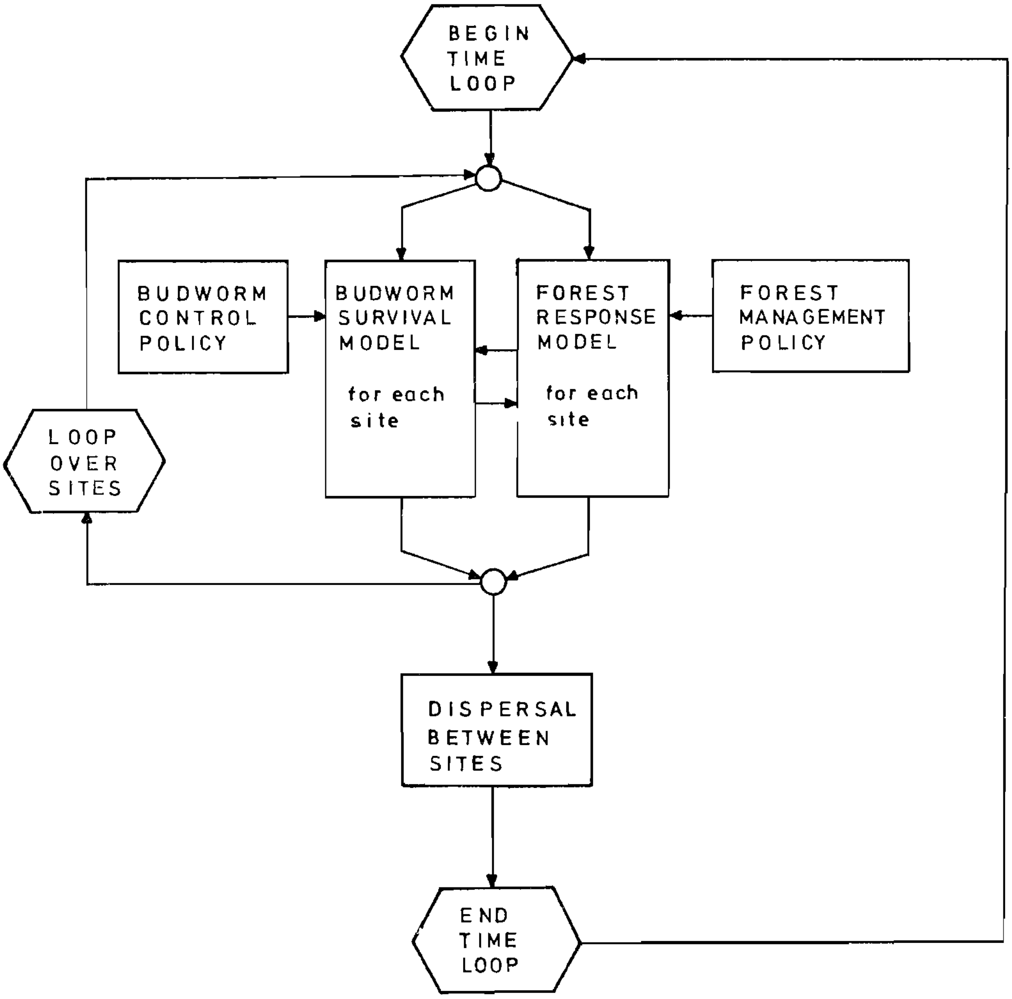


Figure 12: The basic model structure for the budworm/forest simulation model. Budworm survival, forest response and control policies are independent for each of the 265 sites. Once each year dispersal occurs between the sites and then the process is repeated for the next simulated year.

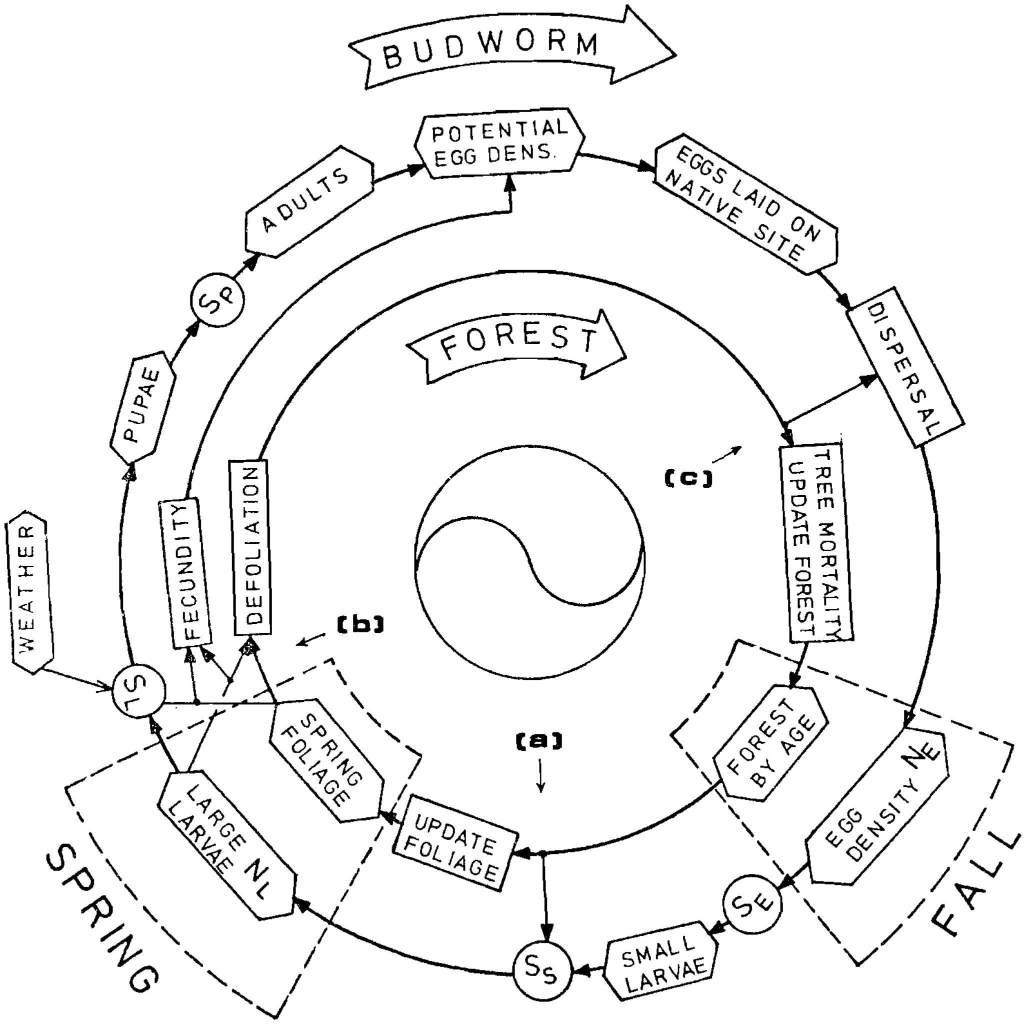


Figure 13:

THE BUDWORM-FOREST CYCLE. The outer ring depicts the budworm survival model. Each small circle represents a survival function relating one stage to the next. A stochastic weather parameter enters through large larval survival, S_L. The inner ring depicts the forest growth and response model. Aging and mortality to trees as well as growth and defoliation of needles occur in this model. At (a), (b) and (c) are points of important model linkages (see text). Attachment points for control and management policies are not shown.

2.3.1 Stochastic model of the weather

1. Need for a Model of the Weather
   - a) temporal persistence triggers outbreaks
   - b) degree of spatial homogeneity determines nature of spread and dispersal
   - c) clarify whether long runs are due to persistence or to the fact that marginal probability of some weathers is high
   - d) if significant persistence can be shown, what is the length of the memory
   - e) use of 3 classes of weather
   - f) initial results using 100-year sequence.

2. Various Models Used in the Study
   - a) trinomial distribution - independent trials - use in programming solution
   - b) Markov matrix for stand model - modal and average values versus end-to-end
   - c) synthesis using raw data - lags, offsets in space and time, log transform - 1000 year production at 9 sites.

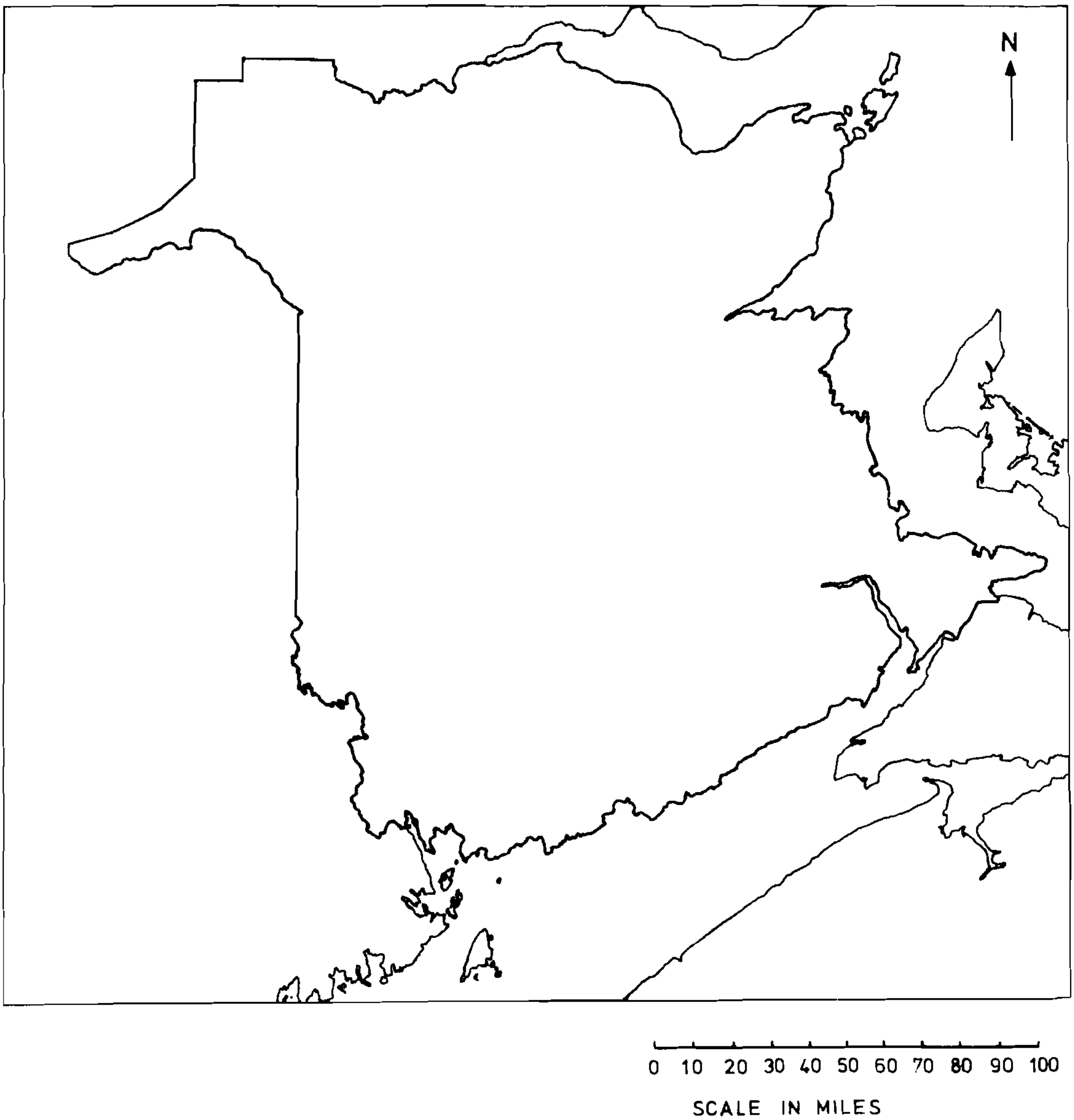
3. Tests on the Data
   - a) turning point
   - b) runs
   - c) lag-1 and lag-2 matrices.

4. Generation of Synthetic Sequences
   - a) basis for the technique in principal components
   - b) results of correlation analysis, showing positive effects within groups (heat and precipitation) and negative effects across them
   - c) comparison with moments calculated from 33-year historical records is quite satisfactory
   - d) use of average trace seems justified.

KEY POINTS

The few simulation runs which have already been made, including those made with incorrect models of weather, show the important influence of weather patterns on system response. It therefore follows that a thorough study of temporal and spatial characteristics is warranted if our long simulation runs are to generate valid statistical measures of performance. The records available in New Brunswick are not long enough to reach definite conclusions about these patterns, but strongly suggest (negative) correlation structures which imply fluctuating time series and a consequent outbreak frequency.

Figure 14: Records from these nine weather gauge stations were used to investigate the statistical patterns of weather.



2.4 MODEL ANALYSIS

2.4.1 The site model

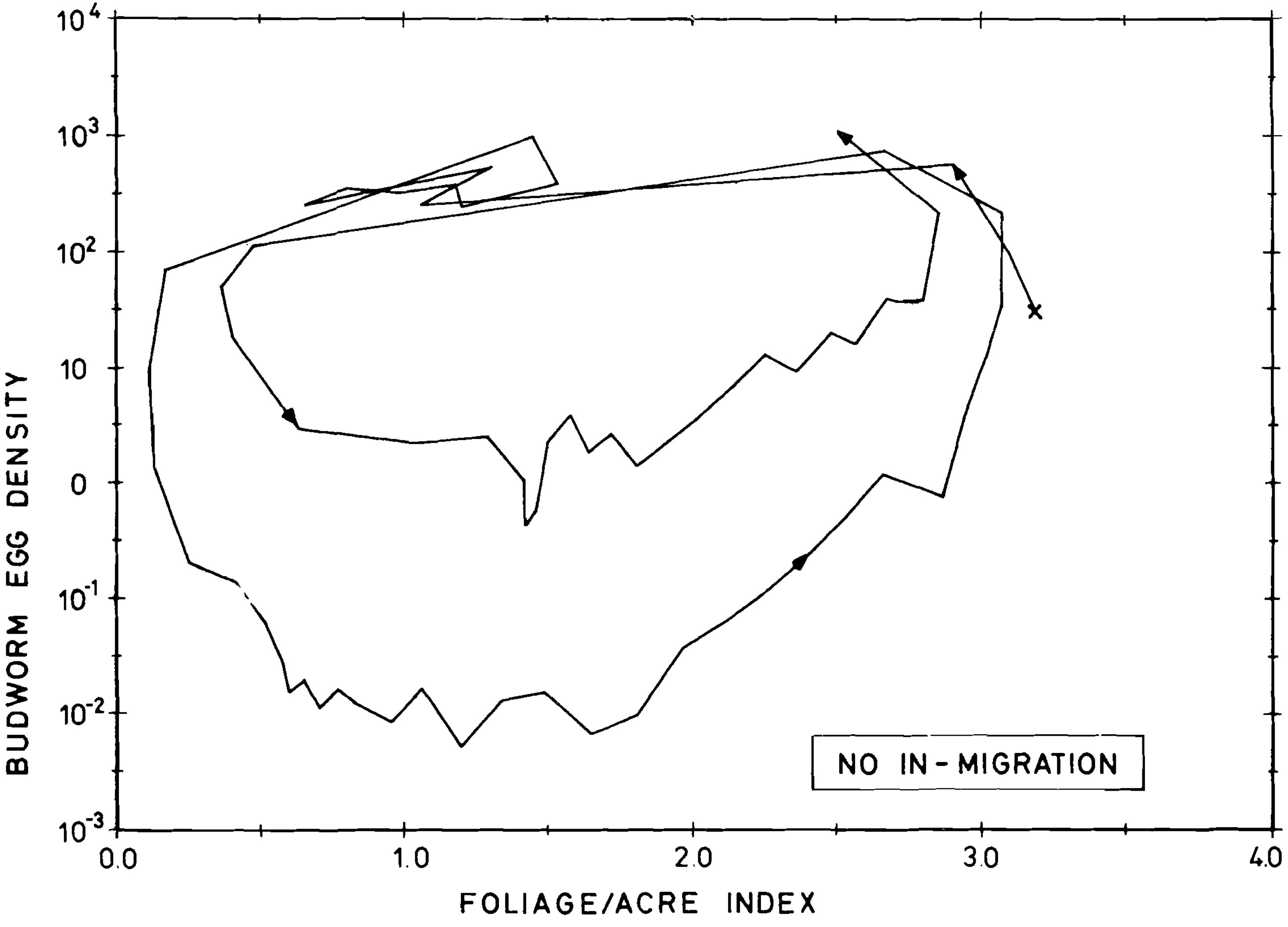
Before an attempt was made to look at the entire regional simulation model, it was worthwhile to examine the behavior of the budworm model for a single site. Additionally, the several difficulties with the IIASA computational facilities prevented the full simulation model's implementation during the course of this project. Thus, the available capacity limited us to the single site model. From the many possible examples and scenarios, two are chosen for illustration.

The first simulates the behavior of a single site with no immigration. That is, it is as if the site were an island surrounded by an area with no potential hosts. The initial conditions assumed were a mature forest with an average tree age of 50 years. A one hundred year synthetic weather trace was applied; no external policies were used. Because there are 28 state variables included in the forest and budworm, it is impossible to depict accurately the state space for this system. Instead, we resort to a pseudo-state variable -- the amount of foliage per acre. This variable exhibits some of the properties we would like in a true state variable. Figure 15 shows the time history of egg density plotted logarithmically against foliage per acre. The initial condition is marked with the X. Note the two large swings with a maximum change in budworm of 5 orders of magnitude. Figure 16 shows a time plot of the number of eggs (arithmetic scale) and the amount of foliage per tree. As it happens in this particular simulation run, in year 71 the budworm level reached such a high point that all the available foliage was removed and all the adults emigrated from the site, leaving none for the following year.

As the budworm has not gone extinct in New Brunswick, this example shows the important effect of dispersal in the spatial mosaic of the problem. As is, this model serves as an indication of the initial outbreak on a single site before dispersal becomes a dominant feature. Figure 17 is a phase plot with the same initial conditions as the above example. But this time we allow all the emigrating budworm to re-enter the plot as if we had a large uniform forest. Additionally, we have placed a lower limit on the budworm population. This limit of 10^{-5} budworm per acre is equivalent to 1 budworm in 500 sq. km. Note that the swings in this phase plot are much wider and that the average length of time between outbreaks becomes longer. Figure 18 shows the time plot for the variables of the first example.

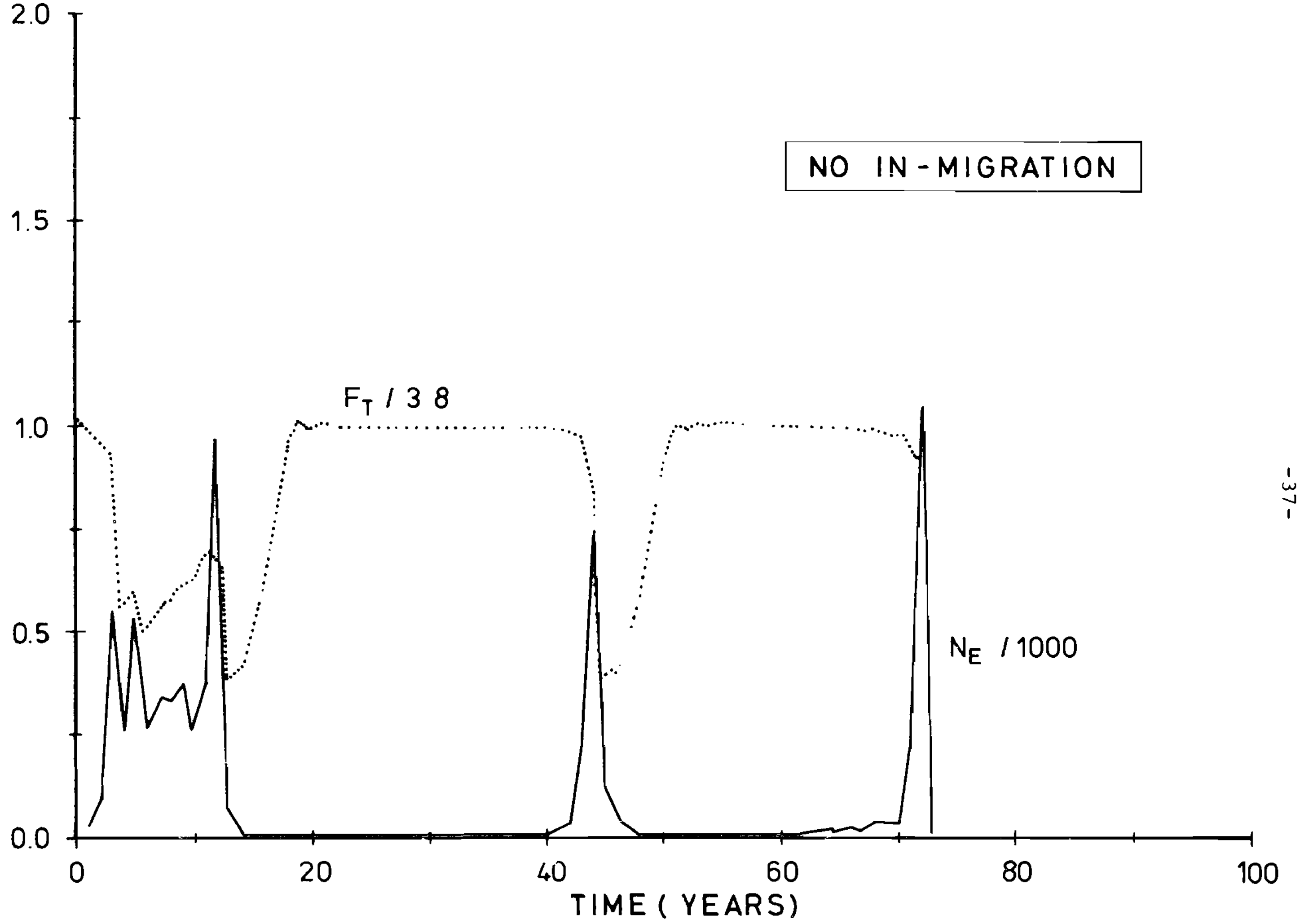
Analysis of a single site model indicates that for most purposes the model can be collapsed into 4 primary dimensions. First is the level of budworm; this can be taken at any stage, but the most convenient has turned out to be the density of large larvae. The second primary dimension is the total amount of new foliage (i.e., green needles) which appears in the spring. The third dimension is the surface area of branches per acre of forest; this effectively collapses the tree age structure into a single quantity. Finally, the fourth primary dimension is the weather. The weather is taken to be one of three categories rather than a continuous variable. The use of these primary dimensions makes it possible to develop several qualitative measures of system behavior. These are discussed in subsequent sections.

Figure 15



BUDWORM SITE MODEL

Figure 16



BUDWORM SITE MODEL

Figure 17

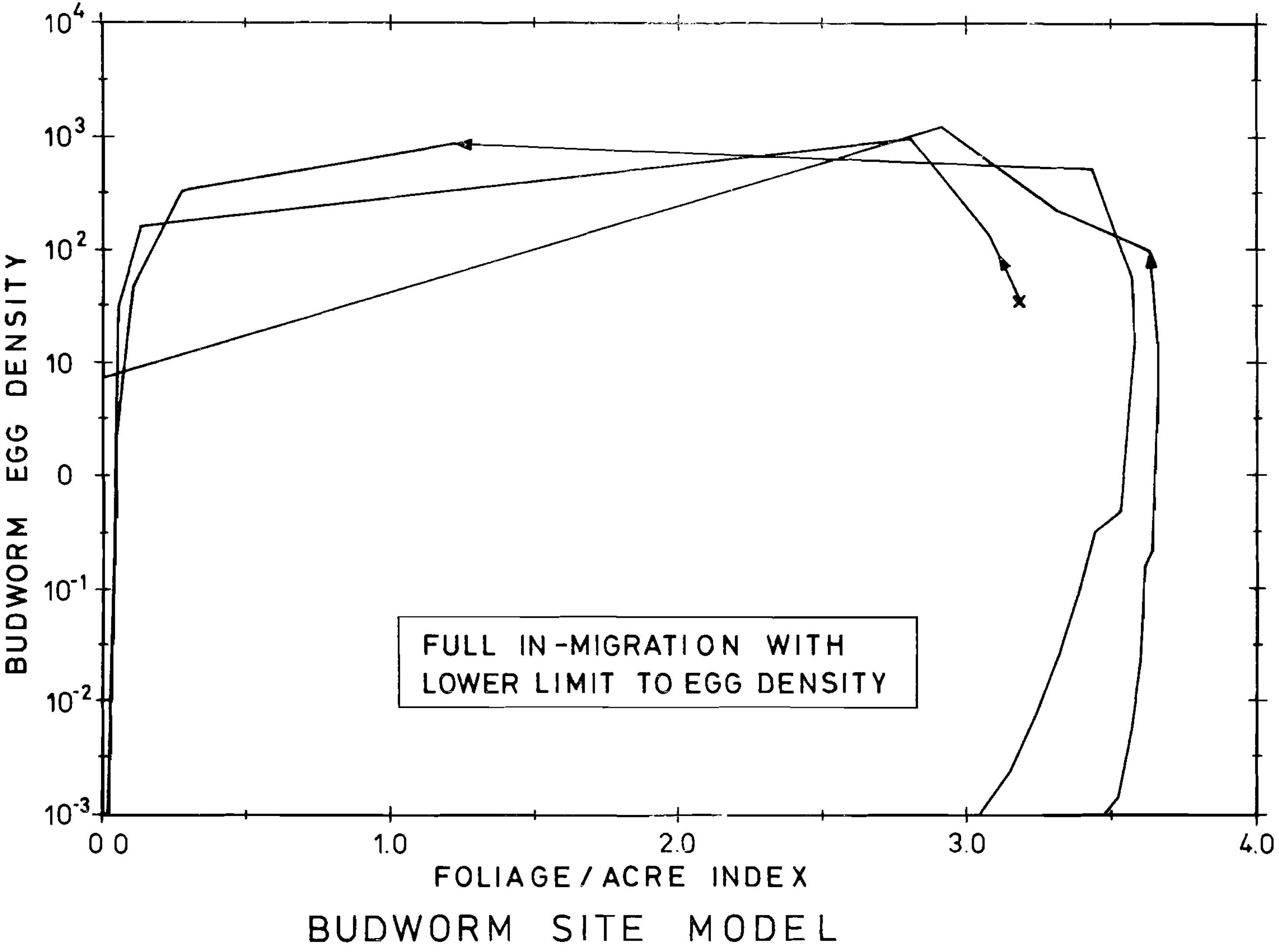
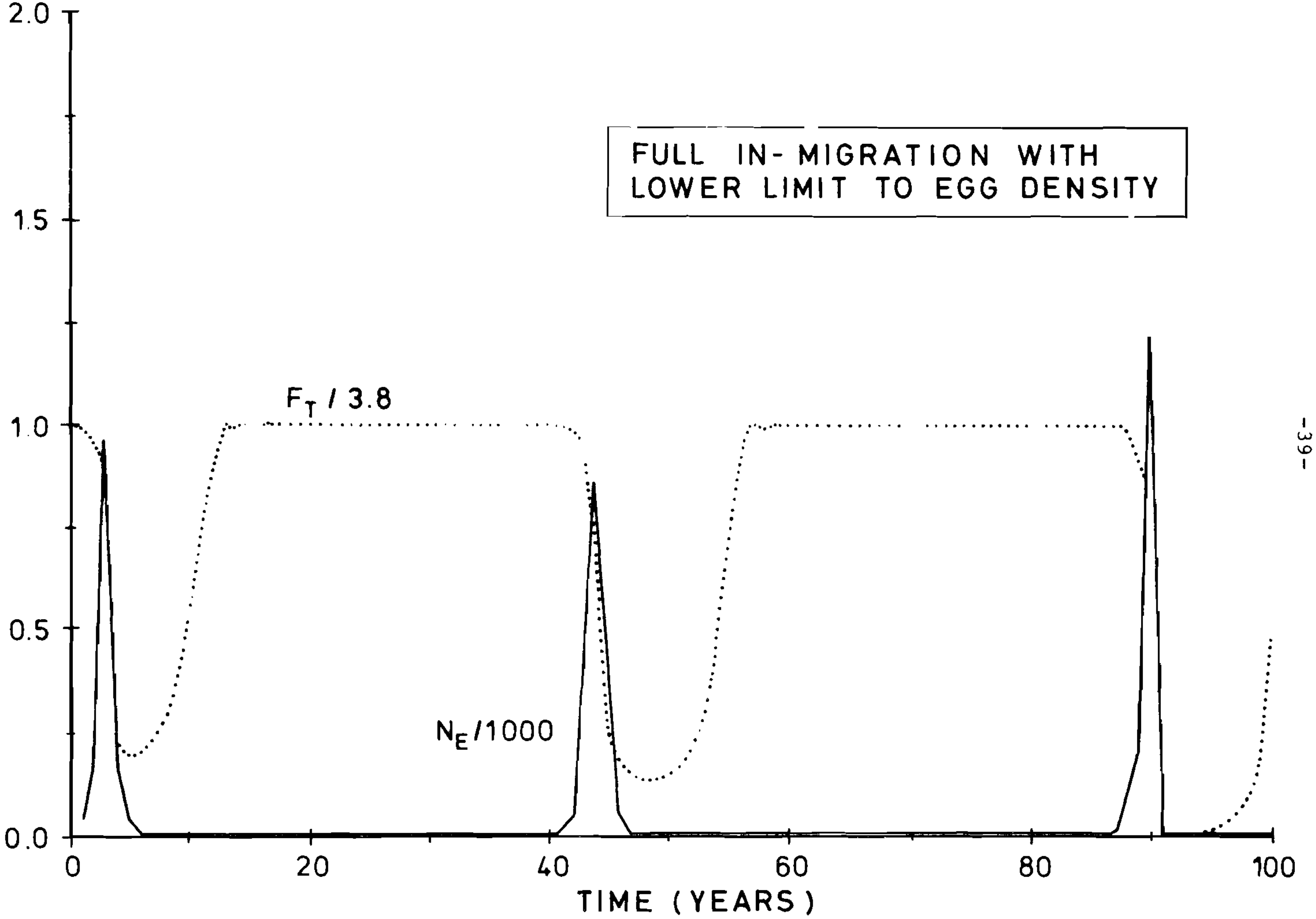

10^4
10^3
10^2
10
0
10^{-1}
10^{-2}
10^{-3}
BUDWORM EGG DENSITY
0.0
1.0
2.0
3.0
4.0
FOLIAGE / ACRE INDEX
FULL IN-MIGRATION WITH
LOWER LIMIT TO EGG DENSITY
BUDWORM SITE MODEL

Figure 18



BUDWORM SITE MODEL

2.4.2 States of the system

The management questions are essentially qualitative; the behavior of the system is essentially described by shifts between qualitative states.

Hence a major compression can be made by redefining the system into a small number of qualitatively distinct states, each of which has a specific ecological meaning and a specific set of appropriate management actions.

The key criterion: the system is dominated by thresholds which define distinct stability regions -- behavior between thresholds is qualitatively the same.

Examples:

Recruitment curves for budworm (i.e., population change between t + t+1 vs. density), Figure 19.

Thus the three weather types can produce a number of different thresholds which separate regions of increasing population from those of decreasing population.

The same phenomenon occurs with foliage, Figure 20. This simply illustrates thresholds in one dimension. There are, in reality, four essential dimensions: foliage, surface area covered by susceptible trees, budworm, and weather -- and other thresholds appear in these dimensions.

The result of carving up this four-dimensional space is a potential 25 distinct states defined by all possible combinations of increase and decrease for foliage, surface area, and budworm at each of the three weather types. Figure 21.

But we may compress further since the dynamics of the system cluster these 25 states into distinct and unique groupings and each of these groupings implies specific levels of impact and specific intensities and kinds of management actions. Fig.22.

Figure 16 provides an illustrative example of an application of these conditions in defining the states at one particular surface area.

Conclusion:

The qualitative behavior of the system can be represented by eight distinct stages. This, then, makes it possible:

(1) to succinctly represent the dynamics as transition and residence probabilities among the states;

(2) to provide an environment for compressed policy analysis outside the simulation model and interacting with the model only as a check. (See section 2.5.5)

Figure 19a: Recruitment curve for egg density in one year against egg density in the previous year for three weather classes.

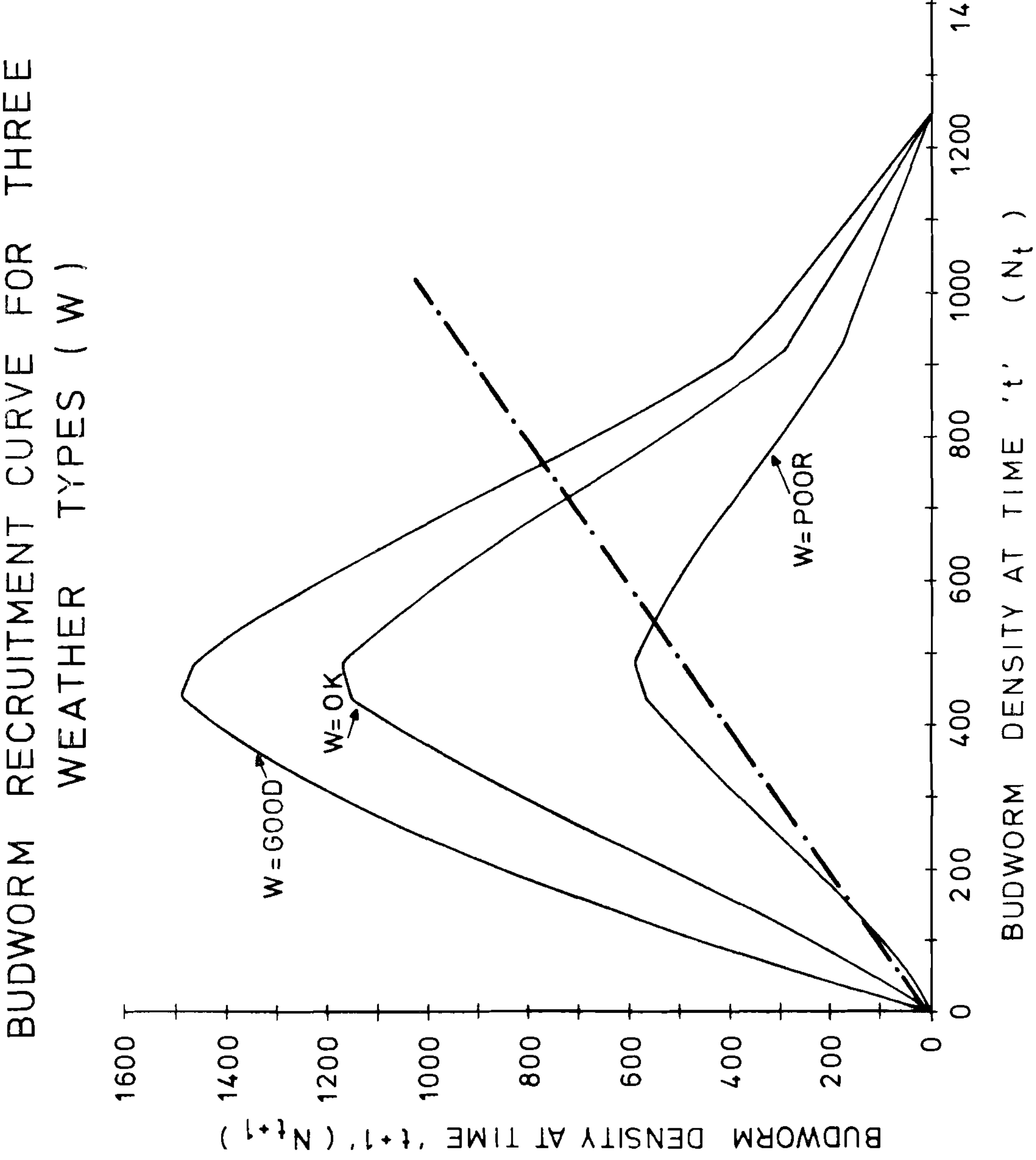
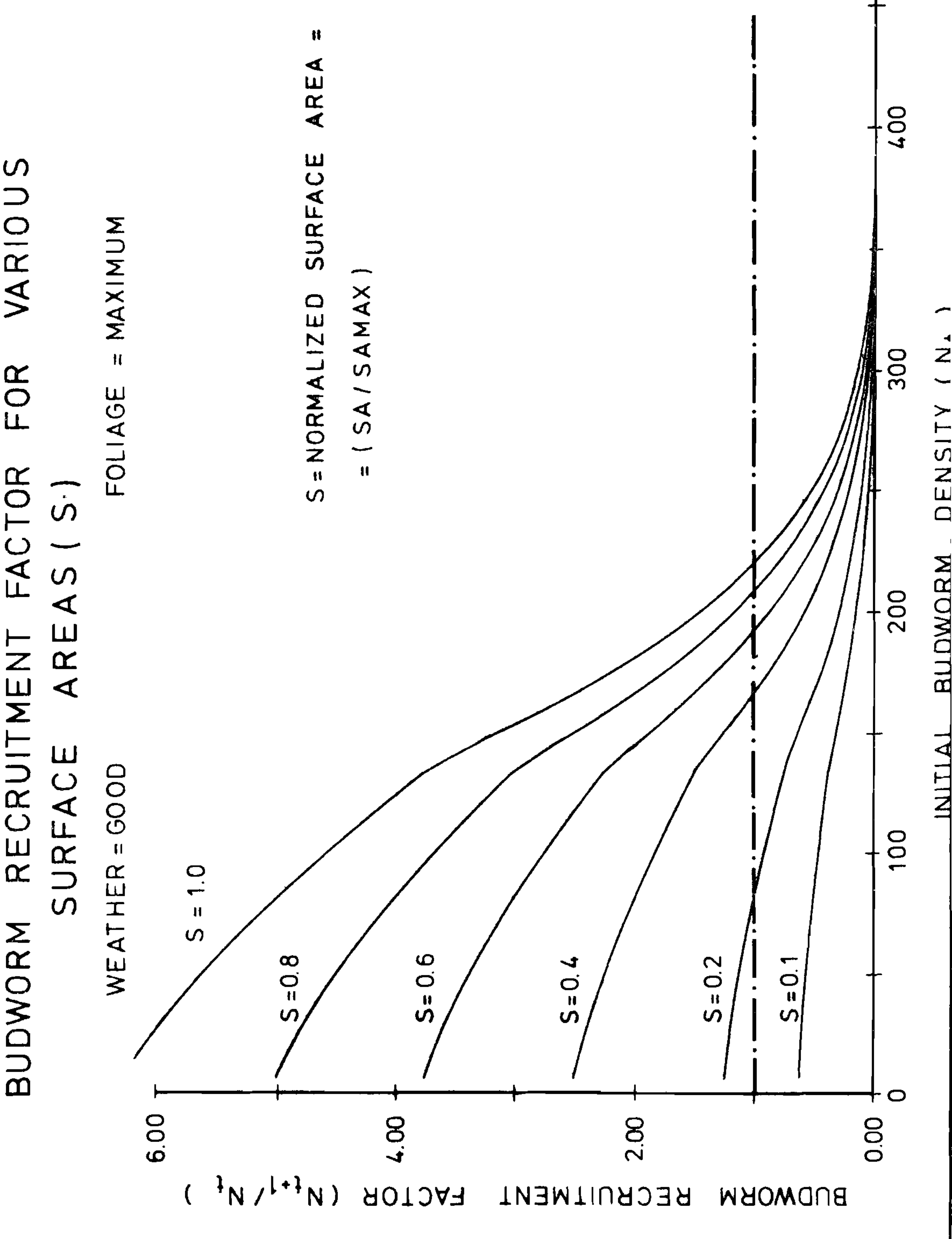


Figure 19b: Ratio of larval density in one year to that in the previous year for various levels of branch surface area. (Also 19c, 19d)



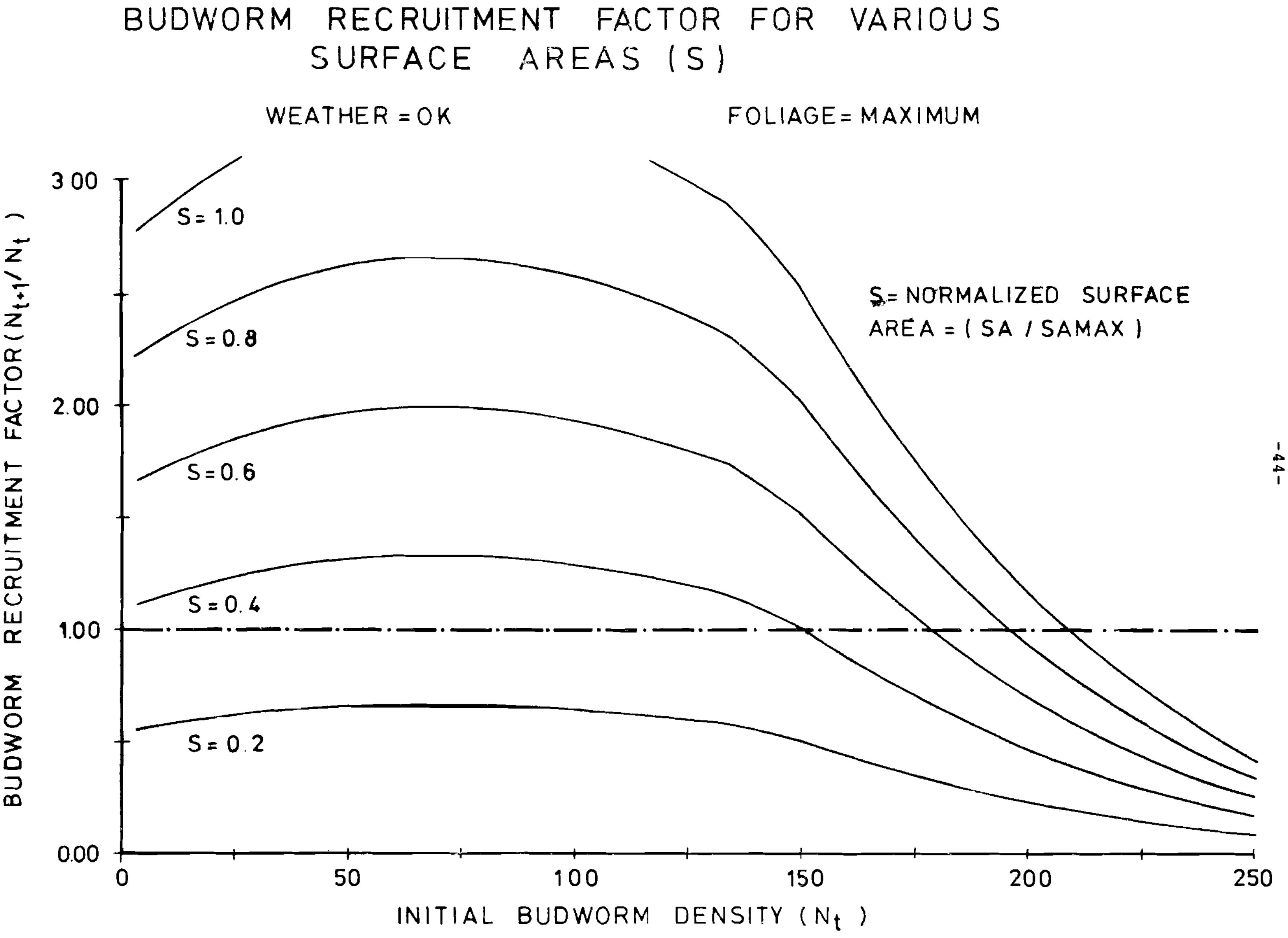


Figure 19c

BUDWORM RECRUITMENT FACTOR FOR VARIOUS SURFACE AREAS (S)

WEATHER = OK FOLIAGE = MAXIMUM

BUDWORM RECRUITMENT FACTOR FOR VARIOUS SURFACE AREAS (S)

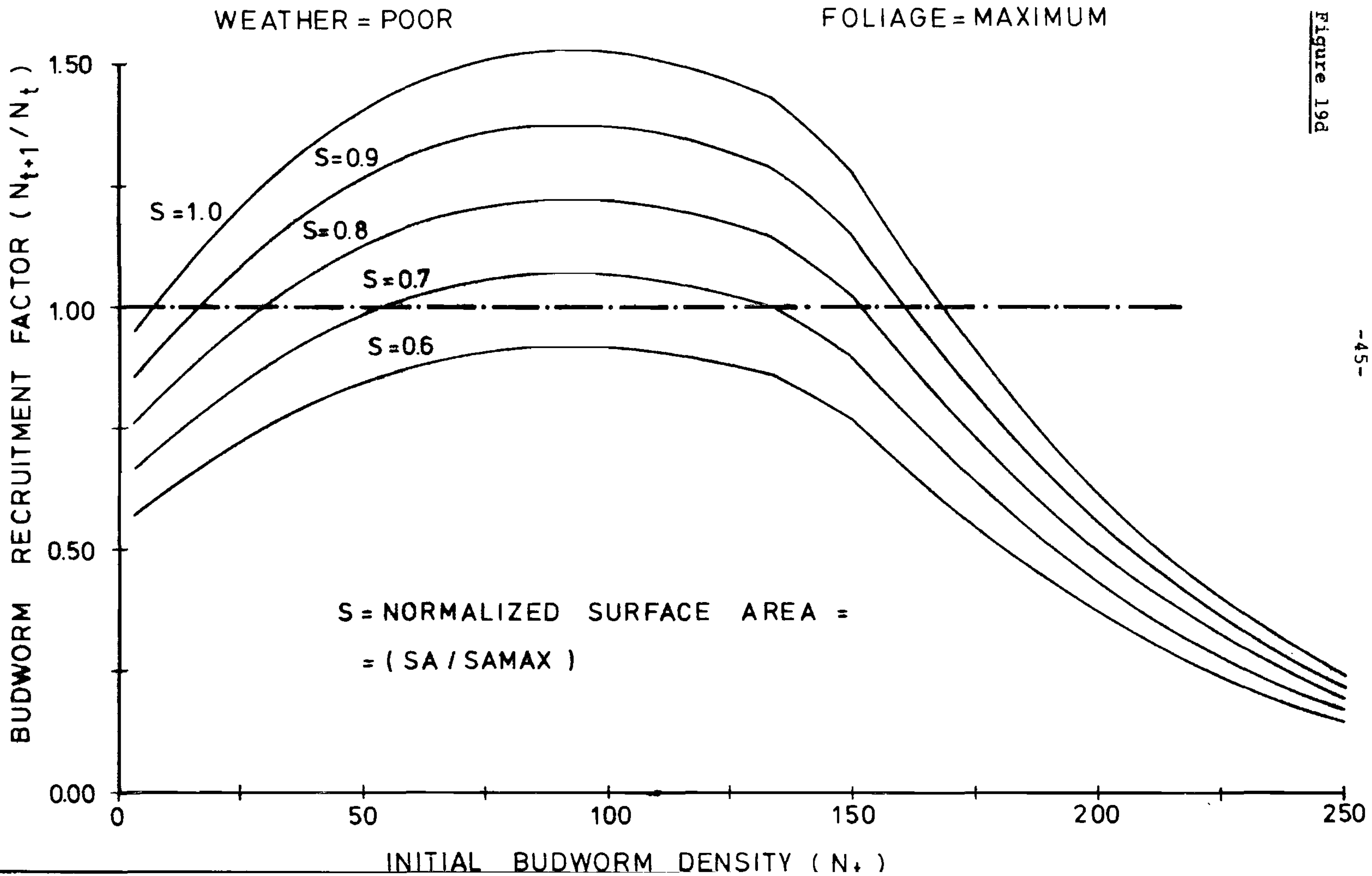
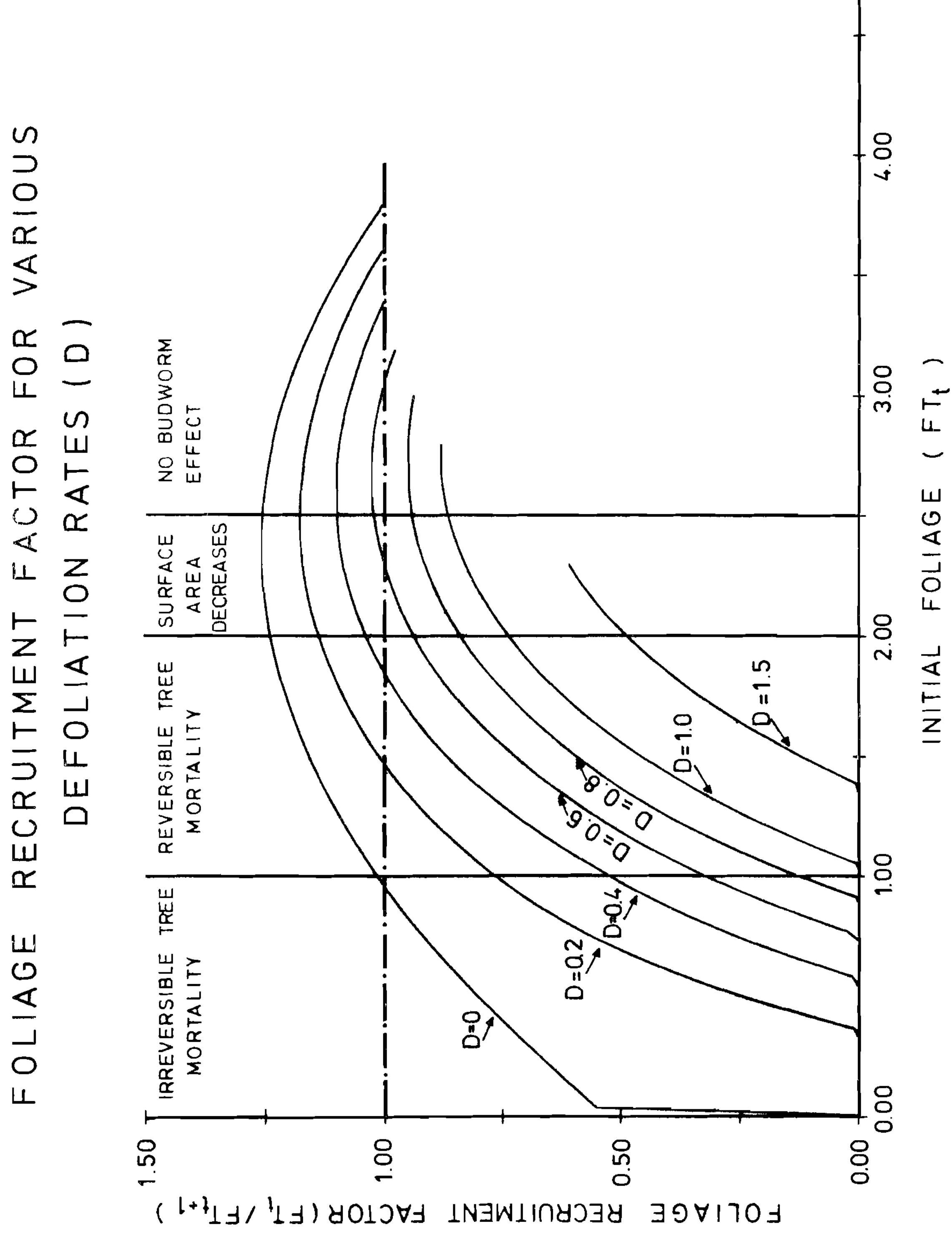


Figure 19d

Figure 20: The recruitment factor for foliage for various levels of budworm expressed as their defoliation rate D.



POTENTIAL STATES OF THE BUDWORM SYSTEM

	Foliage	Surface area	Larvae	Weather
1	-	+	-	1
2	-	+	-	2
3	-	+	-	3
4	-	-	+	1
5	-	-	+	2
6	-	-	+	3
7	-	-	-	1
8	-	-	-	2
9	-	-	-	3
10	-	+	+	1
11	-	+	+	2
12	-	+	+	3
13	+	-	-	1
14	+	-	-	2
15	+	-	-	3
16	+	+	+	1
17	+	+	+	2
18	+	+	+	3
19	+	-	-	1
20	+	-	-	2
21	+	-	-	3
22	+	+	+	1
23	+	+	+	2
24	+	+	+	3
25	?	?	?	?

$$F < 0.90 + .0074 * L$$

Figure 21: The potential 25 distinct states defined by all possible combinations of increase and decrease for foliage, surface area, and budworm at each of the three weather types. State 25 represents irreversible tree mortality.

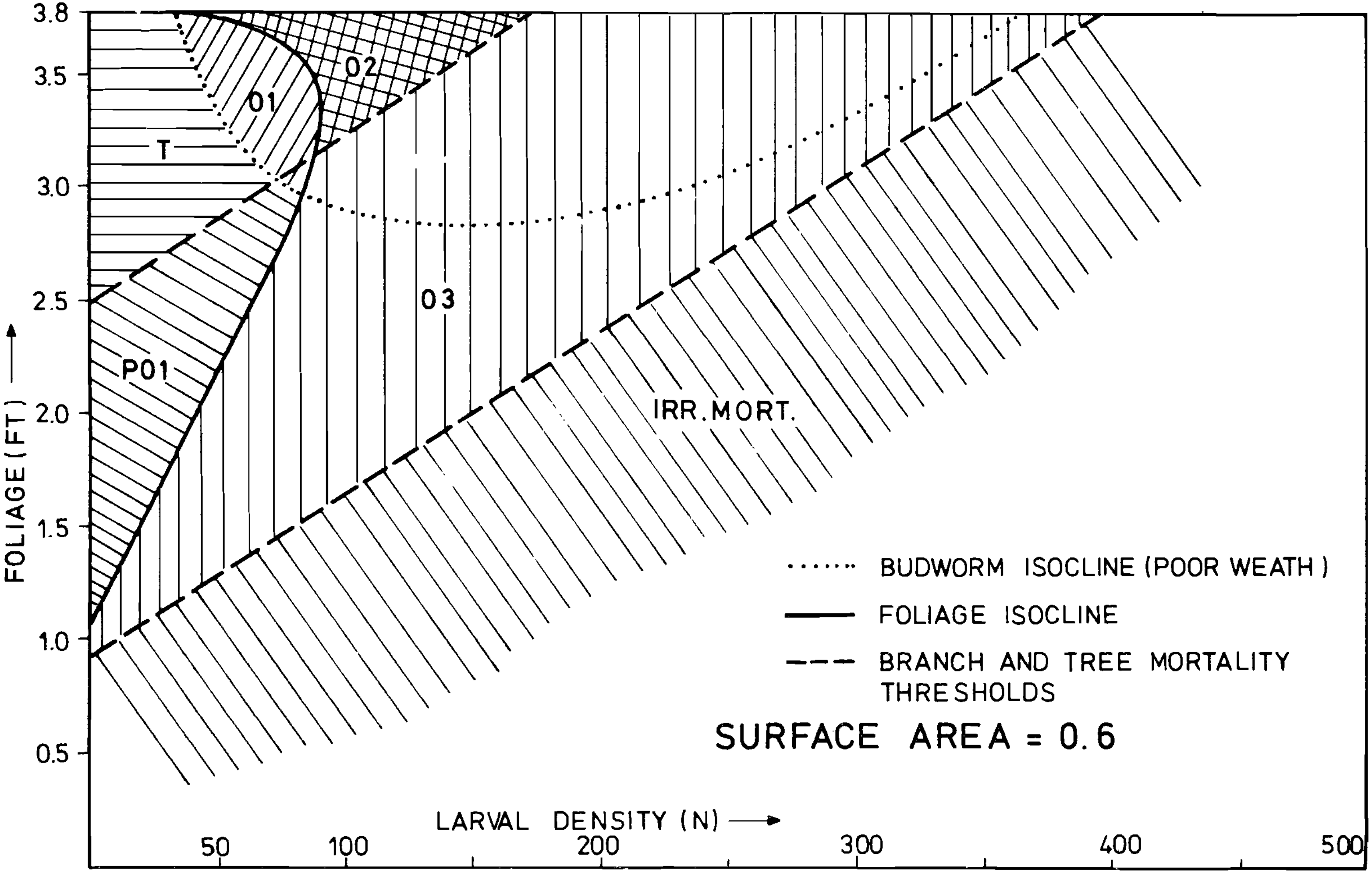
QUALITATIVE STATES OF THE SYSTEM

No.	Super state	Conditions		
		Foliage	Surface area	Larvae
S1	Endemic	+,0	+,0	-,0 if o.k. or poor weather + if good weather
S2	Threat	+,0	+,0	-,0 if poor weather + if o.k. or good weather
S3	Outbreak 1	+,0	+,0	+ all weather
S4	Outbreak 2	-	+,0	+,- or 0
S5	Outbreak 3	-	-	+,- or 0
S6	Postoutbreak 1	+,0	-	-,0 if poor or o.k. weather + if good weather
S7	Postoutbreak 2	+,0	+,0	-,0 all weather
S8	Irreversible tree mortality	Foliage < Irreversible mortality threshold		

+ = Increase
- = Decrease
0 = No change

Figure 22: The 25 states cluster into 8 distinct and unique groupings. Each of these groupings implies specific levels of impact and specific intensities and kinds of management actions.

FIGURE 23: AN ILLUSTRATIVE EXAMPLE OF THE CONDITIONS THAT DEFINE THE 8 QUALITATIVE STATES FOR ONE PARTICULAR SURFACE AREA AND WEATHER.



2.4.3 Validation of multi-site model

Validation data available

- egg densities, foliage condition, spraying, and harvesting acts in each of 265 regions for each of 30 years.
- validation is necessary of the pattern in space and time, and of the numerical ranges

  NOT site and year specific numerical agreement
- Thus choice of statistics:

  egg densities, tree hazard
  3 moments and why.

Difficulties in Validation

- dispersal the major unknown -- needs for timing testing alternate hypotheses
- size of model
- limitations of computer -- PDP o.k. when linked with big machine.

Preliminary Example of Pattern Predicted and Relation to Real World. (Figures 24, 25.)

HISTORICAL DATA

	Egden		Hazard			
	MU	SD	MU	SD	SKEW	KURT
1945	0.300	0.000				
1946	2.550	0.000				
1947	15.000	0.000				
1948	75.000	0.000				
1949	150.000	0.000	1.792	2.706	9.705	10.705
1950	499.385	400.413	2.766	4.625	5.058	6.111
1951	1270.816	955.167	3.955	5.576	1.935	3.027
1952	1062.825	948.155	4.181	5.603	1.296	2.417
1953	572.811	522.321	2.796	4.542	2.689	4.160
1954	462.911	310.688	7.770	5.790	0.028	1.540
1955	564.549	420.328	6.487	5.100	0.013	1.527
1956	579.530	1052.807	8.309	6.054	0.096	1.276
1957	144.767	187.055	8.694	4.449	0.033	2.088
1958	41.906	69.856	2.509	4.056	0.805	2.765
1959	168.964	168.704	2.151	3.608	2.666	4.185
1960	218.543	221.842	3.577	4.375	2.027	3.652
1961	137.283	136.193	3.562	3.821	0.788	1.994
1962	142.343	243.681	3.351	4.278	0.860	2.402
1963	320.461	1474.181	2.762	4.040	1.411	2.757
1964	180.500	203.408	2.321	3.252	2.528	3.863
1965	219.729	272.177	3.887	4.249	0.723	1.938
1966	156.441	145.215	3.672	4.062	0.512	1.659
1967	171.774	134.370	2.223	3.434	2.043	3.416
1968	362.551	361.551	2.811	3.998	1.876	3.226
1969	645.495	493.483	6.845	4.840	0.043	1.477
1970	809.866	576.693	5.574	4.037	0.189	2.073
1971	709.960	454.841	7.947	4.445	0.143	2.031
1972	317.036	232.043	9.528	3.919	0.750	3.398
1973	716.558	458.090	8.951	3.683	0.000	2.048

Figure 24: Historical trend of statistical measures for egg density and hazard for the study area.

FIGURE 25a: COMPUTER SIMULATION MAPS OF BUDWORM EGG DENSITY FOR THREE SCENARIOS. (1) NO SPRAYING; (2) SPRAYING AT INTENSITY 2; (3) SPRAYING AT INTENSITY 6.

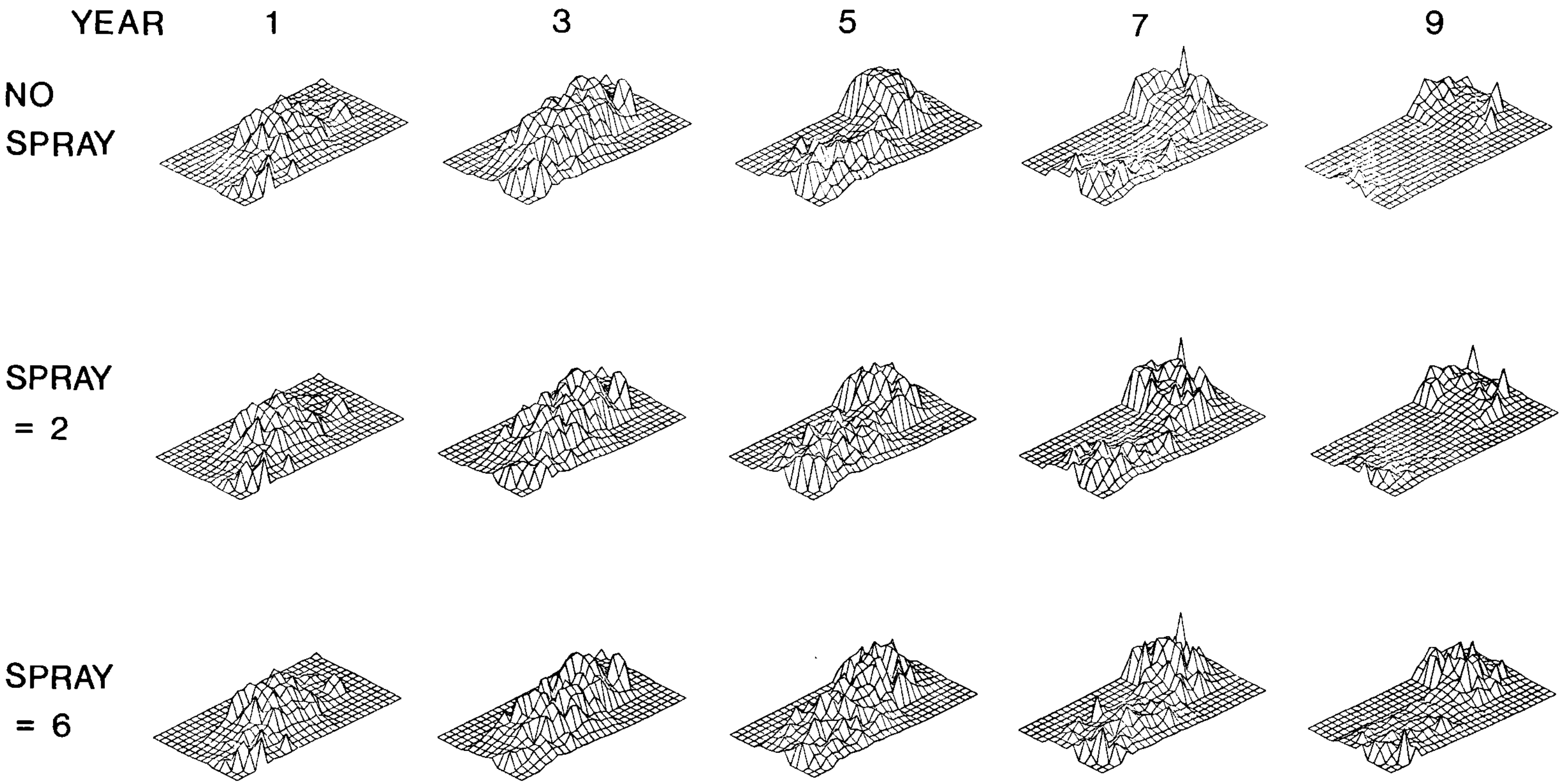
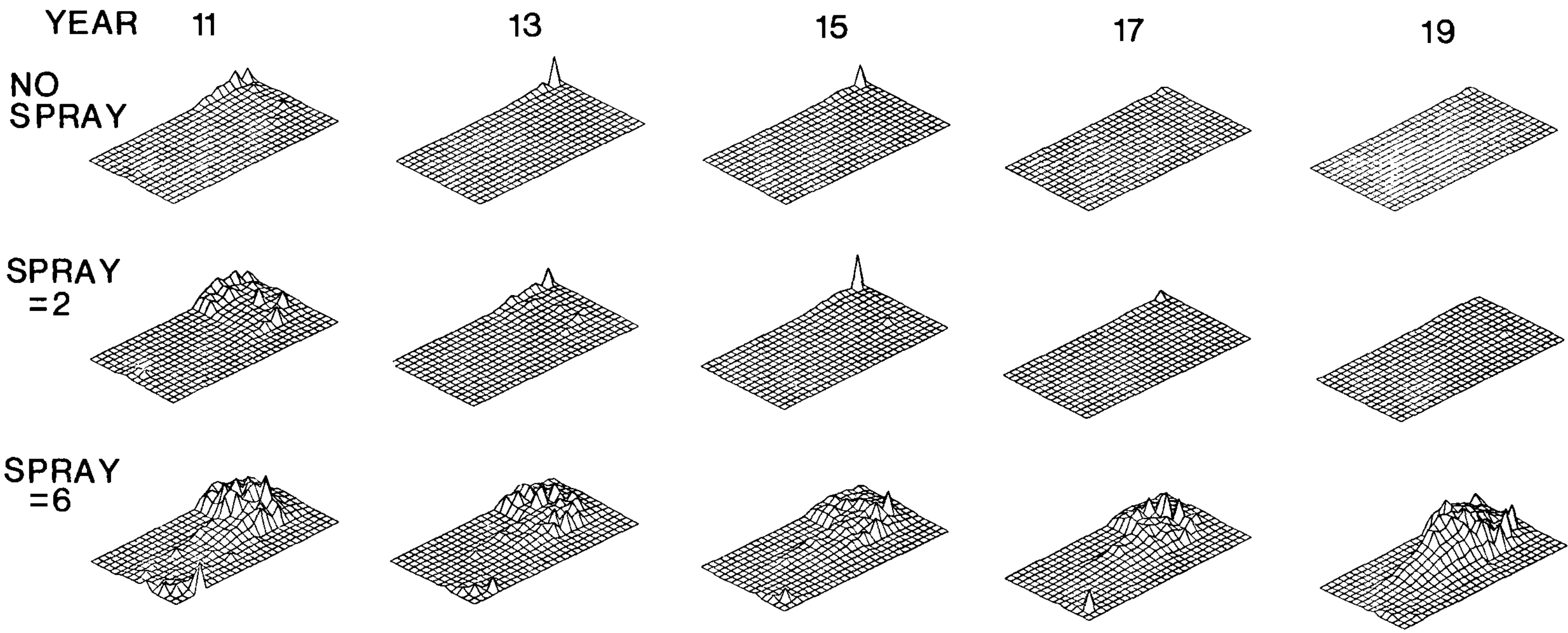


FIGURE 25b



2.5 POLICY ANALYSIS

2.5.1 Introduction

(A) The problem: How do we use our understanding of the ecosystem to evaluate and improve our management of the resource?

- the validated model as a source of potential standing of budworm-forest ecosystem behaviors and its response to management options;
- the techniques of systems analysis as ways of manipulating model options to realize that potential;
- the goal of policy analysis described here as the reconciliation of management feasibility (defined by the model) and social desirability of managed system behavior.

(B) The nature of policy analysis

- the point to be made here is that policy questions are design questions;
- a management policy is a set of rules which specifies the conditions under which various management options will be applied to the ecosystem;
- those rules thus determine the system's behavior in the same way as, say, feeding response curves of budworm larvae;
- by designing our management rules appropriately, we may influence the way the managed system functions; i.e., we design its behavior;

- this "appropriate" design of management rules to achieve some desired pattern of system behavior can only result from an analysis of our ecosystem model; policy is consequence of, not a condition to, that analysis.

(C) <u>The process of policy design</u>

- the design of management policy is seen as a process in which we seek to influence the managed system behavior, bringing what is technically feasible into line with what is socially desirable;
- there are clearly many issues at stake here: a rigorous exploration of possible management alternatives; an estimation of their effects on the system behavior; the whole intractable problem of defining social goals and preferences;
- no single approach can bring about a particularly satisfactory reconciliation of these contrasting dimensions of the policy design problem, and it is only through the judicious combination of a variety of techniques and methodologies that we have been able to make incremental progress;
- the presentations which follow will deal with a number of these methods in some detail:

(1) <u>Indicators</u> -- ways of speaking about and quantifying systems behavior (response to policy) in a manner which is meaningful to us, which relates as directly as possible to the implicit and explicit criteria we use in our judgments of "social desirability."

(2) <u>Preferences</u> -- given that we can satisfactorily describe systems behavior with our indicators, it remains to develop techniques which allow us to consistently "rank" alternative behaviors on a social desirability scale.

(3) <u>Optimization</u> -- application of various mathematical programming techniques under the assumption that you can specify goals and wish to explore management options which will realize the goals.

(4) Simulation and CPA -- sort of the converse of optimization in which you take certain management policies as given and seek to trace their implications for system behaviors.

(5) Generation of policies -- where to combine all of the above in various combinations to yield a small number of qualitatively different management policies for consideration of the policy maker and society in general.

(D) Other miscellaneous worries

- Recall that at the beginning of this section we defined our overall concern as one of investigating how the detailed technical information and understanding concerned in our model of the budworm system could be used to evaluate and improve our management policies.
- In the sections which follow, we treat the ideal case in which the model is assumed to cover the entire field of relevance to the manager and policy maker, and the policy maker is assumed to have an "appropriate" degree of faith in the model.
- We note, however, without further comment for the present, two areas in which these assumptions may commonly and significantly be violated:

(1) Credibility -- no matter how "valid" it may be, the model -- and technical information in general -- will not be used in the management and policy making context unless it is credible to its intended user. Keeping information credible as it is processed through simulations, dynamic programs, and dimension-reducing transforms is an often impossible and always difficult task.

(2) Completeness -- no model is complete, as everyone has remarked often enough. A problem hardly anyone has dealt with is how this incompleteness can be explicitly taken into account in the formulation of management policy. Our indicator work touches briefly here, as we try to provide easy points of contact between the user's mental models of a wide range of concerns and our explicit model of one particular concern. The issue of "too much" specification, as raised by Lindblom and his followers, remains untouched.

(E) Summary

Policy analysis is the process of designing rules for the application of management options. It combines a variety of methodologies and techniques to organize technically feasible management options in a way which induces the managed system to behave in a desired manner. As policies must be implemented within a broader institutional context, questions of credibility and inclusiveness are central to any policy analysis effort.

2.5.2 Indicators

Goal:

(1) to develop a graded series of information displays from very general and comprehensible to very detailed and diagnostic so that the decision maker can choose the appropriate level

(2) to design a specific set for one "decision maker" as an example.

Tactical, Primary Indicators

(1) Economic:

Profit of logging
Cost of spraying

(2) Resource:

Potential merchantable wood
Proportion harvested

(3) Recreational, Wildlife

Detectable budworm damage
Tree mortality
Observed logging effects
Recreational/wildlife diversity

(4) Social

Unemployment (forest industry)

Strategic Indicators

(1) Known relationships with known form

Ecosystem State Indicators

- residence probabilities (r) in 8 states
- spatial variation of Pr
- temporal variation of Pr.

(2) Known relationships with unknown form

Persistence of Forest Species Mix

- surrogate = life span of fir

Micro Diversity
- surrogate = age diversity of fir

Macro Diversity
- surrogate = ecological patch size

Insecticide "side-effects"
- surrogates = average dosage per sprayed plot
  = areal extent of spraying
  = duration of spraying

(3) Unknown relations, impacts, objectives

The effort to prepare the above list makes brutally clear how much knowledge is missing from the available data and the model. There will always be relationships left out whose existence we know but whose form we do not. There will, as well, be missing relationships whose existence we do not even suspect. And what is true of these relationships is equally true of the overall objectives of the development. The societal objectives which seem so clear at the moment can dramatically shift, leaving society with a policy and a system which cannot itself shift to meet these new needs. The growing demand for environmental impact assessment procedures is one clear symptom of such a shift of objectives. An assessment based solely on the presumption of sufficient knowledge can therefore lead to approval of a plan that could not be adapted to absorb the unexpected.

Few systems -- ecological, economic, and social -- are in a state of delicate balance, poised precariously in some optimum state. The ones that are do not last, for all systems experience traumas and shocks over their period of existence. The ones that survive have explicitly been those that have been able to absorb these changes. They have, therefore, an internal resilience. Resilience, in this sense, determines how much arbitrary disturbance, both of rate and of intensity, a system can absorb before it suddenly shifts into a fundamentally different behavior. A review of resilience and stability can be found in Holling, 1973.

In addition to the traditional indicators, it would therefore be useful to have a category which gave some sense of the resilience of a plan -- of its capacity itself to absorb the unexpected. The key requirement of these resilience indicators is that they measure the degree to which alternate options are foreclosed.

But how can these indicators be developed? There are three mutually exclusive classes of resilience indicators:

(a) Resilience in environmental capital

At any point in time, there exists a reserve capital of resources that are drawn upon for any policy. This reserve capital has a certain existing quantity and quality. Therefore, those indicators which measure the amount and kind of resources used should also be given a resilience dimension, so that the remaining environmental capital can be measured. It is this remaining capital inventory that buffers the development in case of the appearance of unexpected and unhappy consequences. Modified developments or new developments of the future draw from this reserve. Example: a recreational land development will produce certain effects which can be evaluated by traditional recreational social indicators. But the land used is drawn from a reserve of a certain size and with certain intrinsic qualitites for absorbing recreation. These quantities and qualities of the remaining reserve should be measured by adding a resilience dimension to existing recreational indicators.

(b) Resilience with respect to systems boundaries

Social-ecological systems are dynamic systems in which the structure and functional interrelations themselves establish intrinsic boundaries or thresholds of stability. Phosphates added to an aquatic ecosystem are incorporated into existing biogeochemical cycles. But there is a limit to the amount that can be added without destroying the integrity of the cycle. Therefore, a measure of an indicator that expressed the absolute amount of phosphate added should be matched with one that expressed the total amount in relation to the system boundary for phosphate. In some cases, the model itself can be used to identify some of these thresholds. In other cases, with less knowledge, the boundary would be expressed as a guess -- a standard or threshold similar to public health standards. Again, the task will be first to identify those social, physical, and ecological variables which are state variables for the system,and second, to add a resilience dimension which measures the amount in relation to the system boundary or standard.

(c) Resilience of benefits

Major emphasis is now placed on indicators which explicitly measure the net economic and social benefits of a development. But there is a resilience counterpart to these as well. If the development plan or policies fail unexpectedly, or if social objectives shift to require their removal, there will be a cost attached to this failure. A model provides an explicit way to measure cost of failure. After a simulation has run long enough with a specific policy to generate a consistent behavior of the indicators, sensitive elements of that policy can be arbitrarily removed, and the same cost and benefit indicators can reflect the consequences of this policy failure. Example: regional insect pest control projects can have a number of forms. One might be intensive and extensive insecticide spraying. Another might mix cultural practices with limited and controlled application of insecticide at critical times or in critical places. Both policies, during their implementation, might achieve similar benefits, but sudden removal of insecticide could occur as result of rising costs or government regulation. In the first policy, such removal could produce intensive outbreaks covering large areas, with disastrous effects on benefits. In the second policy, the loss of benefits could be minor. The impact of policy failure can therefore be expressed by this loss of benefits. These indicators measure not the relative fail-safe features of different plans, but the degree of safe-failure of those plans.

Resilience Indicators:

(1) Environmental Capital

unutilized resource
unutilized recreational areas

(2) Unexpected States

distance to irretrievable tree death
distance to budworm extinction

(3) Cost of Failure

cost of selective removal of spraying acts
cost of removal of harvesting acts.

2.5.3 Preferences

1. What do we want out of the forest?

There are two aims of a decision analysis -- the second is the more formal aim, the first the more realistic.

(a) to help the decision maker understand his own preferences, perhaps clearing up inconsistencies and misconceptions;

(b) to define a criterion by which forest policies may be evaluated.

What are the factors which affect preferences? (Fig. 26)

It has become clear that the aim is to maintain a high level of income from the logging industry whilst at the same time keeping the employment level high and preserving (or improving) the recreational value of the forest.

Hence the value of the forest may be determined from the history

$$(P_t, U_t, R_t) \qquad t=0,1,2,3,4,\ldots$$

where P_t = profit in year t

U_t = level of unemployment in year t

R_t = recreational value of forest in year t.

2. How does the theory work in practice?

It is not appropriate to discuss the theoretical possibilities here. The following relates briefly what happened, and predicts what will happen as the work proceeds.

The decision maker first evaluated a recreational index. (Figs. 27,28)

It was established that preferences for the recreation aspects were independent of the profit and unemployment levels. ($\{R_t\}$ and ($\{P_t\}$, $\{U_t\}$) are mutually utility independent.)

Thus one subproblem is to find a utility function for the time series

$$(R_0, R_1, R_2, \ldots) .$$

The factors involved here are the mean level, maximum level, minimum level, variance, variability, and so on. It seems to be difficult to evaluate a time series where interdependency is very strong, particularly when the idea of time preference (discounting) is introduced. A guess is that the utility function will be something such as

$$\sum_t \alpha^t u (R_t R_{t-1})$$

for some simpler function u.

Similarly for the profit and unemployment.

3. Where did the simulation model come in?

It is possible to establish trade-offs between P, U, R just by inventing figures out of one's head. However, it is of the utmost importance to keep the decision maker's feet firmly on the ground. He must be able to see how his decisions affect the real world (the simulation model).

For example, it can be easy to discard or overemphasize the recreational aspects, or to forget that a decision which leads to losses and unemployment now in favor of high gains later will be hard to implement.

By getting results from the model, it may be possible to see that simplifying assumptions are in order (unemployment is always zero in any sensible policy for example), and to check the accuracy of the utility function for values that it will meet most often.

The drawback of a simulation model is that it can make the decision analysis harder. With a lack of information concerning how histories develop, it is much easier for the decision maker to make simplifying assumptions.

Increased accuracy should not be a drawback, but it is in terms of finding an optimal policy.

The more complex the objective function, the more difficult will be the optimization.

There is a procedural trade-off between accuracy in the objective and the optimization.

4. Conclusions

A decision analysis can be performed with the modest aim of merely clarifying the decision maker's attitude towards the subject matter,and for a complex problem a real world model is essential for testing a decision maker's formal preferences against his intuitive feeling.

If the aim of the decision analysis is to find an optimal policy by an optimization procedure, it may be that oversophistication leads to an intractable problem. Approximation has to come in somewhere.

An analysis of such a problem should include a sensitivity analysis of the optimal policy to the objective function. (It may be that any policy keeping a good profit over 50 years ensures full employment and suitable recreation.)

FIGURE 26

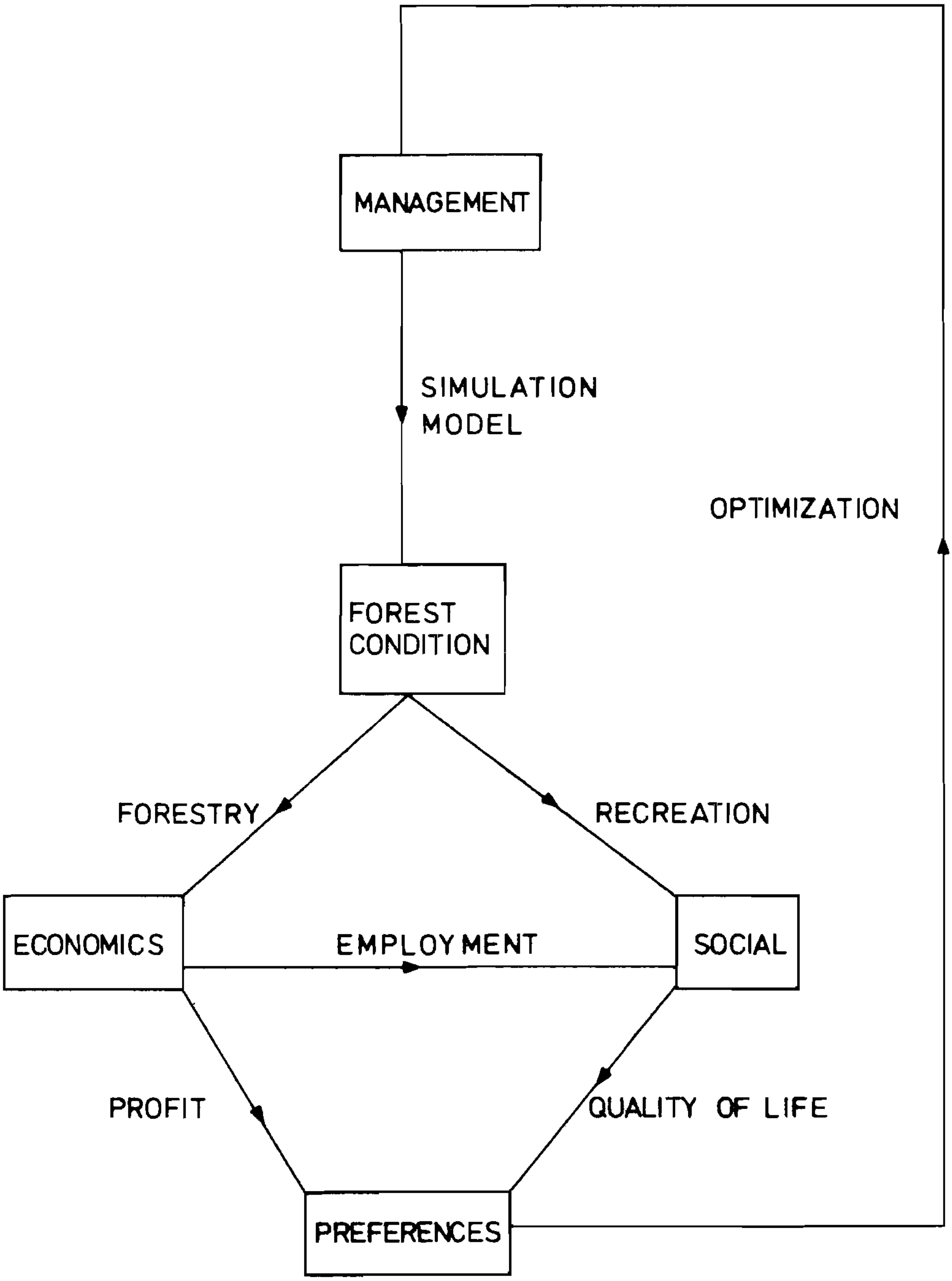

MANAGEMENT
SIMULATION MODEL
OPTIMIZATION
FOREST CONDITION
FORESTRY
RECREATION
ECONOMICS
EMPLOYMENT
SOCIAL
PROFIT
QUALITY OF LIFE
PREFERENCES

FIGURE 27

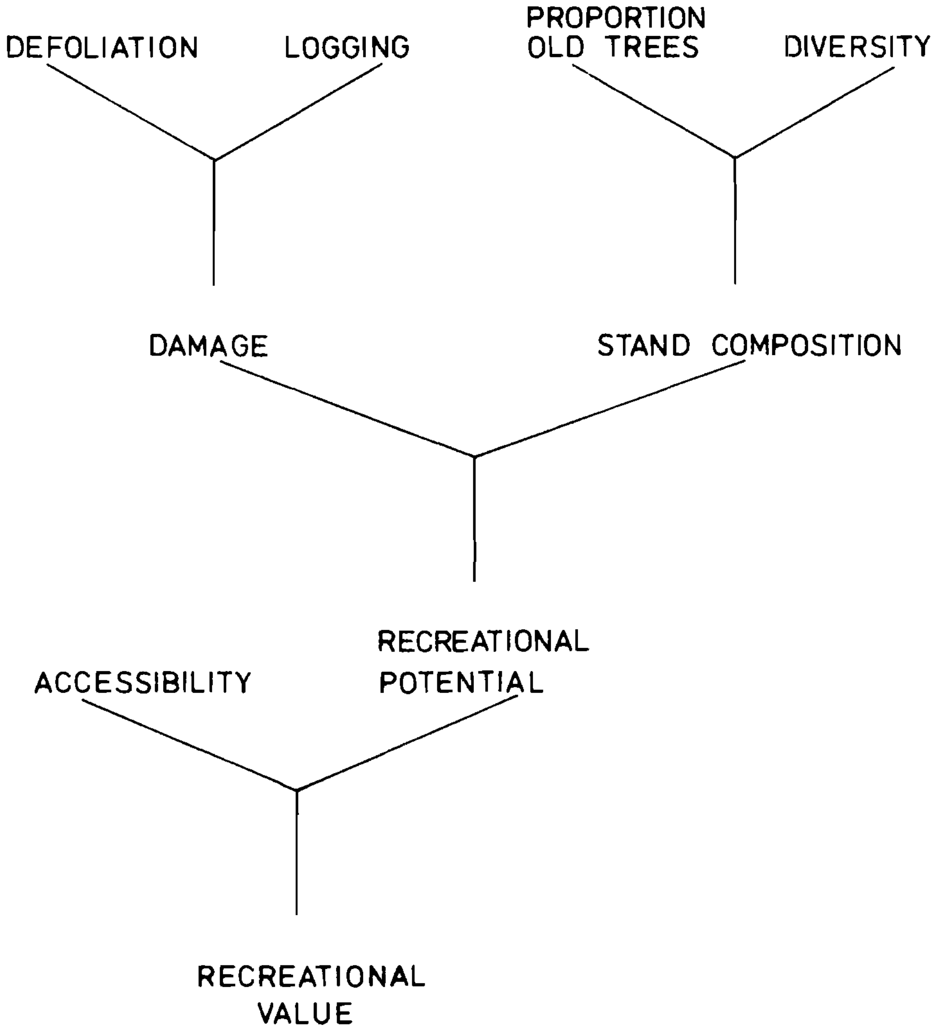
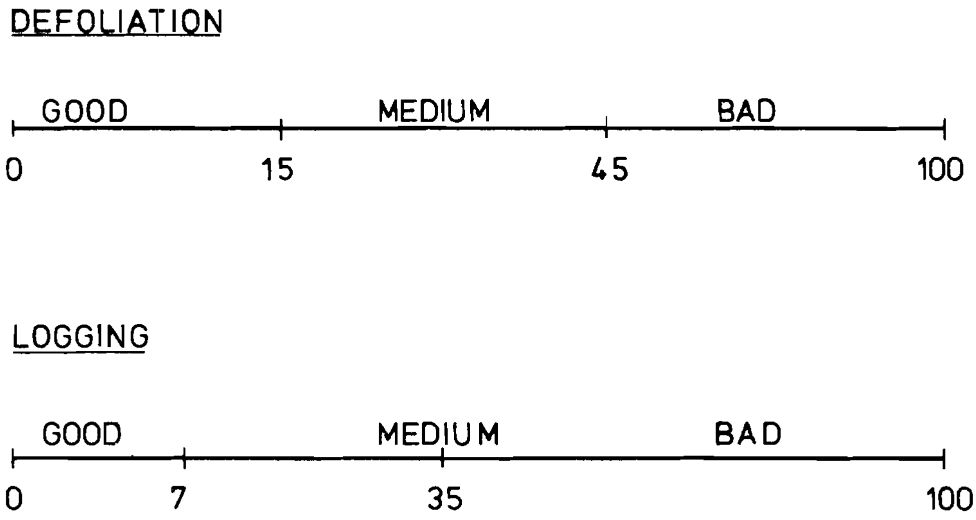

DEFOLIATION
LOGGING
PROPORTION OLD TREES
DIVERSITY
DAMAGE
STAND COMPOSITION
ACCESSIBILITY
RECREATIONAL POTENTIAL
RECREATIONAL VALUE

FIGURE 28



	GOOD	MEDIUM	BAD
GOOD	GOOD	MEDIUM	BAD
MEDIUM	MEDIUM	MEDIUM	BAD
BAD	BAD	BAD	BAD

2.5.4 Budworm-forest optimization model

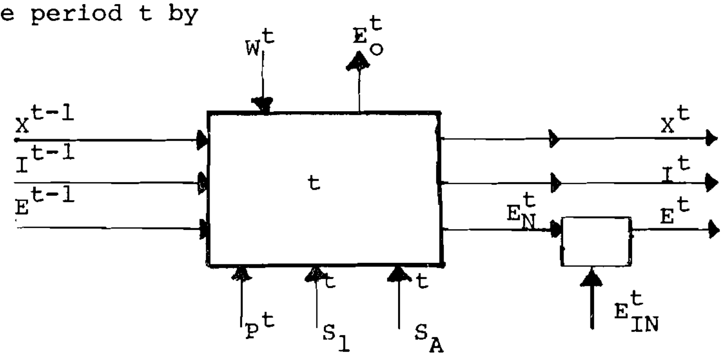
1. The Problem

The simulation model described earlier in this report represents the behavior of the budworm-forest system on any given site and in any given year through a relatively small number of variables and nonlinear relations. The state variables are the forest composition variables, the egg density, and an index comprising the effects of budworm attacks on the forest in the past. Complications arise mainly due to the dispersion of adult budworm moths, which by laying eggs on sites different from those of their origin provide the only link between different sites. If it were not for this, each site would be independent of the others and could be optimized independently.

Let N_s be the number of sites under consideration ($N_s = 265$) and N_t the number of time periods under consideration (around 100). When considering the whole area and including contaminations due to dispersal of adult budworm moths, the total number of variables and relations is $N_t \times N_s \times$ (number of variables (and relations) per site and time period) and the problem becomes untractable for general nonlinear programming methods. Also a more specialized dynamic programming approach gets into trouble due to the large number of state variables ($N_s \times$ (number of state variables in one site).

2. Simplifying Assumptions

If we represent the relations of a model by a box, the information needed as arrows pointing into the box, and the information calculated by the model as outgoing arrows, we can represent the process on any given site and time period t by



where superscript t refers to the time period and

$X^t = (X_1^t, X_2^t, \ldots, X_N^t)$ is the vector of forest composition, i.e. X_i^t area covered by trees of age i in time period t. N number of tree age classes in forest

I^t	index condensing past budworm attack history
E^t	egg density (egg/acre)
W^t	weather type
p^t =	$(p^t_1, p^t_2, \ldots, p^t_N)$ logging vector, i.e. p^t_i acres of age group i trees logged in period t
$S^t_{l_t}$	spraying policy on larvae
$S^t_{A_t}$	spraying policy on adults
E^t_o	eggs laid on other sites by moths originating from the site
E^t_{IN}	eggs laid by moths from other sites who dispersed into site under consideration.

With this notation we can then represent the process in the whole area by the information flow diagram in Figure 29, where the subscripts refer to the site. In Figure 29 only 2 sites are shown explicitly. All the others interact through the dispersion model (DM) and are taken collectively into account by the arrows E_o from other sites, and E_{IN} to other sites.

Observe from Figure 29 that if on any given site, say site j, we have a good estimate of $E^t_{IN_j}$ for all t we can solve site j independently and forget about the interactions.

On the heuristics that an optimal policy would keep the budworm under control in the whole area, and hence the proportion of adults dispersed would be relatively small and would not vary wildly from one site to another, it is reasonable to expect that

$$\left| E^t_{o_i} - E^t_{IN_i} \right|$$

is small with respect to E^t_i and that the error introduced by assuming

$$E^t_{o_i} = E_{IN_i}$$

is negligible.

<u>Assumption 1:</u> For an optimal policy $E^t_{o_i} = E^t_{IN_i}$ for all i = 1,...,265 and t = 1,...,N_t.

It is important to point out that the validity of this assumption can be checked a posteriori by testing the optimal policies obtained from the site optimization on the simulation model.

The site model has a dynamic structure and could be solved by applying a dynamic programming technique. There are N + 1 state variables, where N is the number of age classes in the forest (E^t, I^t and N-1 of the components of $X^t = (X_1^t, X_2^t, \ldots, X_N^t)$, since one of them is dependent on the others through

$$\sum_{i=1}^{N} X_i^t = \text{constant forest area.}$$

To successfully apply the dynamic programming technique it is important to have a small number of state variables, say no more than 6 or 8. This requires a high degree of aggregation in the forest model which necessarily distorts somewhat the economics. Instead an alternative approach can be pursued which does not require aggregating the forest age classes and which allows the computational requirements to be reduced considerably. The details of this approach will be contained in the final report and in the present status report only the simplifying assumptions made will be stated:

Assumption 2: The value of the forest is the sum of the value of its trees, i.e.

$$V(X^t, E^t, I^t) = \sum_{i=1}^{N} X_i^t \, p_i \, (E^t, I^t)$$

where $V(X^t, E^t, I^t)$ is the value of the forest when its state is defined by (X^t, E^t, I^t) and

$p_i(E^t, I^t)$	value of an acre of i year old trees when egg density = E^t and foliage index = I^t.

Assumption 3:

$$\left.\begin{aligned} \frac{\partial p_i(E,I)}{\partial E} &\leq 0 \\ \frac{\partial p_i(E,I)}{\partial I} &\leq \end{aligned}\right\} \quad \forall_i, E, I$$

i.e. the value of a tree is highest in the absence of any budworm effect and diminishes as the index on past history increases or the egg density increases (because of potential damage in the future).

As was mentioned, the problem solution simplifies considerably when making these last two assumptions. This simplified method was programmed and run using data provided by the Canadian Forest Service as to spraying costs and benefits from the lumber industry.

3. Results

The results of the computer runs can be conveniently presented in form of policy tables, as in Figures 30 and 31. There is one policy table for each age group and it tells what the optimal policy is on an area covered by trees of age i, as a function of the values of the index I (F_T in Figures 30 and 31) and the egg density (E_D in Figures 30 and 31). Thus for an area covered with 51 year old trees (see Figure 30), according to the values for F_T and E_D it tells us to a) None, i.e. do nothing this year, b) Log or c) Spray. In this last case the computer also specifies the dosage and whether larvae or adults should be sprayed.

Such tables were generated for different assumptions as to the selling price of one cubic unit (cunit) of lumber and for different values for the discount rate.

It turns out from the optimization that there is an optimal cutting age for undamaged trees and that it is optimal to always log all trees this age and older, no matter what the contamination effect is or has been. This optimal cutting age is given in Figure 32 as a function of the value of a cubic unit of wood and in Figure 33 as a function of the interest rate.

Preliminary runs done in Vancouver using the above policies in the simulation program seem to justify the simplifying assumptions made and give a considerable improvement over management policies currently in use, as can be seen in Figure 34 which gives the fraction of bad recreational sites as a function of time for both policies over the next hundred years as predicted by the simulation model (a definition of bad recreational sites is presented in Section 2.5.3).

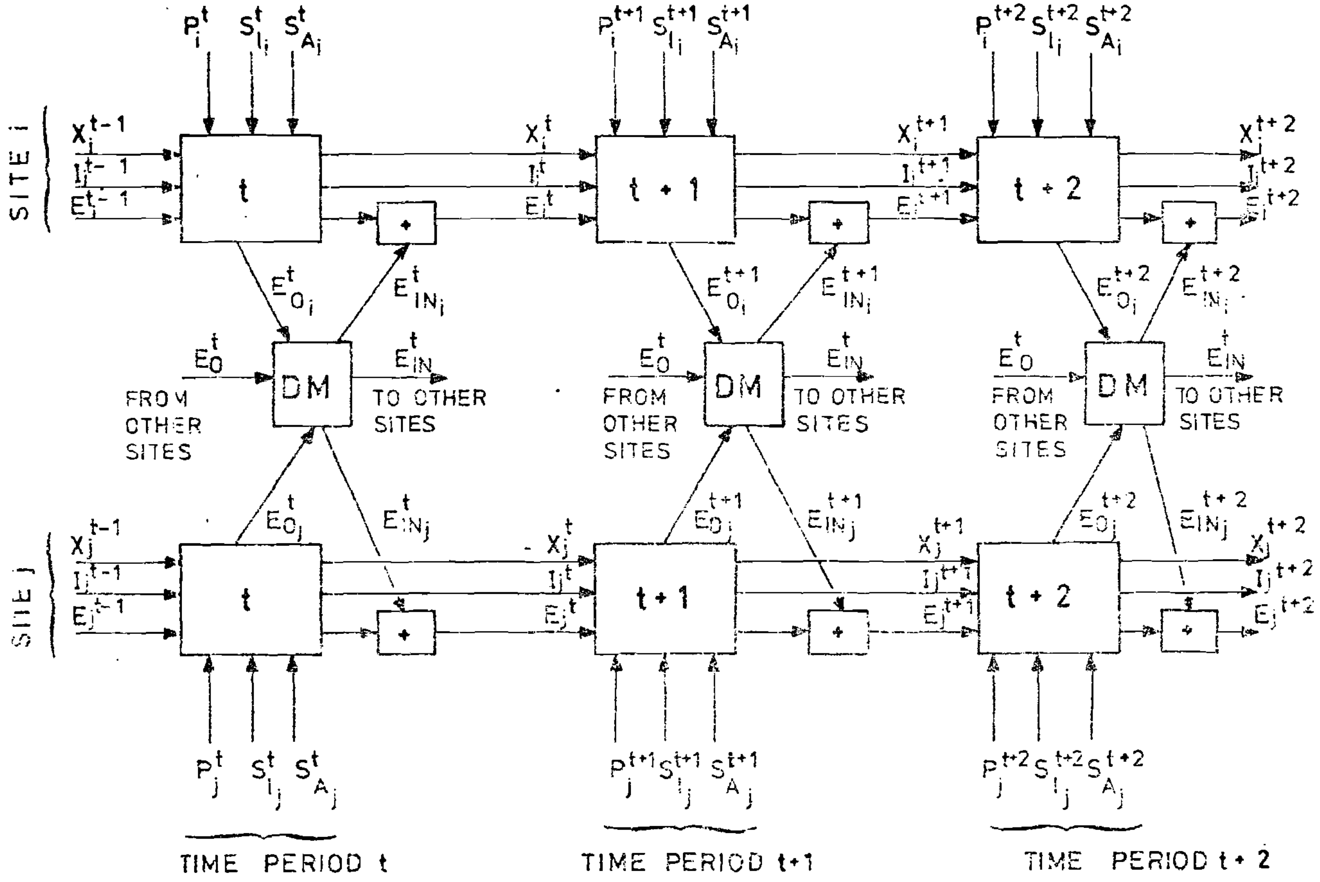


FIGURE 29

Information flow diagram for budworm model

FIGURE 30

POLICY TABLES FOR REPRESENTATIVE AGES

(PRICE = 55 $/cunit ; ρ = .05)

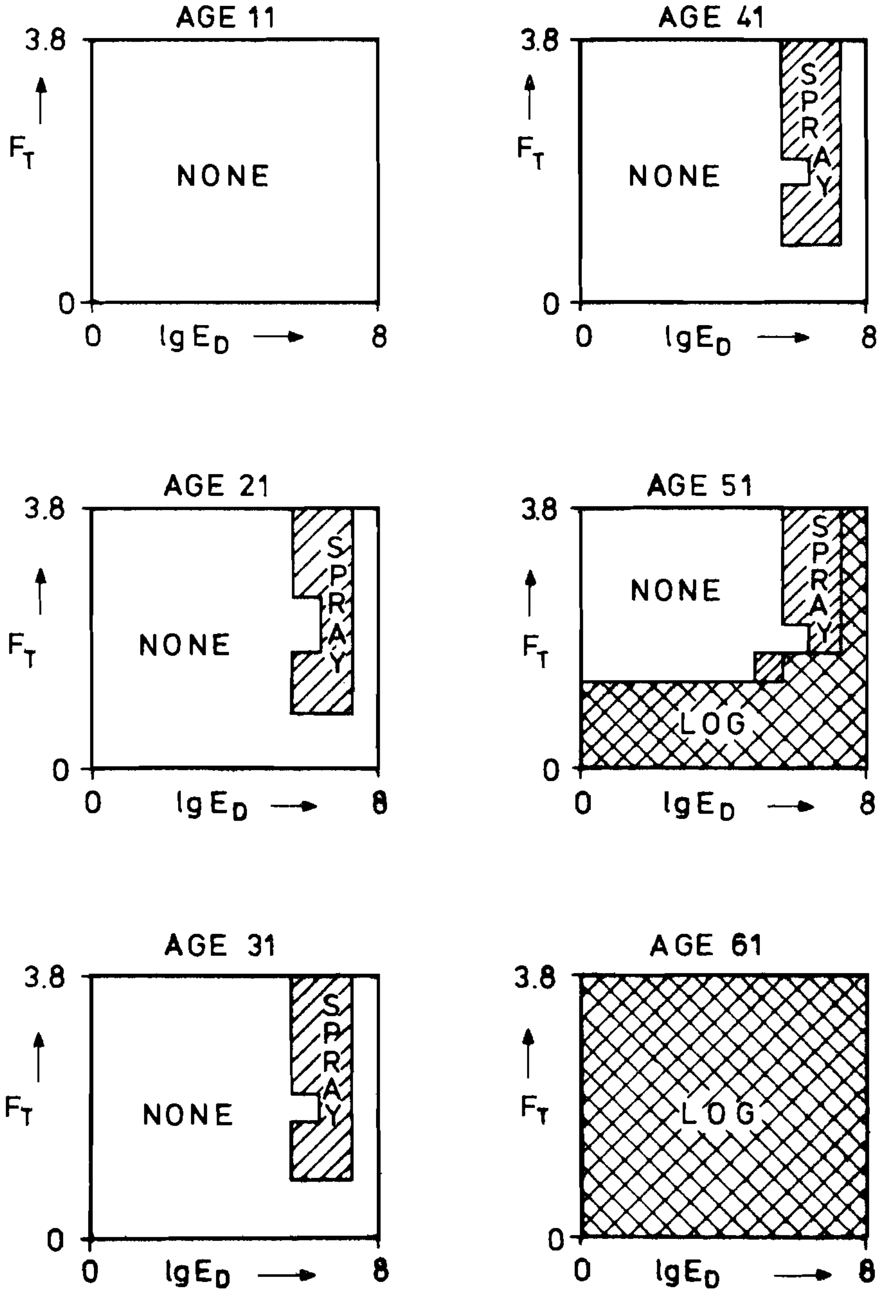


FIGURE 31

POLICY TABLES FOR AGES 42 - 47

(PRICE = 55 $ / cunit ; $\rho = .05$)

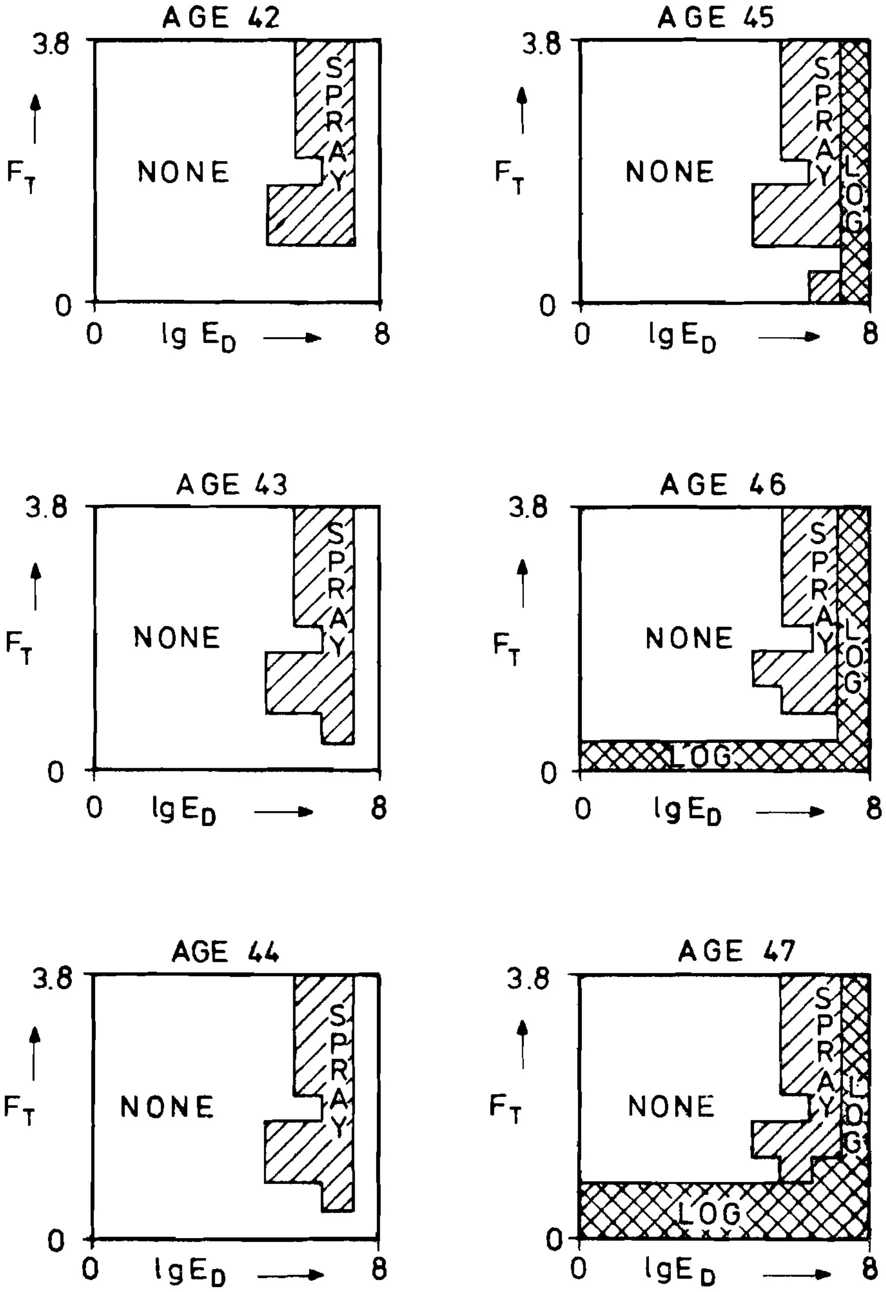


FIGURE 32: OPTIMAL CUTTING AGE VS. SELLING PRICE

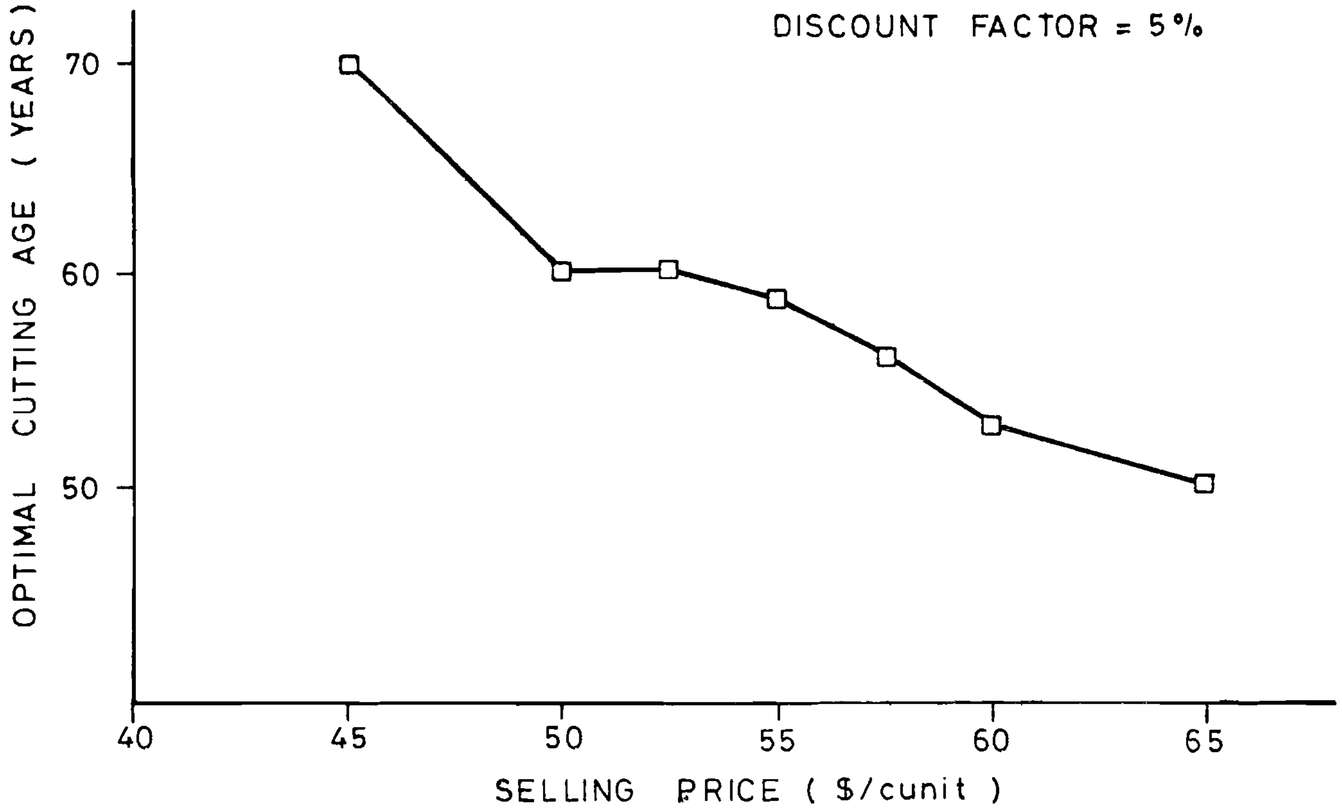
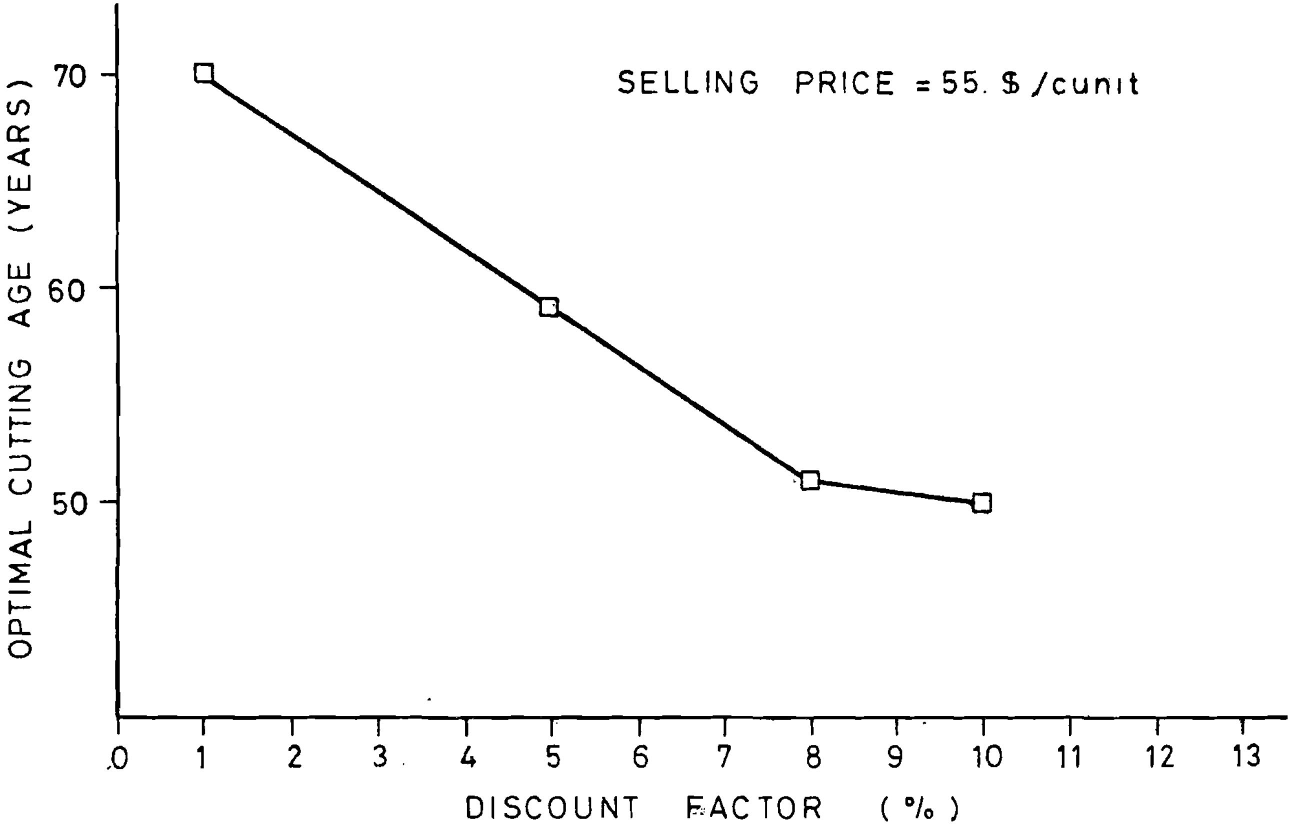


FIGURE 33: OPTIMAL CUTTING AGE VS. DISCOUNT FACTOR



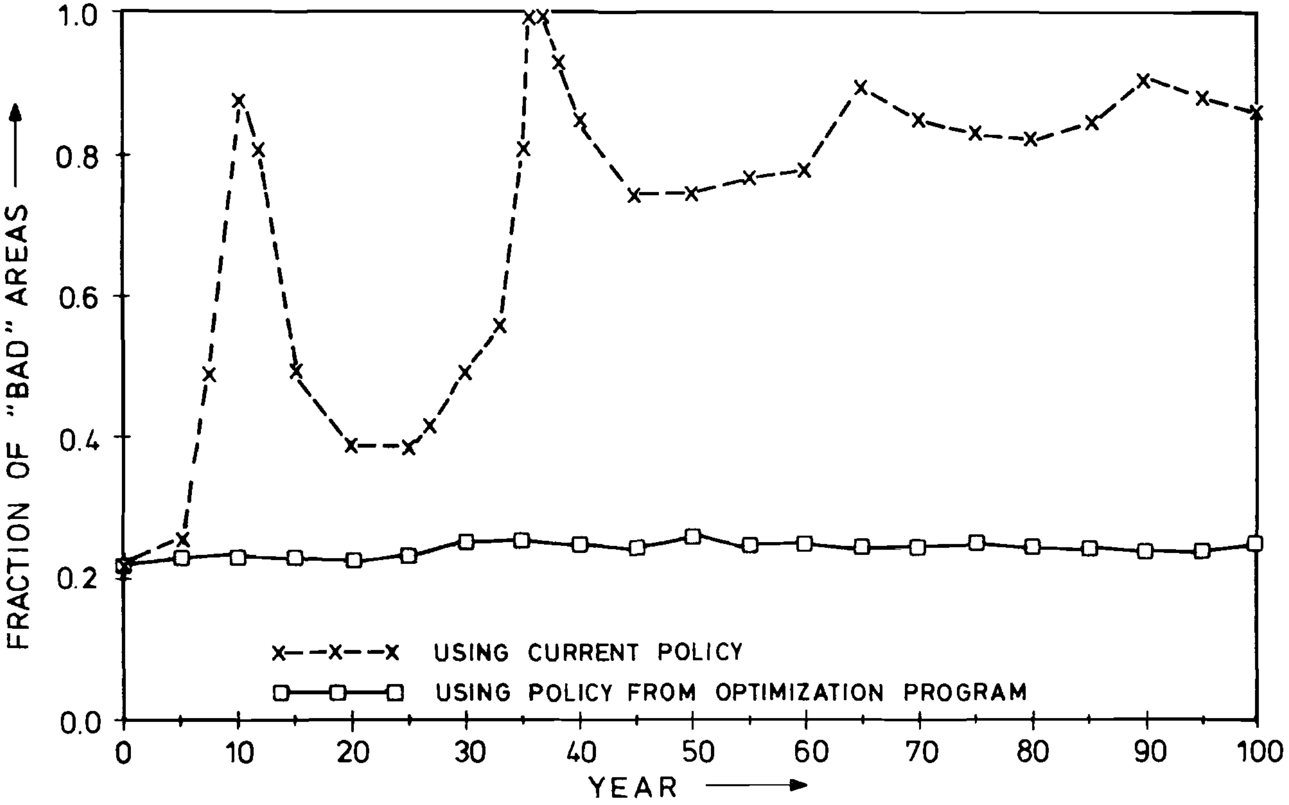


FIGURE 34:FRACTION OF "BAD" AREAS VS.YEAR OF SIMULATION

2.5.5 Compressed policy analysis

1. Justification

(a) The Winkler-Dantzig procedure, which emphasizes dynamic programming, was necessitated because of the nonlinearity of the biological system. Each forest sub-region is characterized by a manageable number of state variables, but if the forest is disaggregated into even a few sub-regions, the total number of system variables is enormous. Linear programming cannot be used, so we compromise by running an aggregated model. This gives a global optimum in a mathematical sense, but this optimum is highly local in a spatial sense.

(b) One procedure is to impose this global policy on the simulation program and then systematically to monitor the outputs and to make appropriate adjustments. But even this is very time-consuming -- a 200-year simulation run requires nine hours on the PDP 11/45. So we seek complementary descriptions of the forest ecosystem which accommodate interactive algorithms for policy generation and testing.

2. Simple approaches

(a) Regression analysis - estimate larval density by the first order autoregressive function

$$\hat{L}_{t+1,i} = a_i + b_i L_{t,i}$$

with values L_t taken from a 30,000-year run of the stand model.

	Migration				No Migration			
i	n_i	a_i	b_i	ρ_i	a_i	b_i	ρ_i	
1	7510	-1.85	.111	.240	-5.43	.191	.429	linear
2	14807	-3.41	.224	.232	-11.6	.414	.435	linear
3	7682	-4.70	.377	.252	-14.9	.576	.409	linear

The use of bivariate linear regression functions obviously should not be promoted, although estimators of higher degree might be more appropriate. A few trial fits show that quadratic functions are not significantly better.

(b) Autocorrelation analysis

Migration and No Migration peak near 50, but their characteristics support different underlying processes. The correlogram is shown as Figure 35.

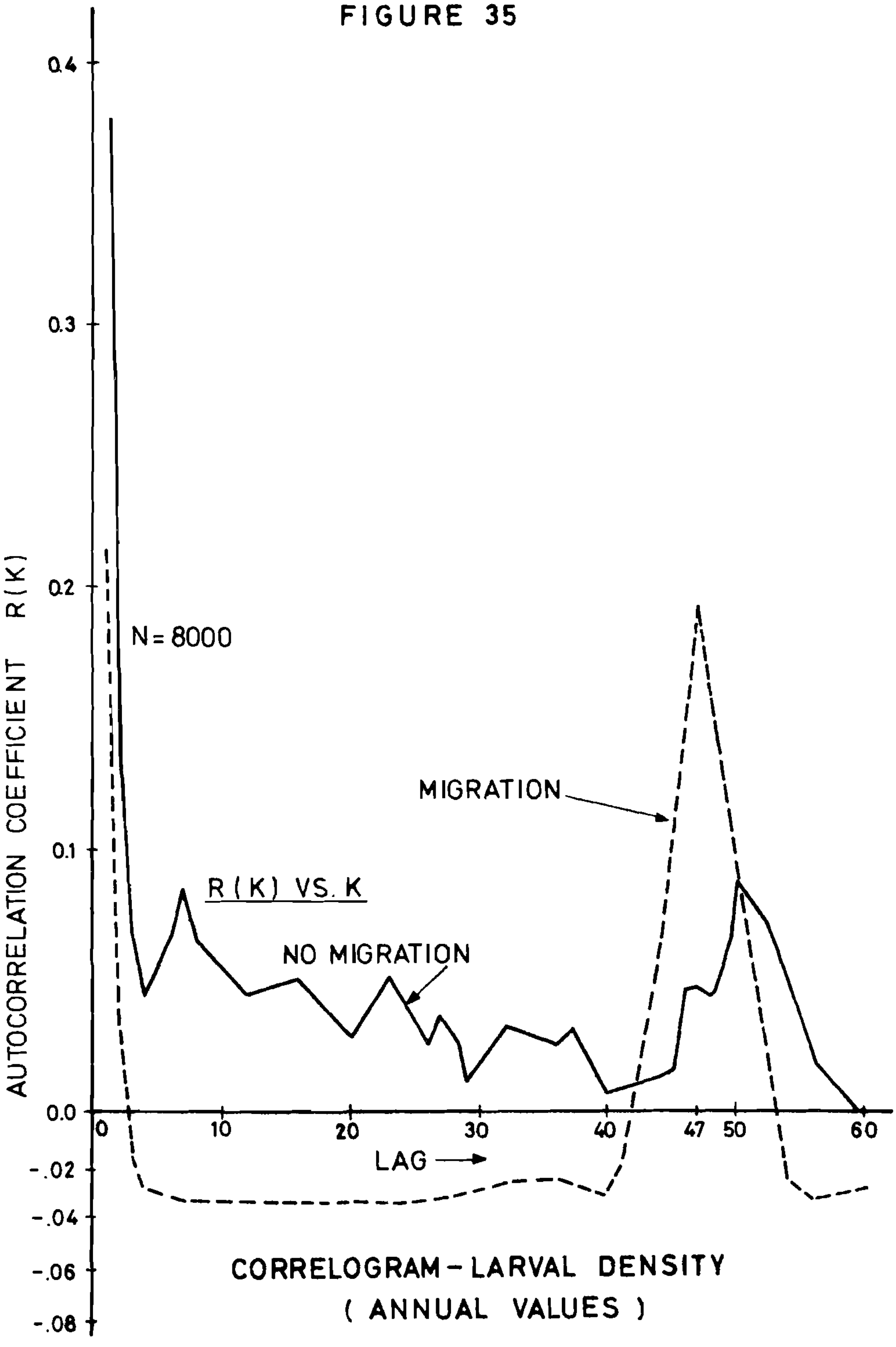
(c) Single stand Markov analysis

As a prelude to more relevant forms of policy analysis, note that policy is specified by a rule to perform one or more acts when a particular system state is attained. This gives a new Markov matrix for each policy, and a new cost. Benefits may be estimated as functions of (i) mean transition times between pairs of states, and (ii) mean detention times in states. These may be summed and discounted, then shown as net of cost (or however). This gives a preliminary formalism for ranking policies. Autocorrelation verifies applicability of single lags. Figures 36, 37, and 38 show the statistics of the consolidation of all system conditions into 8 states, and the Markov transitions between them.

3. Spatial disaggregation

(a) Consider linkages to represent the epidemiology of the system.
(b) Calculation of quasi-steady state values.
(c) These are used to re-calculate transfer and detention time.
(d) Advantages with regard to policy.
(e) Computational experience.
(f) Figure 39 shows the notation used in the policy analysis.

FIGURE 35



CORRELOGRAM – LARVAL DENSITY
(ANNUAL VALUES)

Figure 36

	1	2	3	4	5	6	7	8	
1	927	673	9	5					Endemic
2	108	6257	646	50	2				Threat
3		20	9971	599	35				Outbreak 1
4	4	7		167	198		19	445	Outbreak 2
5	3				270	148		84	Outbreak 3
6	28	7				733	642		Post-outbreak 1
7	544	98		19			3767		Post-outbreak 2
8						529		2984	Destruction

TRANSITION FREQUENCIES, 30,000 years, MIGRATION

	1	2	3	4	5	6	7	8
1	1272	719	4	11				
2	111	10886	418	1267	109			
3		41	5920	377	5			
4	16	392	1	1142	1034		13	212
5	33	272			161	842		6
6	315	425			5	686	315	
7	269	56		13			1535	
8						218		907

TRANSITION FREQUENCIES, 30,000 years, NO MIGRATION

Figure 37

	1	2	3	4	5	6	7	8
1	.574	.417	.006	.003				
2	.015	.886	.091	.007				
3		.002	.938	.056	.003			
4	.005	.008		.199	.236		.023	.530
5	.006				.535	.293		.166
6	.020	.005				.520	.455	
7	.123	.022		.004			.851	
8						.151		.849
S.S.	.054	.235	.354	.028	.017	.047	.148	.117

TRANSITION AND STEADY STATE PROBABILITIES
MIGRATION

	1	2	3	4	5	6	7	8
1	.634	.358	.002	.005				
2	.009	.851	.033	.099	.009			
3		.006	.933	.059	.001			
4	.006	.140		.406	.368		.005	.075
5	.025	.207			.123	.641		.005
6	.180	.243			.003	.393	.180	
7	.139	.030		.007			.824	
8						.194		.806
S.S.	.067	.426	.211	.094	.044	.058	.062	.038

TRANSITION AND STEADY STATE PROBABILITIES
NO MIGRATION

Figure 38

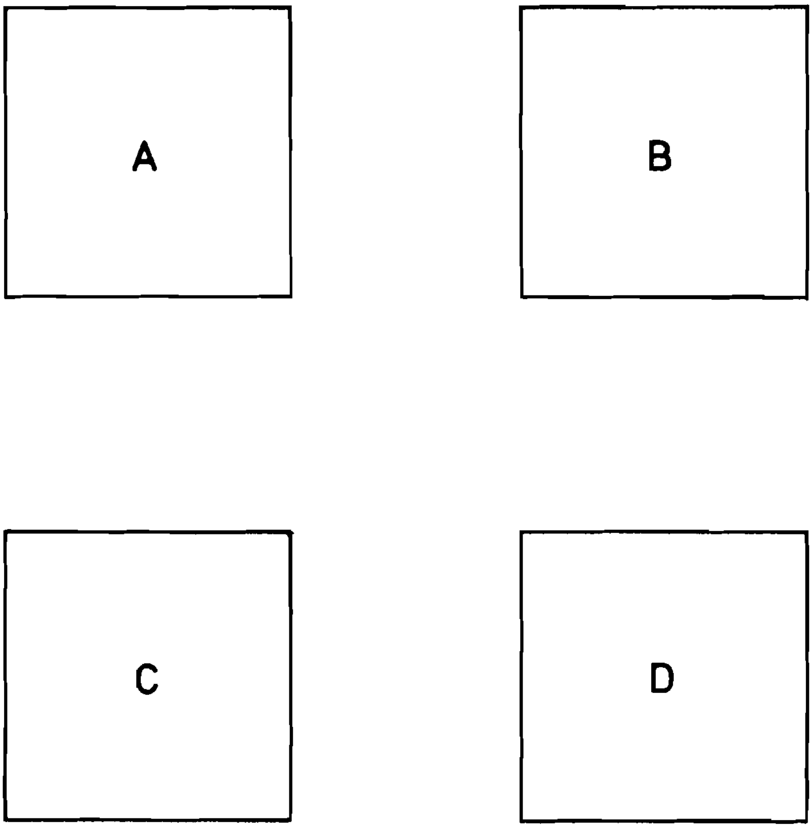
	1	2	3	4	5	6	7	8	Resid.
1	19	3	15	31	119	37	40	43	2.4
2	42	4	13	29	117	35	38	41	8.9
3	39	34	3	36	94	9	12	13	6.4
4	22	16	28	42	61	5	9	34	1.3
5	18	30	36	94	9	12	13	13	2.2
6	20	16	28	42	61	5	9	34	2.1
7	15	11	23	38	126	21	4	50	6.7
8	13	10	22	36	124	43	7	49	6.6

MEAN FIRST PASSAGE (yrs)
MIGRATION

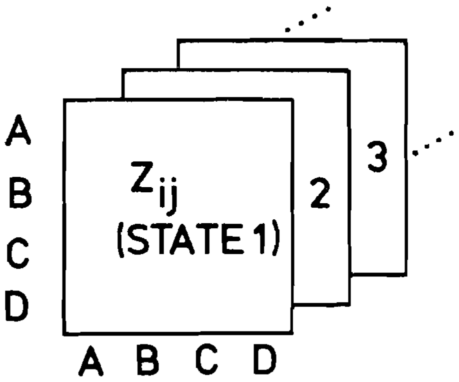
			3	4	5	6	7	8	Resid.
1	15	3	53	15	24	26	86	132	2.7
2	38	2	50	12	21	24	84	129	6.7
3	46	21	5	17	27	29	89	133	5.2
4	30	6	56	11	11	13	73	117	1.7
5	26	5	55	17	23	8	69	133	1.1
6	21	5	55	17	26	17	61	134	1.7
7	13	8	58	19	29	31	16	136	5.8
8	26	10	60	22	31	5	66	27	5.2

MEAN FIRST PASSAGE (yrs)
NO MIGRATION

FIGURE 39



SPATIAL DISAGGREGATION



WAFFLE OF LINKAGES

4. Policy manipulation

(a) Based on treating so as to move residence probabilities toward a given target vector.

(b) Pose as a 0,1 problem, where the decision is to apply act A_i in regions characterized by S_i, or not.

(c) Assumptions of ergodicity and additivity are tenable; subsequent work must prove this.

(d) Development of A_{ijk} array, and 0,1 approximation -- the influence coefficients across all states. The definition of time and transient probability levels is difficult.

(e) Weighted objective function and cost function (Figure 40).

(f) Random sampling, systematic sweetening and mathematical programming as tools for locating the optimal solution; deficiencies of the procedures.

(g) Computational experience.

Key Points

Because of the high dimensionality of the full system, it is prudent to seek compressions of system description and performance which retain the richness and variety necessary to discriminate among policies and which are sufficiently descriptive to reflect and convey ecological values, while being appropriate for simple search procedures. Elementary theory of Markov matrices provides the basis for economic valuation; this is elaborated by linkages which model spatial disaggregation. A linear model of system response is developed to identify near-optimal policies under a quadratic objective.

Figure 40

Initial residence probabilities: p_j
Final residence probabilities: p_j^*
Desired residence probabilities: π_j

Initial deviations: $\Delta_j = \pi_j - p_j$
Final deviations: $\Delta_j^* = \pi_j - p_j^*$

Budgetary constraint: c^*
Weighting factors: w_j

$$\begin{aligned} p_k^* - p_k = {} & a_{11k}\,\Delta_{1k}\,x_{11} + a_{21k}\,\Delta_{1k}\,x_{21} + \dots + a_{m1k}\,\Delta_{1k}\,x_{m1} \\ & + a_{12k}\,\Delta_{2k}\,x_{12} + a_{22k}\,\Delta_{2k}\,x_{22} + \dots \\ & \dots \\ & + a_{1nk}\,\Delta_{nk}\,x_{1n} + a_{2nk}\,\Delta_{nk}\,x_{2n} + \dots + a_{mnk}\,\Delta_{nk}\,x_{mn} \end{aligned}$$

$p_k^* - p_k = \sum_j \Delta_{jk} \sum_i a_{ijk}\,\Delta_{ij}$; this defines Δ_k^*

$$\boxed{\min \sum_k w_k\,(\Delta_k^*)^2}$$

subject to:

$$\sum_k p_k \sum_i c_{ik}\,x_{ik} \le c^*$$

$$x_{ik} = 0,1$$

$$-1 \le a_{ijk} \le 1$$

2.5.6 Generating policy alternatives

(A) Overview

- Under CPA, we discussed the general approach of policy analysis through incremental improvements on exogenously determined policies.

- At the present stage of our research we have generated a set of 6 extreme management policies for implementation on the full simulation model. The long term behavior of the forest system under each of these policies is monitored and evaluated, using the indicators, preference analysis, and statistical indices discussed earlier. Desirable aspects of each policy are isolated and used as the basis for further policy design improvement.

- We have no policy evaluation results to demonstrate at present, simply because the ecosystem simulation model plus policy rules form a package which exceeds the memory capacity of IIASA's PDP system. What we can do, however, is briefly outline the program we intend to implement on our own facilities in Vancouver.

(B) The first generation policy alternatives

(1) No management;

(2) Unconstrained stand optimization;

(3) Constrained stand optimization, where the maximum processing capacity of the existing logging industry is set externally on (2);

(4) Recreation maximization, acting as an additional constraint on (3) above;

(5) Budworm minimization, replacing the spraying policy of (3) above;

(6) Variability transformation, operated independently of (2) above; this will rely heavily upon approaches discussed under CPA.

(C) The second generation policy alternatives

- This is where we will begin to modify and integrate the six extreme policies discussed above. It is pointless to speculate at any length about anticipated results, but one example may provide some flavor of the direction the work will take.

- Preliminary analysis suggests that once policy (6) has transformed the forest system from high temporal-low spatial variability to low temporal-high spatial variability, the latter state will be relatively persistent. That is, we expect it to drift only slowly back into a time-variant system and believe this trend will be easily reversible with minor policy interventions. The system will thus be transformed from its present, delicately poised state -- artificially maintained at high spraying cost and in constant risk of massive outbreak -- into an almost self-sustaining system in which the inevitable local outbreaks fail to propagate, and thus constitute an acceptable aspect of system behavior. Once more, instead of massive investments in a fail-safe system, we will have designed one which is safe for failure.

- If these hopes for the development of variability transforming policies turn out to be justified, then the next stage of policy design will begin to test the economic and recreational policy packages described earlier on the transformed system. It is not unreasonable to suspect that the almost self-sustaining nature of the transformed system will allow us to pursue such "social benefit" policies most of the time, reverting to variability-oriented policies only as circumstances demand that the system be nudged back towards its desired long term state.

- Now, this sounds suspiciously like a case of having your cake and eating it too, but optimism isn't quite heresy even in ecology, and we find it a pleasant way to end a story.