DEMONSTRATION OF A MODEL FOR ROOT DISEASE IN B.C.: EXAMPLE SCENARIOS OF A DRY SITE

by

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FOREWORD

This report is one of a series of internal reports distributed by Forest Protection Branch, B.C. Ministry of Forests, to record accomplishments and interim or provisional results for the information of staff, colleagues, and others.

In the Canada-British Columbia Forest Resources Development Agreement (FRDA) 1985 to 1990, over 100 pest control projects were directly funded by the province and administered by protection staff. To facilitate application of the results, and development of improved forest health management strategies, the contractors reports have been edited and distributed as internal reports. Accordingly, any opinions and recommendations expressed are those of the contractor, and not necessarily those of the ministry or the FRDA management committee.

For details or more information about the report or project, please contact forest health staff at Protection Branch or at the forest region offices.

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The guidelines for internal reports outlined in the Protection Manual were adhered to as closely as possible. All manuscripts were altered to comply with a common format, but entire reports were not rewritten to conform to a standardized outline.

Most Executive Summaries were the work of Graham Hawkins of MoF Inventory Branch (formerly with Pacific Coast Forest Biology). All word processing was accomplished by Catriona Kaufman of Top Kat Services. Will Gordon of R. White Woods inc. prepared all maps and figures.

R. White, editor
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EXECUTIVE SUMMARY

The objectives of the study were to:

1. simulate control and management scenarios for a representative IDF stand in the Kamloops Forest Region;

2. develop a permanent display of the model simulations and comparison of the management options for external and demonstration use by the British Columbia Forest Service.

The PROGNOSIS root disease model of the U.S. Forest Service was used to simulate management options and disease impact for a selected representative, selectively logged mixed species (Douglas-fir leading) stand in the IDF, near Kamloops. Data on laminated root rot incidence in the Lanes Creek site were input for 12 runs of the model over a 100-year period: eight management options plus four controls. Data included a detailed stand inventory, different from both standing (leave) trees and stumps, and location and size of infection centers relative to healthy stems.

Simulated scenarios included the following:

- no management, control (no root disease), no management plus simulated budworm outbreak, clear-cutting in 20 years with lodgepole pine regeneration, removal of infected stumps followed by planting of susceptible species at lower densities, clear-cutting in 20 years with estimate of residual species, clear-cutting in 20 years with estimate of deciduous, further selective cut in 20 years, shelterwood-cut followed by natural regeneration. Mortality and stand growth and yield were output for the whole stand during each run. Further selective cut and shelterwood removal resulted in significant volume loss. Clear-cut and estimate of lodgepole pine produced a moderate merchantable volume. Spruce budworm outbreak produced no noticeable effects on root disease levels. Rotations of deciduous and residual (ponderosa pine) species also resulted in modern yields. Results were approximate: simulations of deciduous growth and yield were implied. In addition, stump removal was most effective in maximizing yields, but the model was found to be insensitive to variation in the density of infected stumps. Either the model was not realistic in this respect or the model results realistically suggest substantial losses even at low inoculum densities. A permanent display was designed and produced. The results of this model were then demonstrated for the Kamloops Forest Region, using the permanent display. This display illustrated the effects of root disease and various management options for a typical IDF stand.

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1 INTRODUCTION

1.1 Project Background

Root diseases are pervasive throughout most of the forested lands of western North America. Smith (1984) estimated that root disease cause an annual average timber loss in the western United States of almost 240 million board feet. In British Columbia alone, estimates of losses of Douglas-fir to one root disease species - *Phellinus weirii* - exceed one million cubic metres annually (Wallis 1976). Problems with root disease occur throughout the province, with coastal stands being primarily attacked by *Phellinus*, while interior stands may be subject to *Phellinus*, *Armillaria*, black stain, or *tomentosus* root diseases.

To assist silvicultural planners in managing stands with root disease infection, a team of research scientists, forest managers, silviculturalists and modelers began in 1984 to develop a simulation model of *Armillaria* spp. and *Phellinus weirii* root disease spread and effects on tree growth and mortality. Used in conjunction with a stand growth simulator, this model can help planners assess the impacts of different management scenarios on the yields of stands with root disease infection. The resulting model (completed in 1986) represents the best current understanding of root disease dynamics in western North America. Currently linked to the PROGNOSIS stand growth model, the model is now being used by silvicultural planners in the U.S. Forest Service on a pilot project basis.

Discussions during late 1987 and early 1988 with MoF staff and ESSA Ltd. indicated substantial interest in using this model in British Columbia. Interest was expressed initially in using the model to help make forest and pest managers more aware of the effects of different management activities on root disease and provide some guidelines as to how best to conduct timber management in areas of root disease infestation. Through a preliminary test application of the model, the MoF wanted to assess how useful the model was to managers, and to develop a strategy for model implementation in the MoF, based on the need for such a modeling tool. Among the side benefits of "test case" application of the model would be an indication of how much model reparameterization would be required to implement it in B.C. (the model is currently calibrated for the Inland Empire region of the western United States).

Between January and March 1988, a series of model scenarios was developed and analyzed for two *Armillaria*-infested stands located near Golden, B.C. in the Nelson Forest Region. Results of these analyses were presented and discussed at two workshops to pathologists, silviculturalists, district managers, and industry representatives. Based on the scenario results, participants at both workshops agreed that the model would be useful to the MoF in at least three ways:

a. as a tool for gaming with alternative stand management options;

b. as a tool for educating forest managers, licensees, and contractors on the problems and management of root disease (including techniques for root disease inventory); and

c. with further development, as a component in the timber supply planning process.

It was clear from the scenario results that much more model gaming and analysis was needed in order to understand more completely the dynamics of root disease impacts in B.C. stands, and in developing management guidelines. For more details on this project, see Sutherland and McNamee (1988).

1.2 Project Objectives

The objective of the project was to explore the capabilities of the root disease/PROGNOSIS model for *Phellinus weirii* root disease management through simulating a variety of control and management scenarios for a selected Douglas-fir stand infested with *Phellinus weirii* in the interior dry-belt region near Kamloops. Eight management scenarios and four control scenarios were developed and simulated for the Lanes Creek stand near Kamloops, B.C. This analysis complements the scenarios analyzed in Sutherland and McNamee (1988) because of the focus on a different root disease pathogen (*Phellinus weirii* as opposed to *Armillaria* spp.) and in a different ecosystem classification stand. The scenarios described below were presented and discussed with over 40 participants during the Forest Pest Review Committee meeting held in Kamloops, May 25-27, 1988.

2 OVERVIEW OF THE ROOT DISEASE MODEL

The root disease model (McNamee *et al.* 1987) simulates the dynamics of infection and spread of *Armillaria* spp. and *Phellinus weirii* root disease from tree to tree inside centers or patches of infection. The model uses the spatial relationships between location of inoculum patches, and the distribution, species, and sizes of trees in the stand (as well as other factors) to predict the spread of infection. Persistence of infection between stand rotations is also simulated.

The major relationships captured in the model are:

- the relative susceptibilities of trees to infection and death resulting from root disease attack;
- disease-related growth reductions;
- decay of infected root systems; and
- lifespan of root disease pathogens.

Physical or biological events that weaken or kill trees (including windthrow, and attack by pine beetles or bark beetles) can optionally be included in the simulation.

Only a brief overview of the root disease model is given below. Much more detailed descriptions of the root disease model structure, including all of the model relationships and parameters are provided in McNamee *et al.* (1987) and Sutherland and McNamee (1988).

2.1 Root Disease Model

The root disease model provides a dynamic representation of the spatial epidemiology of *Armillaria* or *Phellinus weirii* within the stand. The model is presently parameterized to reflect the best current understanding of *Armillaria* and *Phellinus weirii* epidemiology in the Inland Empire region of the western United States. These parameters can be easily adjusted to more accurately reflect particular pathogenicities and stand conditions in other areas.

The model is based on the concept that the distribution of root disease in a stand can be characterized as a number of spreading root disease centers, each of which contains both infected and non-infected trees and other inoculum sources. The disease patches are defined by their locations in the stand (spatial coordinates) and their size (radii). This structure can be used to represent the following different situations and spatial characteristics of root disease:

1. a stand with a series of discrete centers of infection which may or may not overlap;

2. a stand with scattered mortality throughout and no well-defined root disease centers. This can be considered as one large infection zone with a certain level of infected and non-infected trees and dead trees and stumps; and

3. a young stand with a large amount of inoculum from disease centers in the previous stand. This will give rise to a number of new disease centers in the regions of previous infection.

The root disease model itself is divided into the following three major submodels:

1. **Stand Interface.** This model computes the sum effects of root disease and other agent impacts on the stand growth and yield indicators;

2. **Root Disease.** This submodel computes the spread of root disease and its impact on the stand, given the nature of the host stand and management actions taken in the stand. It can simulate the dynamics of either *Armillaria* spp. or *Phellinus weirii*; and

3. **Other Agents.** This submodel computes the impact of other major sources of timber mortality in the stand which may influence root disease dynamics (e.g., insect pests, windthrow events). This submodel was not used in the scenario analysis below.

The stand growth model to which these root disease submodels are attached is responsible for simulating stand growth and mortality dynamics, and for implementing stand management actions (such as harvesting, thinning, regeneration, etc.). A brief description of the PROGNOSIS stand model (to which the root disease model is currently attached) is provided in section 2.2 below.

There are two major classes of management actions in the model (Table 1): actions that influence the nature of the forest and actions that directly influence the spread and impact of root diseases. Most of these management actions are under the control of the stand growth model itself. The root disease model implements only one management action specifically used for control of root disease - that of "pushing" or removal of infected stumps and their root systems. This option can be requested in specific years and with a factor specifying the efficiency with which roots are removed.

Management indicators are those variables which are used to evaluate the consequences of management actions on the stand and on root disease. There are two classes of indicators in the model (Table 2): indicators of the biological status of the

timber resource, and indicators pertaining to the progression and impact of the root disease itself.

2.1.1 Spatial resolution of the model

The model provides a detailed representation of timber and root disease dynamics within a single stand. This is an area ranging in size from one to hundreds of hectares, and can be considered homogeneous in terms of physical characteristics such as slope. This level of spatial resolution is most useful for silvicultural planning, and at the same time preserves the essential spatial dynamics of root diseases.

Within the modeled stand, the model maintains essentially two separate areas: those areas not currently infected with root disease (areas "outside" root disease centers), and those areas "inside" root disease infection centers. The infected portion is further disaggregated into separate circular infection centers, each characterized by the location of their centers and their radii. This spatial resolution allows expanding infection centers to be modeled as unique entities with expansion rates which can be calculated according to certain rules. In addition, the residual distribution of inoculum in the stand (e.g., after a clear-cut) can be considered, and the probability of new infection centers being initiated at various locations can be estimated.

This structure can be used to represent a wide continuum of root disease situations:

1. a stand with a series of discrete infection centers which may or may not overlap;

2. a stand with scattered mortality throughout and no discrete centers. This can be considered as one large infection zone with a certain level of infected and non-infected trees, and infected dead trees and stumps; and

3. a young stand with a large amount of inoculum from disease centers in the previous stand which will give rise to a number of new infection centers in the region of previous infection.

2.1.2 Time scale of the model

The time horizon of the model is from 80 to 300 years. Within these time frames, users can examine the effects of different management actions over one or several stand rotations.

The root disease model runs on the same time step as the stand model to which it is attached (in the case of PROGNOSIS a typical time step is 10 years). If root disease carryover from one rotation to the next is simulated (McNamee *et al.* 1987), the user must run the model in shorter time steps (e.g., five-year steps) in order to effectively

characterize disease in the new, developing stand. Particular root disease processes, such as spread rate, are simulated on an annual basis and extrapolated for the length of the model time step.

2.2 The Stand Growth Model

Underlying the root disease model is a stand growth simulation model that simulates the growth, yield, and regeneration of the stand, and implements the various management actions selected by the user (see Table 1). After the root disease model computes the impacts of root disease in infected areas of the stand for a given growth cycle, it passes measures of tree growth and mortality back to the stand model such that the state of the stand as a whole can be updated.

The root disease model is designed to be linked with any stand model that supports descriptors of trees or tree classes (including species, density, dbh, height, etc.), and which can operate on the spatial and temporal scales required by the root disease model. Currently, the root disease model is linked to the PROGNOSIS (version 5.2) stand growth model (Stage 1973; Wykoff *et al.* 1982; Ferguson & Crookston 1984).

The PROGNOSIS model is designed to project the development of mixed species, even and uneven aged stands. The model is initialized with a list of sample trees which collectively represent what the results of an inventory of that stand would be at various points through time. Information about sample trees is used in conjunction with a description of the inventory sampling design to estimate stand statistics, such as volume per unit area. Other information about sample trees (e.g., total height, crown ratio, past growth increment), and about the site of the stand (e.g., slope, aspect, elevation, and habitat type) may optionally be provided by the user. PROGNOSIS produces stand yield estimates that are weighted average effects of the various factors that influence stand growth. One or more "extensions" to PROGNOSIS can be used to explicitly include interactions between the stand and events, such as establishment of regenerating stands, pest outbreaks, and understory development. In addition, the results of PROGNOSIS runs can be evaluated by a separate economic analysis program. For further information about PROGNOSIS, see Wykoff *et al.* (1982) and references cited therein.

2.3 Using the Combined Root Disease/PROGNOSIS Model

2.3.1 Model inputs

To run the current version of the combined root disease/PROGNOSIS model, users must first describe the stand inventory through the use of a keyword system (fully described in Wykoff *et al.* 1982). Secondly, users must provide a root disease inventory for the stand such that the model can build an internal representation of diseased areas in the stand (see below). This inventory is also provided to the model in the form of

keywords. Finally, users can control the operation of the root disease model, and modify various parameter values through a number of keywords. The specific details of the keywords needed for operating the root disease model are described in detail in Sutherland and McNamee (1987).

2.3.2 Root disease inventory

To make projections for stands with root disease, the root disease model requires four types of inventory of root disease infections and extent to characterize a scenario:

1. root disease type (*Armillaria* or *Phellinus*);

2. number and location (X and Y coordinates) of root-diseased patches (centers), as well as the radius of each center;

3. density of live infected and non-infected trees (trees/ha) inside root-diseased patches (as well as the extent of infection in infected trees); and

4. characteristics of dead infected trees and stumps in root disease centers:

    - stump type (heartwood - non-heartwood)

    - dbh for the stump class

    - number of stumps represented by the stump class.

In practice, the requirements for item two above (number and location of centers) can be considerably relaxed. The user may specify all three parameters for each center (X coordinate, Y coordinate, and radius), or simply the total area in root disease and the number of centers. In the latter case, the model assumes all centers are the same size and are randomly distributed across the stand.

2.3.3 Model output

Currently, output from the root disease model displays output in tabular form summarizing conditions in the stand during the period covered by the simulation. The outputs specific to the root disease model are: a keyword summary echoing the keywords in effect for the simulation, a summary table displaying the effects of root disease inside disease centers, and a detailed table describing species-specific consequences of root disease infection on growth and mortality.

The summary output from the Root Disease Model is designed to illustrate a number of important indicators of root disease effects in the diseased areas of the stand:

1. measures of the extent of root disease infection, including the number of inoculum centers, the annual spread rate, and the total area of the stand with root disease.

2. the number of infected stumps, and the basal area of those stumps.

3. the density of trees killed by root disease in the current growth cycle and the timber volume loss represented by those trees. Note that the number of trees killed by other agents (if called) are not included here; those losses will be reflected in the stand averages summarized by PROGNOSIS.

4. the density of non-infected trees inside the disease patches.

5. the number of infected trees in the patches and the average percentage of their root systems which are infected.

6. indicators of the volume, and total basal area of live trees in diseased areas.

All the root disease summary outputs are aggregated across the tree species in the root-diseased areas. An example summary table from the Root Disease Model is shown in Table 3.

The detailed output table displays some measures of the effects of root disease on the attributes of each tree species in diseased areas. At stand inventory, and at the end of each cycle, the numbers of trees killed during that cycle, and the numbers of alive non-infected, and alive infected trees are displayed. In addition, the five percentile classes for three dbh are presented, along with the size of the largest tree in the class, for both the trees killed and live trees. This is intended to illustrate species-specific growth effects in the root-diseased areas of the stand.

3 MANAGEMENT SCENARIOS

3.1 Introduction

For stands infected with root disease many possible silvicultural and harvesting options exist depending on the management phase of the stand (e.g., planting, spacing, commercial thinning, harvesting), the desired goals for root disease control (e.g., spread reduction, tree mortality reduction, site rehabilitation), and the expected cost/benefit relationships for the various options (Morrison 1981). Some of the stand management options currently in use for diseased stands, or under preliminary assessment by the MoF are:

- stump removal after harvest;
- chemical treatment of stumps;
- plant an alternative rotation of hardwoods;
- clear-cutting;
- spacing or selective logging.

Other options, such as fertilization of regenerating stands and pushover logging in suitable stand types are in experimental phases of assessment.

3.2 Scenario Descriptions

Out of the many possible stand management scenarios suggested by the above list, the project team chose the following for analysis (Table 4):

- no management (scenarios 1-3);
- clear-cutting (part of scenarios 4-7);
- stump removal after harvest and plant the most desirable species at a reduced stocking density (scenario 4a);
- plant a less susceptible species (scenario 6);
- plant an alternative rotation of hardwoods (scenario 7);
- spacing or selective logging (scenarios 8-11).

A total of 12 runs of the model were made: eight "management" scenarios on a diseased stand and four "control" scenarios where equivalent management actions were taken in a non-diseased stand (see Table 4). Taken together these scenarios allow each management action in diseased stands to be compared with either its complement in a non-diseased stand (to see the comparative effects of root disease impact), or to compare the management actions against a preferred option to assess the relative benefits of alternative actions.

Each scenario was run on the Lanes Creek stand (see its description below) for 100 years (1987-2087). The inventory year used to initialize the model was 1987. For these scenarios, management actions (if any) were taken 20 years after inventory (i.e., in 2007) to give the initial conditions for root disease time to equilibrate in the stand.

Note that one scenario (scenario 3) was designed to examine the interaction of two pests (spruce budworm and root disease) in an unmanaged stand. The two budworm outbreaks were simulated by adjusting growth and mortality parameters via PROGNOSIS keywords; the root model was run as normal.

Natural regeneration was simulated with the Regeneration Establishment Extension to the PROGNOSIS model (Ferguson & Crookston 1984). This model stocks new trees in the stand at user-defined intervals based on the current stand description (including habitat type), and silvicultural prescription; such stocking can be scheduled several times. For these model runs, regeneration establishment was scheduled only once: the year after the clear-cut or other management disturbance, although the Regeneration Establishment Model can be called more often. This reduces the confounding effects of different densities resulting from different treatments. However, it likely underestimates expected tree densities in the new stand. As well, the regeneration model (like PROGNOSIS) is calibrated for the Inland Empire region of the U.S. Thus, the species mix of regenerating trees may only approximate the actual mix that would occur in the example stands.

For all runs involving regeneration establishment, site preparation procedures were: mechanical scarification (27% of stockable plots), burning (30% of stockable plots), and no preparation (the remaining plots). Tallies to measure regeneration were scheduled for five and 15 years after the date of disturbance.

3.3 Description of the Stand

3.3.1 Stand inventory

The Lanes Creek stand is located north of Kamloops and is a mixed species, mixed age IDFa stand (Figure 1), infected with *Phellinus weirii* root disease. The stand has had management in the past: it was selectively logged in 1958. The stand inventory used in this study was carried out in the winter of 1987 (Table 5). Currently,

approximately 120 years old, the stand is dominated by Douglas-fir, with spruce and minor birch components (birch was ignored in the simulations). A detailed inventory of the sample trees in the stand is provided in Table 6. Site index and habitat type characterizations of the stand were made by MoF in Kamloops in conjunction with the ESSA project team.

3.3.2 Root disease inventory

The root disease inventory for the Lanes Creek stand was done in the spring of 1988 (Table 7). Two line intercepts (each 600m in length) were run through the stand parallel to each other and 50m apart; stems were counted 25m on either side of the lines. Two root disease centers (1.12ha and 0.75ha in size) were found from this survey. Infected trees were identified from crown symptoms and from increment bores. Infected stumps (standing dead, or stumps remaining from harvest activities) were identified by eye, or by taking samples from the outer layers.

3.4 Scenario Results and Discussion

Output from the model runs were translated from the summary tables (e.g., Table 3) into time series graphs of the most important indicators of stand yield, growth and root disease infection (see Appendix A for the complete set of output graphs). All stand growth and yield values indicated are for the stand as a whole; no attempt was made to separate stand attributes inside and outside root disease patches.

3.4.1 Stand growth and yield

Indicators of stand volume (Figure 2) and mean annual increment (MAI: Figure 3) showed similar qualitative trends for all scenarios. Overall, management options 4a (clear-cut/stump removal/replant with Douglas-fir at 1 200 stems/ha) and six (clear-cut/replant with a less susceptible species (Ponderosa pine)) yielded the highest merchantable stand volumes after 80 years of growth in a *Phellinus*-infested stand (Figure 3.2). The stump removal option was able to eradicate root disease from the clear-cut stand well before any mortality could accrue to the new stand (see below); thus the yield estimates for the regenerated stand are those expected in a stand free from root disease. As a less susceptible species, Ponderosa pine is only 25% as likely as Douglas-fir to become infected with *Phellinus* upon root contact in the model, and will take three times as long to be killed by the disease as fir trees of similar size. Given its growth characteristics in the model, it is attractive as an alternative plantation species.

Management scenarios 8 (selective cut from below), and 10 (shelterwood removals) yielded stand volumes from 33-39% lower than scenario 41, and 53-57% lower than scenario 6. In scenarios 8 and 10, the stand loses a significant portion of its expected production (over 30%) to the impacts of *Phellinus* persisting in the stand (compare the

final volumes of scenario 8 with 9, and 10 with 11 in Figure 3.2). The losses due to root disease are roughly comparable to those observed in the "no management" scenario (scenarios 1 and 2; Figure 2). These management options (as well as the no management option) leave large numbers of infected stumps in the stand. Because none of the cuts were severe enough to break contact between adjacent root systems, and because *Phellinus* infection is assumed to persist in stumps after death (see below), mortality rates due to root disease after the cut is heightened, and remains relatively high until the end of the rotation.

Management option 4 (clear-cut/replant with lodgepole pine at 1 600 stems/ha) produced a moderate level of merchantable volume. The susceptibility of lodgepole pine to *Phellinus* infection in the model is similar to that of Ponderosa pine (see above). However, its growth rates on the modeled habitat type is substantially less, and there was still a 16% volume loss due to root disease impact (compare scenarios 4 and 5 in Figure 2).

Surprisingly, planting a hardwood (simulated birch) produced only moderate yields in these runs. Because birch is not one of the 11 species for which the version of PROGNOSIS we used has growth and mortality parameters, we simulated birch as follows:

a. birch growth and mortality were estimated using the growth equations for mountain hemlock; and

b. birch was assumed to be 25% as likely as Douglas-fir to become infected on root contact, and birch was assumed to take 10 times as long to be killed as Douglas-fir of similar size.

Therefore, this result should be treated with caution: the sample data used to characterize growth of birch (mountain hemlock - see above) are very small in this habitat (Stage, personal communication) and may be unreliable.

The simulated budworm outbreaks in an unmanaged stand with root disease (scenario 3) caused a 22% reduction in final stand volume (Figure 2). No noticeable effects from this additional mortality were observed on the amounts of inoculum in the stand, or on the spread of root disease (see Appendix - Figures A7 and A8).

3.4.2 Root disease control

How well do the alternative management actions control *Phellinus* infection in the stand? Table 8 shows two measures of root disease infection at the end of each scenario for those eight management options that were run with root disease established in the stand at inventory. In general, the clear-cut and replant management options (scenarios 4-7) show lower spread of disease, and allow lower inoculum levels

(except scenario 7) than do either the "no management" (scenario 1) or selective cutting options (scenarios 8 and 10).

Scenario 4a (stump removal) was the only scenario to completely remove *Phellinus* root disease from the stand. This scenario was run with a root removal effectiveness of nearly 100%, which is a likely overestimate of the true effectiveness rate (probably between 75% and 95% for the normal stumping practice: Merler, personal communication). However, despite this, it is likely that there would have been negligible impacts from *Phellinus* in the new stand even with a lower stump removal effectiveness because of the length of time between the clear-cut/stump removal and root closure in the regenerating stand. Little inoculum would remain to contact and infect the new root systems.

Compared with inventory conditions, all scenarios (other than scenario 4a) show an increase in root disease area by the end of the simulations, but a decline in inoculum levels (see Appendix - Figures A7 and A8 for more detailed time-series of these indicators). These results highlight two important characteristics of the behavior of *Phellinus* infection in the model. First, and most important, the model is not very sensitive to the initial density of infected *Phellinus* stumps - in all scenarios inoculum density dropped to a fraction of the initial inventory within three growth cycles (Appendix - Figure A8). Thus, most of the cumulative growth and mortality effects of *Phellinus* infection in the new stand occurred under conditions of low densities of infected stumps (between two and ten square metres/ha). Higher inoculum levels may have high impacts (e.g., see Appendix - Figure A4 for MAI estimates), but the model results suggest that substantial losses will occur at even low inoculum densities. This highlights the need to be able to detect and inventory even low levels of *Phellinus* infection in stands, and manage them accordingly).

Secondly, *Phellinus* inoculum is assumed to have a 20-year minimum life span before it begins to decay away (McNamee *et al.* 1987). Again, Appendix - Figure A8 shows the effect of this 20 minimum on the dynamics of the inoculum (inoculum densities begin to drop rapidly after 20 years of the start of the model). This means that *Phellinus* infection is very persistent in stands, and that any management strategy that can leave infected stumps of any size where uninfected root systems can contact them (especially in any sort of selective logging regime) risks substantial yield losses to disease, and offers little chance of disease control in the next rotation.

4 REFERENCES

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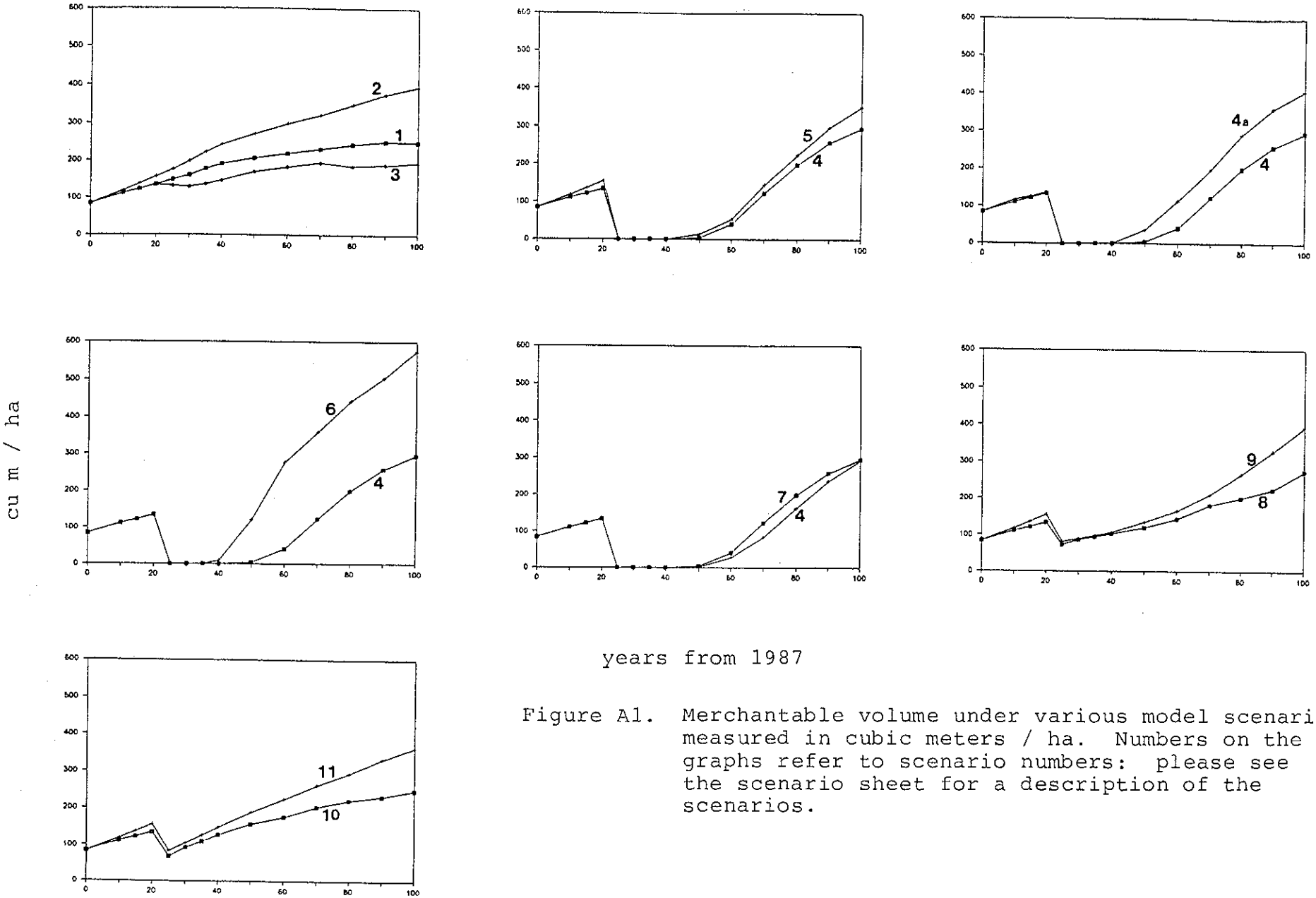

Figure A1. Merchantable volume under various model scenarios, measured in cubic meters / ha. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

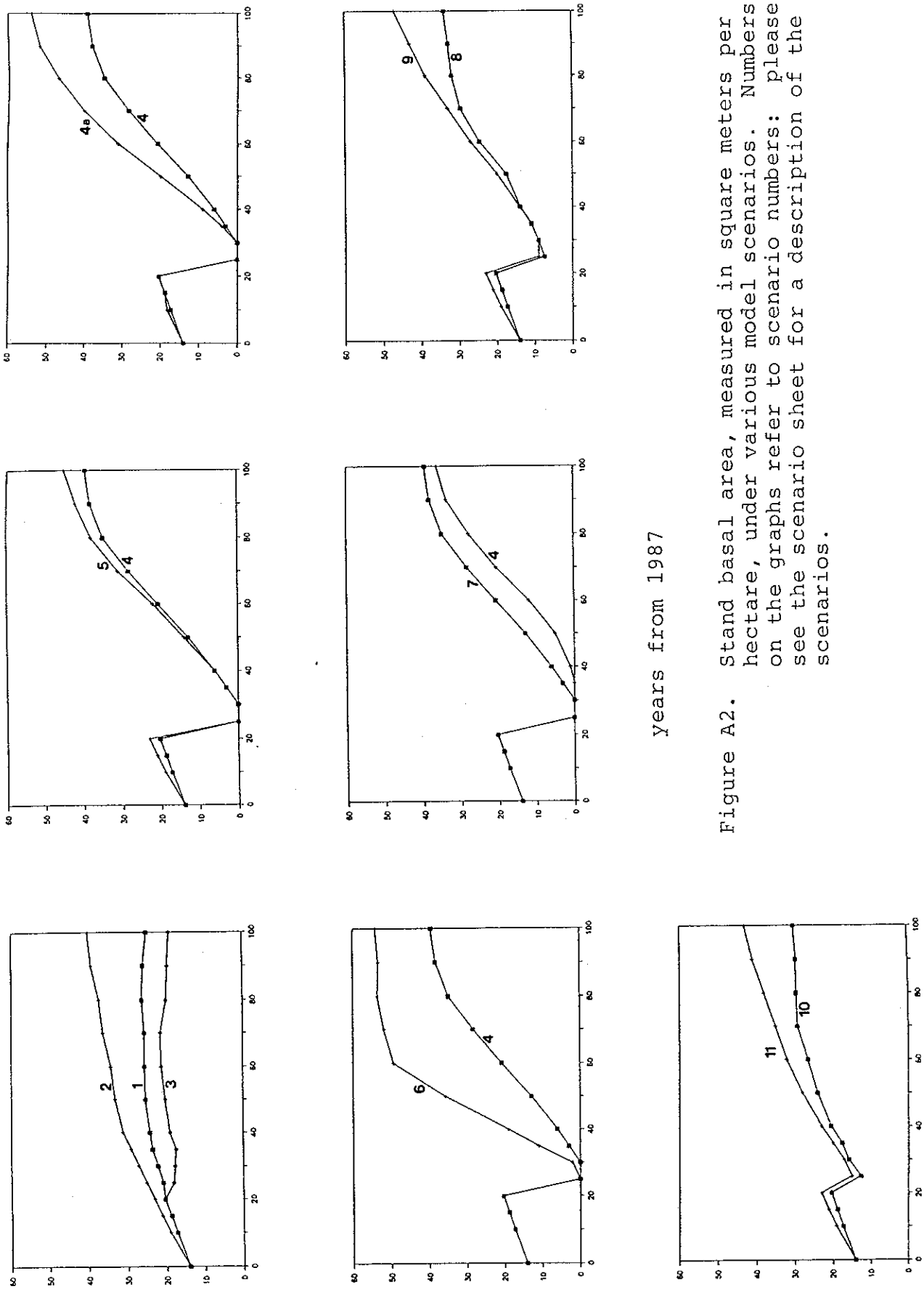

Figure A2. Stand basal area, measured in square meters per hectare, under various model scenarios. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

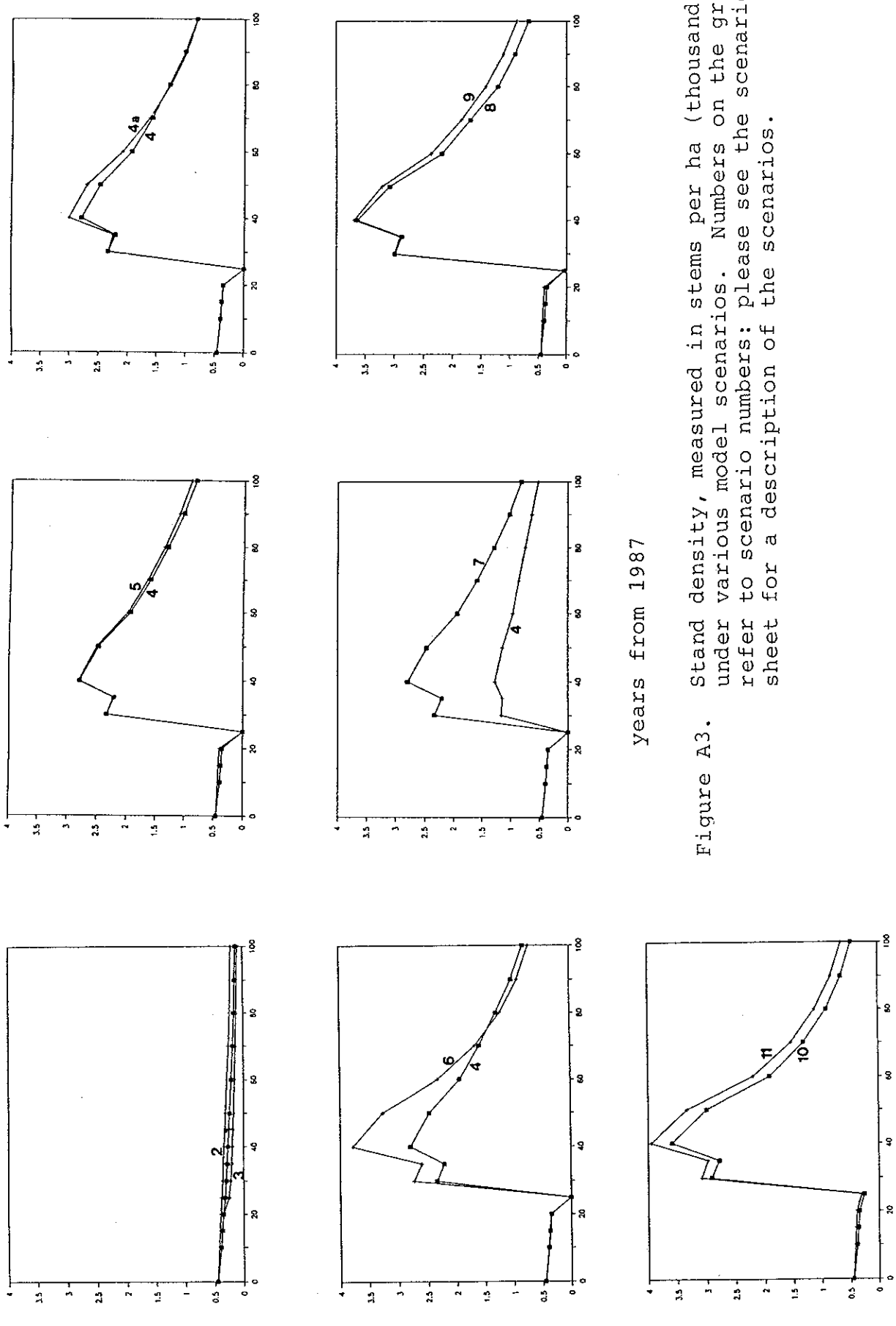

Figure A3. Stand density, measured in stems per ha (thousands), under various model scenarios. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

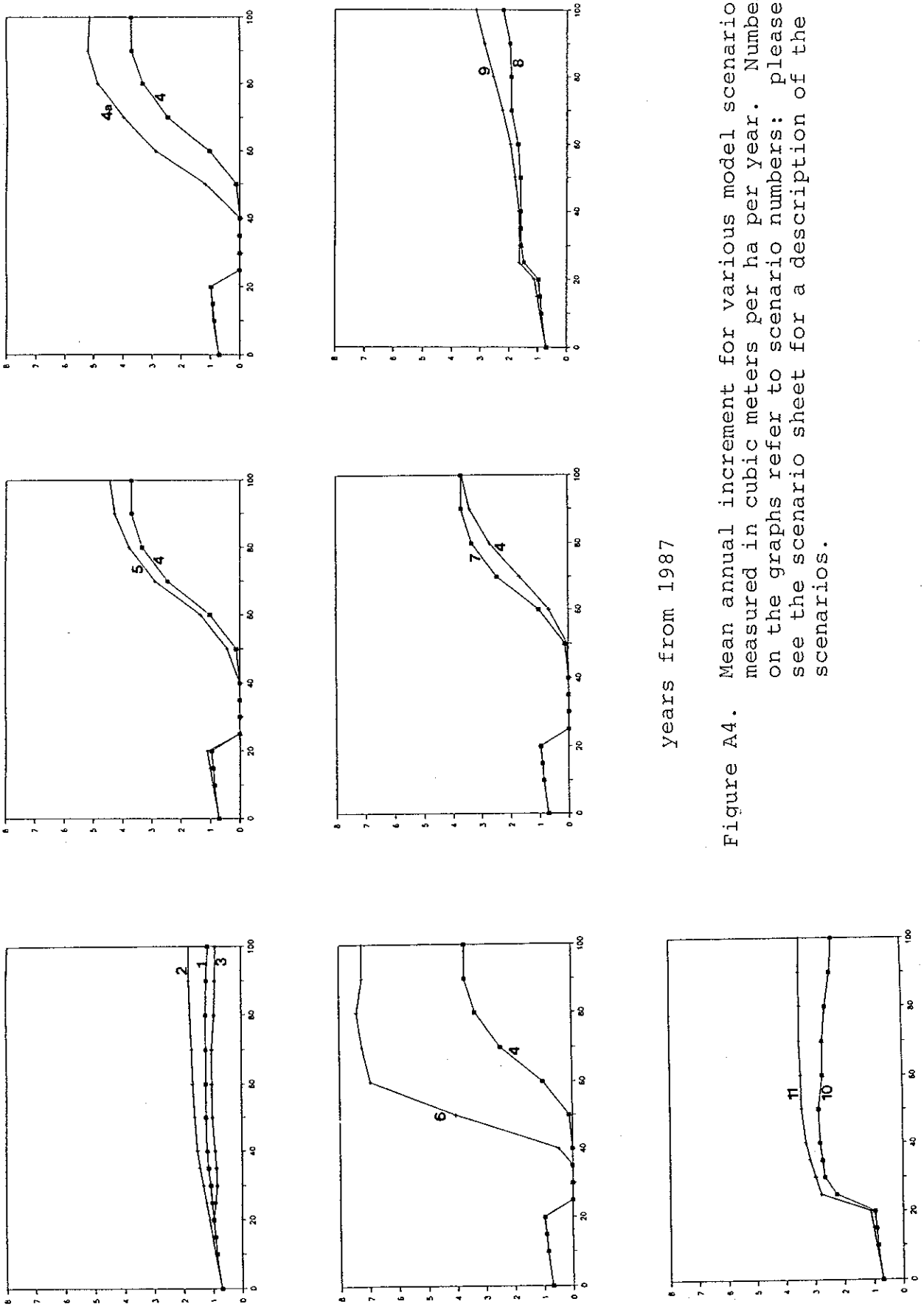

Figure A4. Mean annual increment for various model scenarios, measured in cubic meters per ha per year. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

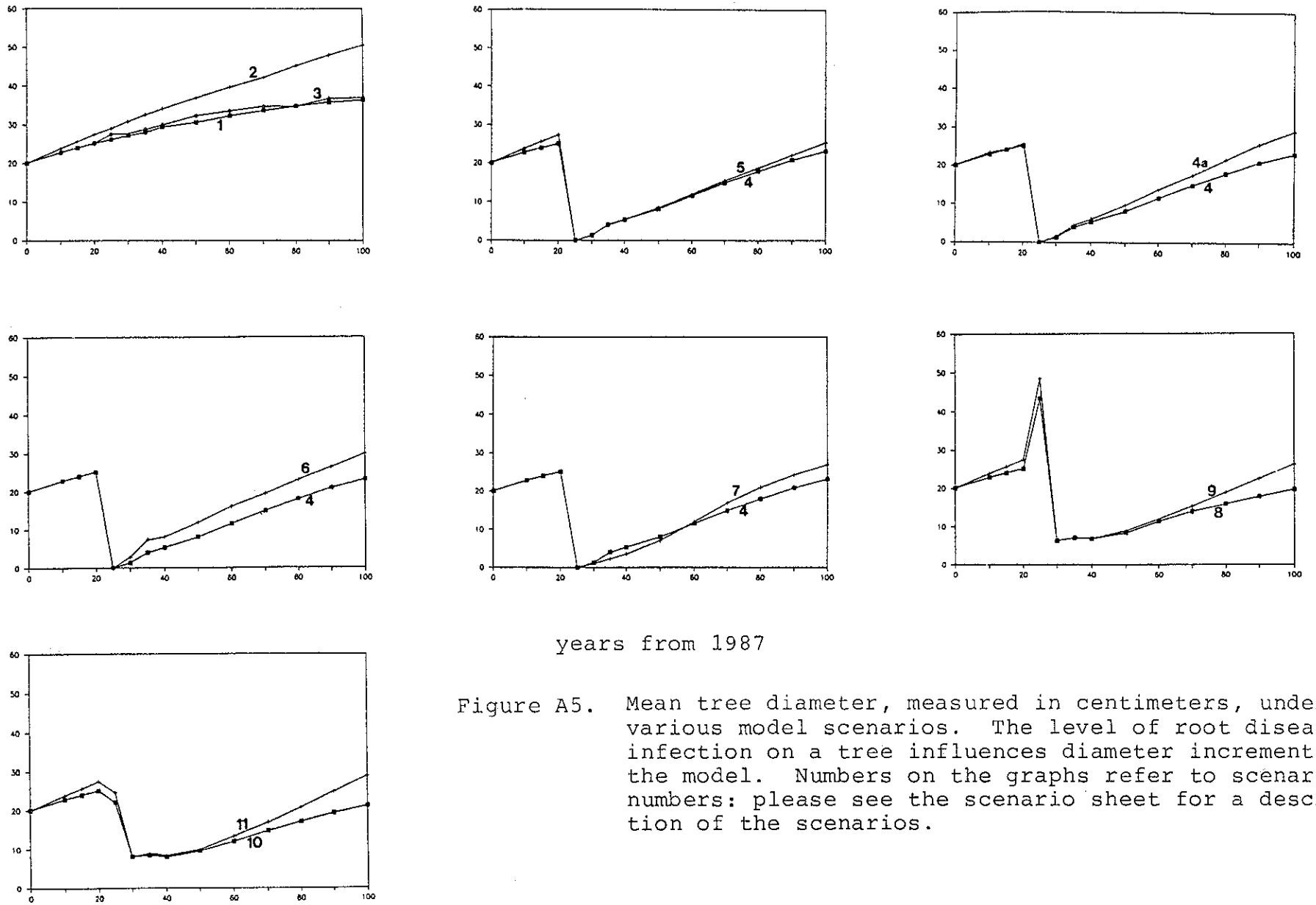

Figure A5. Mean tree diameter, measured in centimeters, under various model scenarios. The level of root disease infection on a tree influences diameter increment in the model. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

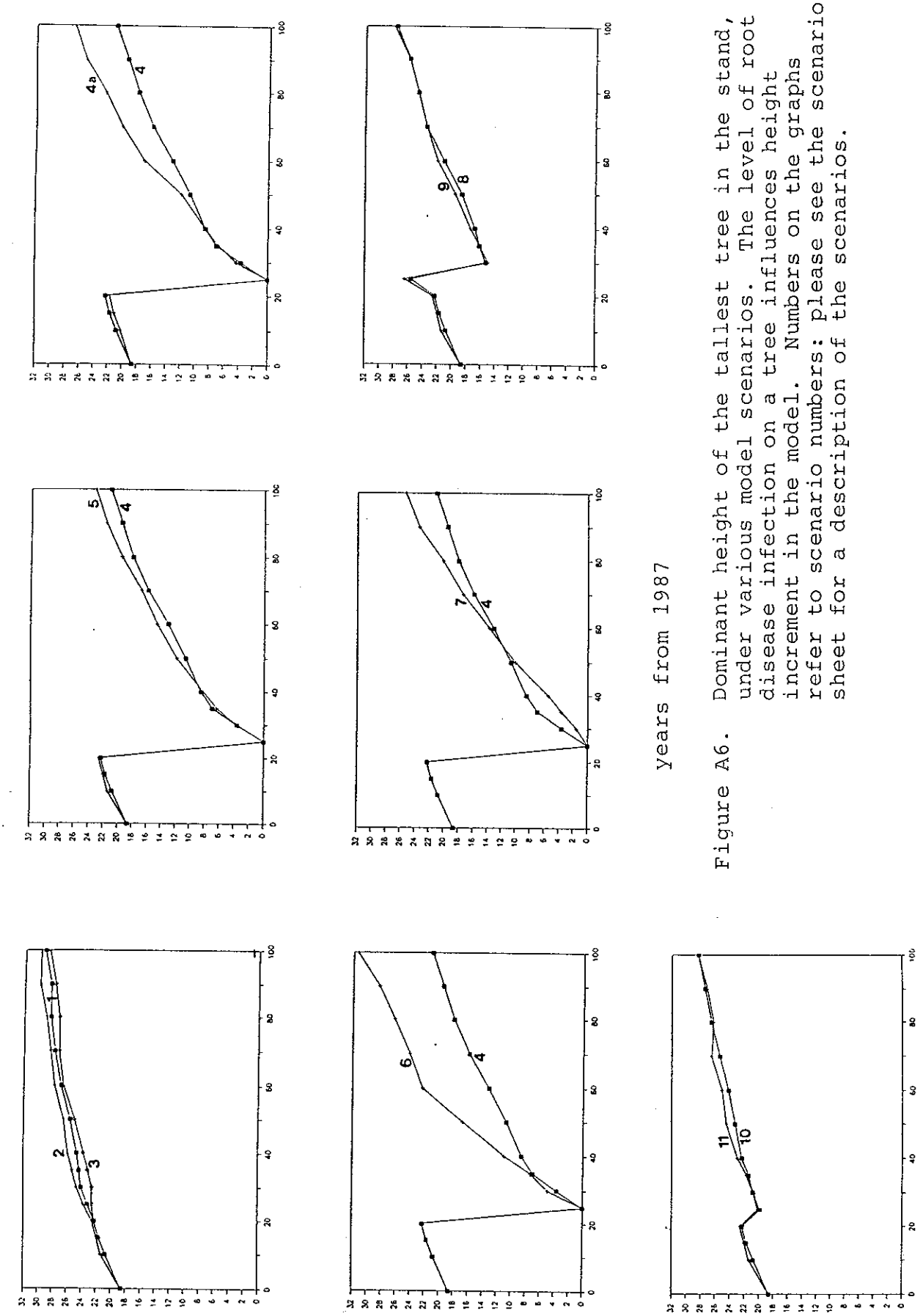

Figure A6. Dominant height of the tallest tree in the stand, under various model scenarios. The level of root disease infection on a tree influences height increment in the model. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

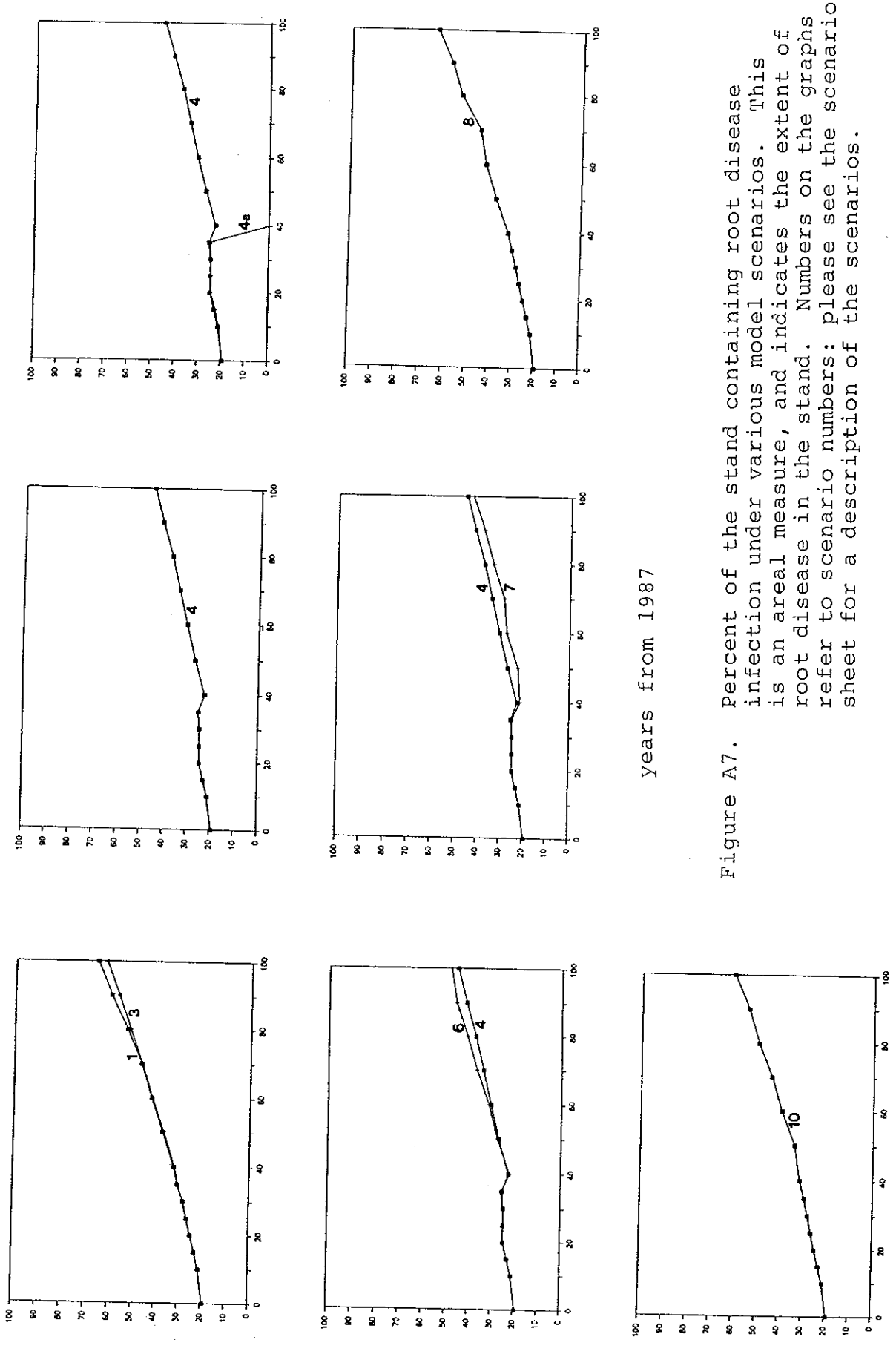

Figure A7. Percent of the stand containing root disease infection under various model scenarios. This is an areal measure, and indicates the extent of root disease in the stand. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

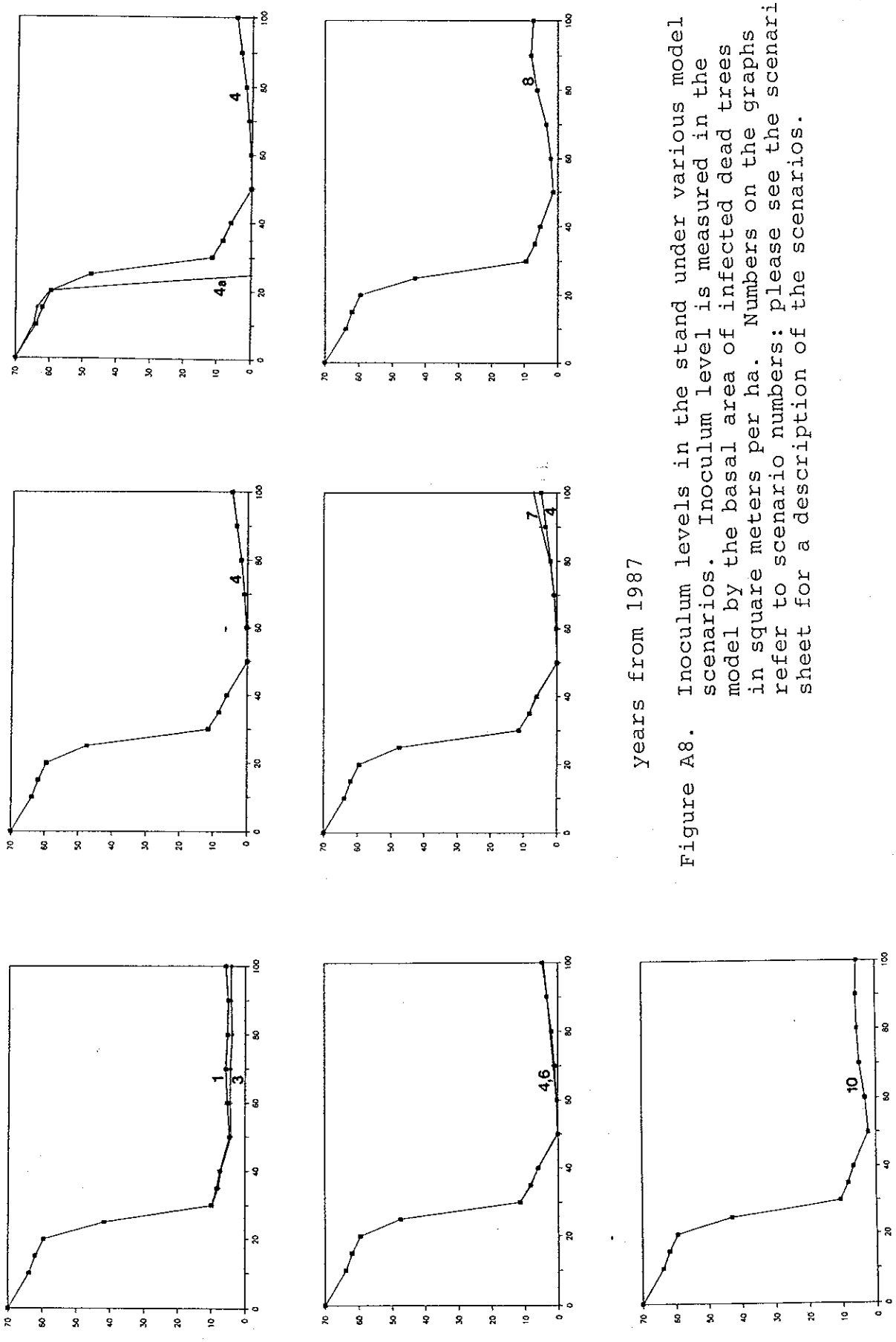

Figure A8. Inoculum levels in the stand under various model scenarios. Inoculum level is measured in the model by the basal area of infected dead trees in square meters per ha. Numbers on the graphs refer to scenario numbers: please see the scenario sheet for a description of the scenarios.

TABLE 1 MANAGEMENT ACTIONS FOR THE STAND AND FOR ROOT DISEASE

A. SPECIES MANIPULATIONS

- shelterwood
- clear-cut, plant species
- clear-cut without planting
- selective thinning
- understory fire
- seed source selection
- fire management
- sanitation cutting
  - diseased trees
- site preparation
  - burning
  - fertilization
  - scarification

B. DIRECT ROOT DISEASE TREATMENT

- stump removal

TABLE 2 MANAGEMENT INDICATORS FOR THE MODELED STAND AS A WHOLE AND FOR ROOT DISEASED AREAS

A. STAND

- sample tree attributes
  - growth rate
  - mortality rate
  - height
  - diameter
  - volume
- stand attributes
  - periodic annual increment
  - volume
  - species composition
  - diameter distribution
  - basal area
  - tree height
  - stand density

B. ROOT DISEASE

- area infected
- number of infected stumps/unit area, by diameter class and species
- spread rate
- number of trees killed
- volume of wood killed
- number of root disease centers
- basal area inside root diseased area
- wood volume inside root diseased area
- density of infected and uninfected trees inside root diseased areas

TABLE 3 **AN EXAMPLE OUTPUT TABLE FROM THE ROOT DISEASE MODEL (Note that the units are in imperial measure [not metric]. Shown is the summary output table for Scenario 4 for the Lower Creek stand)**

ROOT DISEASE MODEL VERSION 1.0
SUMMARY STATISTICS FOR ROOT DISEASE AREAS

		Disease Statistics			Dead Tree Characteristics				Live Tree Characteristics								
					Stumps		Losses from Disease		Uninf.	Infected		Overall					
Year	Age	No. of Cents	Disease Area Acres	Spread Rate Ft/Yr	Total/ Acre	Ba/ Acre Sq Ft	No. of Trees Killed	Volume Losses Cu Ft/ Acre	No. of Trees/ Acre	No. of Trees/ Acre	Ave. % Roots Infected	Merch. Cu Ft/ Acre	Ba/ Acre Sq Ft	Identifiers			
														Stand	ID	Mgmt	ID
1987	120	2	1.91	.00	174.	305.	0.	0.	131.	52.	80.0	1203.	62.	Lane	Crk	RN04	
1997	130	2	2.10	.70	223.	278.	63.	252.	79.	34.	62.9	1499.	67.	Lane	Crk	RN04	
2002	135	2	2.23	.95	230.	270.	24.	391.	58.	33.	48.2	1368.	59.	Lane	Crk	RN04	
2007	140	2	2.48	.86	227.	259.	13.	235.	43.	38.	50.7	1377.	58.	Lane	Crk	RN04	
2012	145	2	2.48	.00	107.	207.	0.	0.	0.	0.	0.	0.	0.	Lane	Crk	RN04	
2017	10	2	2.48	.00	75.	50.	0.	0.	946.	0.	.0	0.	1.	Lane	Crk	RN04	
2022	15	2	2.52	.47	56.	36.	8.	1.	888.	0.	.0	0.	12.	Lane	Crk	RN04	
2027	20	100	2.26	.66	54.	26.	12.	1.	1116.	4.	44.8	0.	26.	Lane	Crk	RN04	
2037	30	100	2.68	.54	61.	0.	45.	17.	954.	7.	62.9	52.	54.	Lane	Crk	RN04	
2047	40	100	3.04	.60	73.	1.	33.	46.	761.	10.	53.9	560.	86.	Lane	Crk	RN04	
2057	50	100	3.89	.66	65.	4.	34.	110.	578.	18.	46.4	1658.	117.	Lane	Crk	RN04	
2067	60	100	3.76	.70	61.	8.	28.	150.	447.	31.	50.4	2650.	137.	Lane	Crk	RN04	
2077	70	100	4.15	.50	62.	14.	33.	294.	328.	41.	49.4	3330.	146.	Lane	Crk	RN04	
2087	80	100	4.54	.74	63.	20.	28.	343.	245.	44.	49.6	3719.	146.	Lane	Crk	RN04	

TABLE 4 SCENARIO DESCRIPTIONS FOR THE LANES CREEK STAND (Scenario numbers in this table match the numbers used on the model output graphs)

Management Scenario	Control Scenario
1 • simulation of inventory conditions • no management • root disease	2 • same "management" as 1 • no root disease
3 • simulation of inventory conditions • no management • root disease • simulated budworm outbreaks on Douglas-fir in 2007-2012 and in 2057-2062, causing 70% reduction in dbh growth, 30% reduction in height growth, and 100% mortality to trees less than 15cm dbh	• compare with scenarios 1 and 2
4 • clear-cutting in 2007 • regeneration with planted lodgepole pine at 1 600 stems/ha in 2008 • natural regeneration • root disease	5 • same management as 4 • no root disease
4a • clear-cutting in 2007 • complete removal of infected stumps in 2007 • regeneration with planted Douglas-fir at 1 200 stems/ha in 2008 • natural regeneration • root disease	• compare with scenario 4

6
- clear-cutting in 2007
- regeneration with planted ponderosa pine at 1 600 stems/ha in 2007
- natural regeneration
- root disease

- compare with scenario 4

7
- clear-cutting in 2007
- regeneration with planted birch at 1 600 stems/ha in 2008
- natural regeneration
- root disease

- compare with scenario 4

8
- selective cut from below to 50% volume reduction in 2007
- natural regeneration
- root disease

9
- same management as 8
- no root disease

10
- shelterwood cut (thin from above down to 12.5cm dbh) in 2007
- natural regeneration
- root disease

11
- same management as 10
- no root disease

TABLE 5 STAND DESCRIPTION FOR THE LANES CREEK STAND

Attribute	Condition
Inventory Year	1987
Stand Age	120 years
Elevation	900m
Slope	3%
Aspect	SE
Stand Area	10ha
Habitat Type (U.S.)	*Pseudotsuga menziesii/ Calamagrostis rubescens*
Basal Area	62 square meters/ha
Stand Density	452 stems/ha

TABLE 6 SAMPLE TREE INVENTORY FOR THE LANES CREEK STAND (This inventory was taken in Winter 1987)

Species	Height (m)	10 Year Inc. (cm)	Age (year)	DBH (cm)	Density (stems/ha)
Douglas-fir	27.0	1.8	99	41.6	30.0
Douglas-fir	20.6	4.3	44	36.3	38.0
Douglas-fir	15.8	2.8	97	23.9	71.3
Douglas-fir	14.6	2.8	103	34.0	71.3
Douglas-fir	11.8	3.8	27	20.3	9.5
Douglas-fir	5.0	2.8	15	6.6	124.0
Spruce	29.3	2.8	n/a	46.5	10.0
Spruce	16.5	1.8	83	23.9	14.0
Spruce	15.3	1.0	80	22.1	14.0
Spruce	5.0	2.8	15	6.9	72.0

TABLE 7 ROOT DISEASE INVENTORY DESCRIPTIONS FOR THE LANES CREEK STAND
(This inventory was collected in the spring of 1988. Note the stumps are considered only as trees infected with root disease at the time of death.)

Attribute	Condition
Primary Root Disease	*Phellinus*
Stand Area Infected	1.87ha (18.7%)
No. of Initial Centers	2
Percentage of Trees Infected in Centers	29%
Stump Density in Centers	72/ha
Stump Basal Area	70 square meters/ha
Average Root Infection on Infected Trees	80%

TABLE 8 TWO INDICATORS OF *PHELLINUS* ROOT DISEASE IMPACT IN THE LANES CREEK STAND FOR THE EIGHT SCENARIOS IN WHICH ROOT DISEASE WAS INCLUDED IN THE SIMULATIONS
(Values are for the last year of the simulation (year 2087). Scenario numbers are those described in Table 4.)

Scenario	Percentage of Stand Area with Root Disease	Basal Area of Infected Stumps (cu m/ha)
1	65.4	5.74
3	61.7	4.13
4	45.4	4.59
4a	0	0
6	48.2	4.13
7	42.7	6.89
8	63.5	7.35
10	60.2	5.51

FIGURE 1 **CURRENT (WINTER 1987) DENSITIES OF STEMS BY DBH AND SPECIES IN THE LANES CREEK STAND**
(There are dominant, co-dominant, and understory components to the stand. Ages for sampled trees range from 15 to 103 years.)

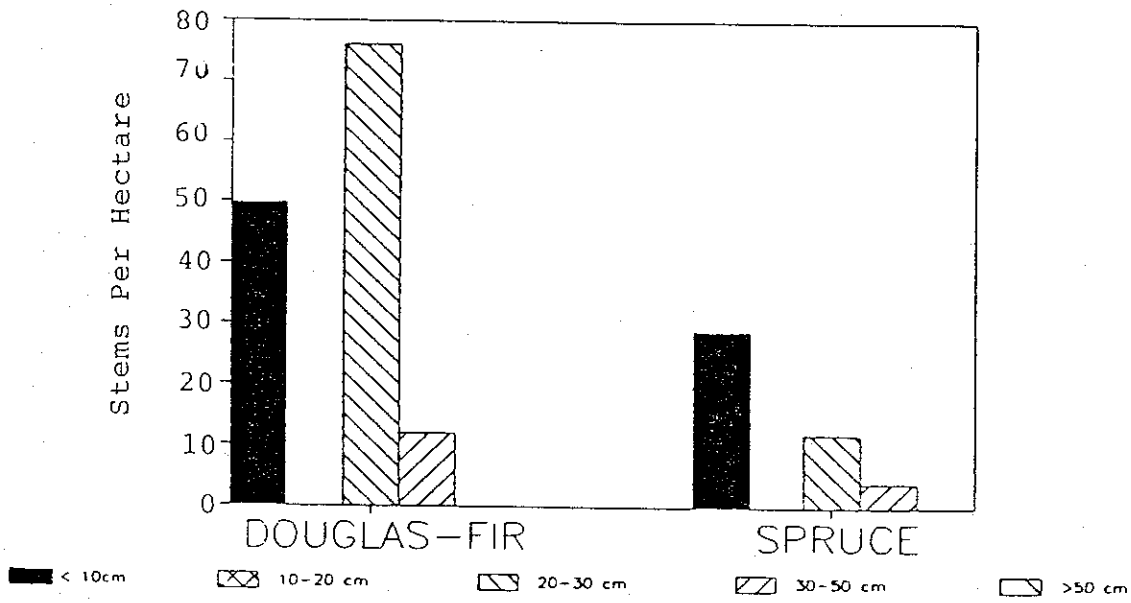

FIGURE 2 **FINAL MERCHANTABLE VOLUMES (cu m/ha) AT THE END OF EACH SCENARIO (YEAR 2087)**
(Black bars represent management scenarios with root disease; shaded bars (where present) are matched with the black bar to their immediate left, and represent the same management but with no root disease in the stand.)

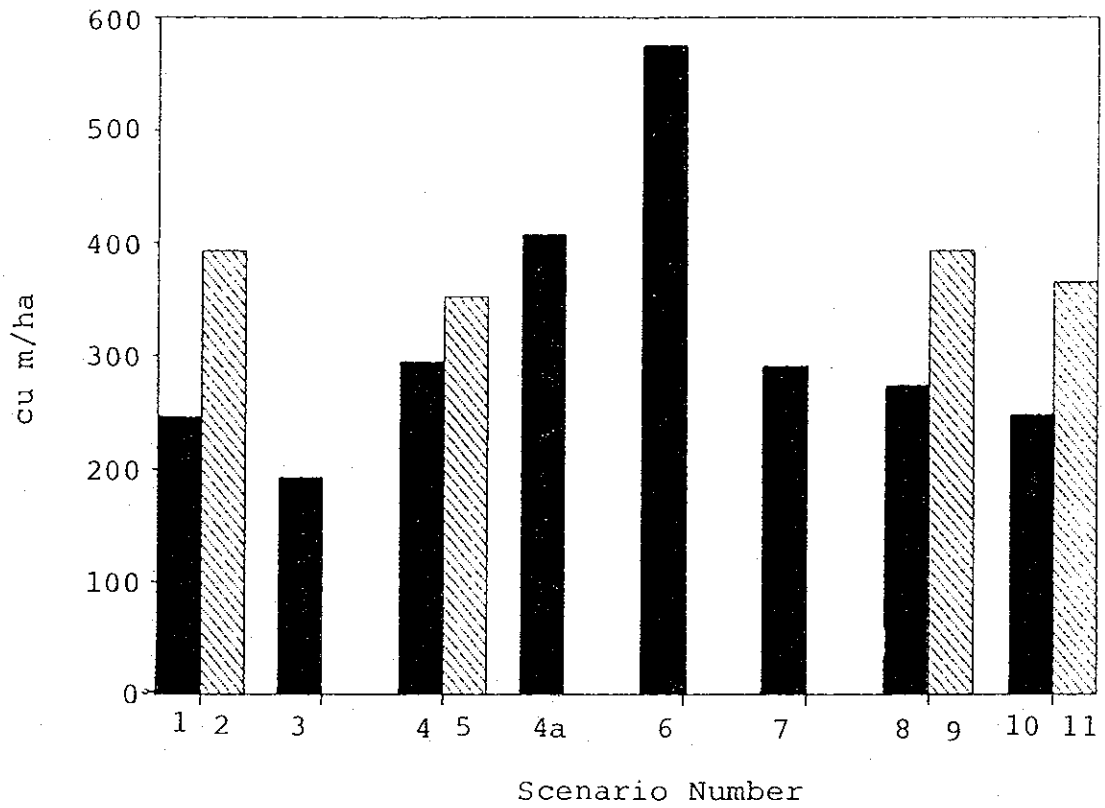
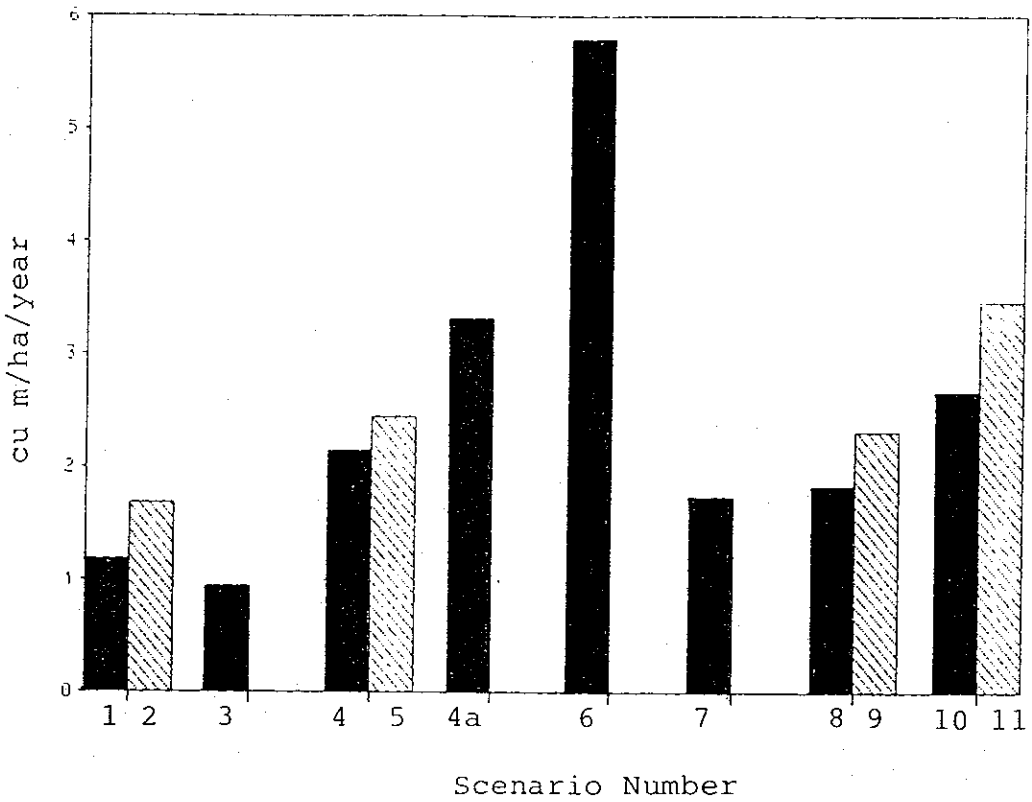
FIGURE 3 **MEAN ANNUAL INCREMENTS (MAI) FOR EACH SCENARIO AVERAGED OVER THE LAST 60 YEARS OF EACH SCENARIO**
(Shading is as described in Figure 2.)