

SPATIAL AND TEMPORAL DYNAMICS OF FOREST DISTURBANCE: A STOCHASTIC SIMULATION MODEL

By

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Abstract

Forest systems are made up of a large number of processes interacting in complex spatial and temporal scales. Simulation can be used to study the way processes interact in space and time.

A model, which approximates a system of forest growth, forest fire, bark beetle dynamics and harvesting, is constructed to observe spatial and temporal behaviour. System performance is analyzed through a sensitivity analysis of response indicators under different management regimes designed to simulate harvest and fire suppression. Variability between simulated landscapes is averaged to determine trends in model behaviour. Normalized spectral density estimates are used to detect periodicity in simulated behaviour.

Harvest is found to lessen the impact of fire and beetle outbreaks whereas fire suppression is found to increase beetle populations. Periodic behaviour of beetles and forest spatial structure are found to be affected by harvest whereas fire suppression is found to be responsible for changes in periodic behaviour of live biomass.

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Dedication

To my grandfather, Dr. Vilius Peteraitis, who inspires me to learn.

Spatial and Temporal Dynamics of Forest Disturbance: A Stochastic Simulation Model

1 Introduction

Natural and anthropogenic disturbances affect most forests (Forman and Godron 1986, Turner 1987). Disturbances change spatial characteristics, which in turn affect spatial processes. Behaviour, particularly in disturbance systems involving multiple spatial *and* temporal scales, can be difficult to visualize. Simulation can be a useful tool in such cases (Turner and Dale 1990).

This thesis uses a model of a disturbance system to make inferences from spatial and temporal statistics designed to describe simulated behaviour. The assumption is that a simulation model, built to emulate the spatial and temporal behaviour of a real system, will provide useful information about the *potential* behaviour of that system. It is also assumed that attempting to analyze simulated behaviour will provide useful information about the requirements of studying systems similar to the one modeled.

I built a spatially explicit, dynamic, stochastic model that approximates the behaviour of forest fire, insect outbreaks and forest growth. The model produces simulated time series data that act as *indicators* of simulated forest conditions. Behaviour is studied through comparisons of spatial and temporal statistics across a range of combinations of simulated harvest intensities and simulated fire suppression efforts, which represent possible management practices. Spectral analysis, useful for detecting periodicity

(Chatfield 1984, Press et al. 1992, Turner et al. 1990), is used to study the periodic behaviour of simulated response indicators.

The model represents an abstraction of a disturbance-dominated forest landscape, where processes interact in space and time. The system has, as its basis, a bark beetle population model, a forest growth model, a forest fire model and a harvest model. Forest growth, bark beetles dynamics and harvest are modeled deterministically. Conversely, forest fire is modeled stochastically. In all cases, behaviour is affected by spatial conditions.

Although processes operated at different spatial and temporal scales, the model is designed to express them in a common scale, thereby simulating cross scale interaction.

The overall objective of this study was to test simulated management strategies against two simulated natural disturbance regimes: spruce bark beetle and forest fire. The analysis was designed to provide a meaningful interpretation of how changes in management might affect system performance. Control variables were chosen to reflect an adequate range of possible choices of management and to consider both spatial and temporal effects. Management alternatives were compared through simulation of possible scenarios. Monte Carlo simulations were used to determine how variation in spatial characteristics and stand characteristics translated to variation between and within levels of simulated harvest and fire suppression.

The modeled fire regime was compared to empirical observations of fire return intervals and fire size distributions. Forest growth was checked for consistency with recognized growth and yield projections and harvest rates were selected to fall within reasonable rotation age intervals. Preliminary results were compared to expected results at various

stages of development. Forest age class distribution curves were checked for consistency with the fire and harvest regimes imposed.

1.1 Goals and Objectives

1.1.1 Quantify changes in landscape structure under alternative management strategies.

Landscapes have characteristic measures that describe spatial properties (O'Neill et al. 1988). Under different simulated management alternatives, landscapes were tested for their tendency to form different spatial structures. A sensitivity analysis illustrates behaviour across management combinations.

1.1.2 Quantify periodic behaviour under different management strategies.

Response may be periodic and the period measurable. I will show that periods may change or disappear under certain management scenarios.

2 Literature Review

Forman and Godron (1986) describe a landscape as a heterogeneous land area where interacting components repeat in similar form throughout the extent of the area. It is composed of dynamic physical and biological components that can have both function and form. The purpose of this section is to gain a better understanding of the landscape processes that make up a real forest ecosystem where forest fire and insect outbreak are present. The background given in this section influences choices for formulation of the model in section 3.

2.1 System Background

Fires and insect outbreaks are two of the major disturbance regimes important in structuring boreal forest landscapes (Payette 1992, Holling 1992). Fires create spatial mosaics of forest patches varying in age, size and species composition (Yarie 1981). Forest insects such as bark beetles also influence spatial patterns in forest landscapes. Bark beetles (Coleoptera: Scolytidea) are among the most destructive forest insects in North America (Berryman 1972). Among bark beetles, the spruce bark beetle, *Dendroctonus rufipennis* (Kirby), is the most significant natural mortality agent to White spruce, *Picea glauca* (Moench) Voss, (Reynolds and Holsten 1996, Dyer 1973). Between 1976 and 1980, 29% of Lutz spruce, *Picea glauca x lutzii* (Little), were killed in the Chugach National Forest in Alaska due to spruce bark beetles (Holsten et al. 1995).

Evidence indicates that fuel buildup increases fire risk, thus further threatening forest resources (Auclair and Bedford 1994, Holsten et al. 1995). Given the magnitude of the threat to timber resources by spruce beetles and fire in Alaska and other similar regions, considerable effort has been invested in the management of these disturbances (BC MOF 1995, Canadian Committee on Forest Fire Management 1996). Efforts to control beetle outbreaks include tree baiting and pheromone trapping (BC MOF 1995, Shore et al. 1990), although the most effective method of control is prompt removal of infested trees (Shore et al. 1990).

Similarities exist between logging and forest fire insofar as they remove tree canopy and change microclimate at ground level (Carleton and MacLellan 1994). Differences arise from the fact that fires occur under varying complex conditions involving climate

differences and topographic effects. Logging practices on the other hand occur as a result of economic and political decisions. Insofar as this project is concerned, the point is not whether fire is an integral part of the forest ecosystem but how harvest, fire and insects behave together in shaping the forest ecosystem.

Humans also play a role in shaping forests. Humans remove resources and attempt to control processes that occur naturally. Practices include harvesting, fire suppression and pest management. Suppressing fires causes a shift in the spatial properties of forests. The spatial mosaic of forest patches may be important to a variety of organisms (Forman and Godron 1986). In an effort to correct the effects of fire suppression, some fire prescriptions have been targeted at reducing accumulations of fuels (Baker 1993, Mutch 1994, Dawson and Greco 1990). Fire can also be used as a means to control forest pest populations or alter their habitat, and surface fires planned to coincide with pest and disease lifecycles can control them (Brennan and Hermann 1994). Fire suppression has been active longer in some areas than others. Cumming (1997) shows that fire suppression efforts significantly reduce the mean annual area burned.

Spruce bark beetles attack fallen wood (USDA 1992, BC MOF 1995). Besides attacking fallen wood, beetles also attack live trees. Beetles, fire and man can be thought of as consuming forest resources. Recent trends are to manage for sustainability on the landscape level. I aim to develop a method to better understand how system behaviour may be affected by management decisions.

2.2 Disturbance

Disturbances are inevitable and lead to changes in natural systems. A disturbance in a forest ecosystem is an event that causes the death of at least one canopy tree (Runkle 1985). White and Pickett (1985) refer to a disturbance as “...*any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment.*” p. 7. Disturbance by forest fire, bark beetles and harvest affects the availability of resources. Other disturbances include windthrow, landslide, avalanche, flood and drought. Although any one of these may have an impact on forest resources, disturbance in this thesis, will be limited to fire, beetles and logging.

Disturbances have temporal and spatial components. We can measure the frequency at which they occur, as well as sizes and shapes of disturbed areas. Periodic behaviour and epidemic levels can be lurking undetected in an ecosystem. Bergeron and Dansereau (1993) found that spruce budworm outbreaks became a major disturbance when fire return intervals increased to >200 years. Fire suppression efforts could conceivably be taking us to such critical levels.

Spatial characteristics of disturbances vary. Fires are typically stand replacing in boreal forests (Johnson 1992). Beetles, although destructive, do not initiate stands the way fires do. Harvest, although stand replacing, occurs in predictable shapes and sizes, typically determined by policy rather than by stochastic rules governing behaviour (Carleton and MacLellan 1994). Regardless of what determines the spatial characteristics of disturbances, the resulting landscape structure will influence further disturbance activity

until new conditions prevail. This can be caused by burning dead wood accumulated after beetle outbreak or, given sufficient time, by regeneration following a forest fire. There is a two-way interaction between disturbance and spatial pattern of landscapes. This is true for fires (Turner and Romme 1994) and potentially true for beetle outbreaks. In the following sections, disturbance is discussed in the framework of the model, which is grid based. The term *cell* refers to the smallest spatial unit of the grid and *neighbour* refers to one of eight grid neighbours.

2.2.1 Bark Beetles

Spruce bark beetle, *Dendroctonus rufipennis* (Kirby), populations have been at epidemic levels in areas of the Yukon and Alaska since the mid 60's. White spruce is particularly at risk to beetle attacks, although Lutz and Sitka spruce, *Picea sitchensis* (Carr.), are also host species (Reynolds and Hard 1991, Holsten and Werner 1990). Beetles produce dead wood, which contributes to the fuel load and increases fire risk (Auclair and Bedford 1994, Holsten et al. 1995).

The life history of beetles is as follows; Each spring adults emerge from host logs and trees when temperatures reach about 16 °C and search for a new host (USDA 1992, Holsten and Werner 1990, BC MOF 1995). If the host is recently dead, weakened, or if host resistance is overcome, beetles reproduce and lay eggs in the phloem of the host tree. Spruce beetles over-winter as larvae in the first year and as adults in the second. This occurs within the host in which they hatched (BC MOF 1995). The two-year life cycle has been known to occur in a single year when temperatures are above normal (Werner

and Holsten 1985, BC MOF 1995). One-year life cycles have been found to occur as often as 30% of the time (Holsten and Werner 1990).

Beetle populations normally persist at low densities living on windfall and recently dead trees or trees that are weak and damaged by stress such as lightning or drought (Rykiel et al. 1988). Occasionally bark beetle population explosions occur and competition for resources causes beetles to attack live trees (USDA Forest Service 1992). In sufficient numbers beetles can overcome a tree's resistance and kill it (Borden 1982). Beetles generally attack larger diameter trees (Berryman et al. 1984).

Beetles attack in two stages. First stage beetles (*pioneers*) account for a smaller portion of the total beetle population. They attack fallen trees or recently dead trees in close proximity to their point of origin (Borden 1982). Attack densities are limited by an upper threshold (*carrying capacity*) of the amount of beetles that wood can support. Beetles that attack recently dead wood are successful since resistance is gone. Beetles that attack live biomass are resisted by defense mechanisms and killed in proportion to the level of resistance of host trees. Upper densities of beetles have been found to be between 107 and 120 per square meter of bark (Shore et al. 1990). Berryman et al. (1984) model stand resistance to beetles to be inversely proportional to stand biomass. The British Columbia MOF Beetle Management Guidebook (1995) gives a high risk rating to stands with average dbh greater than 40cm.

Beetles can propagate several miles from their point of origin (USDA Forest Service, 1992). Where they choose to migrate is largely a function of beetle populations in surrounding areas. Once pioneer beetles become established they produce aggregation

pheromones (frontalin and seudenol) that attract later emerging beetles (Borden 1982). However, when the density of successful beetle penetrations approaches or exceeds the carrying capacity of the wood, the production of aggregation pheromones ceases and anti-aggregation pheromone production begins (Borden 1982).

2.2.2 Forest Fire

Many species are adapted to fire and even depend on fire to reproduce and control understory fuel buildup. Lightning strikes account for a large majority of fire ignitions and fires in boreal forests are typically stand replacing (Johnson 1992), although evidence shows that patches of vegetation are often left behind (Eberhard and Woodard 1987, Delong and Tanner 1996). Forest regions in Alaska and the Yukon have seen dramatic increases in fuel loads from spruce bark beetle attack in recent years. Given the evidence that fires tend to propagate better in the presence of abundant fuels on the forest floor (Dawson and Greco 1990, Mutch 1994), beetle killed biomass may have an influence on fire (Geisler et al. 1980, Holsten et al. 1995).

Burn rate and *fire return interval* are characteristic descriptors of fire regimes. R , the burn rate of a forest, is given by

$$R = \sum_{i=1}^t A_i / (A \times t) \quad (2.1)$$

where A_i is the area burned in the i^{th} year of t years and A is the total landscape area. It is the proportion of forest burned per year including re-burns. The fire return interval, which is the number of years between burns, is the reciprocal of R (Van Wagner 1978, Johnson

and Van Wagner 1984). Fire return intervals in Alaska region boreal forests have been reported at 130-200 years (Barney 1971).

Johnson and Van Wagner (1984) discuss two possible fire models. The negative exponential distribution model assumes all ages of forests have equal probability of burning. The Weibull distribution model assumes that older stands are more likely to burn than younger ones. Large fires tend to create their own weather conditions, which influence fire behaviour more than stand conditions (Johnson 1992, Turner and Romme 1994). Since larger fires account for the majority of area burned, fire weather would prevail and age selection would have a negligible effect. Bimodal distributions have been found in certain fire regimes indicating possibly more than one behaviour pattern (Turner and Dale 1990, Payette 1992, Turner and Romme 1994). Anderson (1996) found that for the moist cool sub-boreal spruce region north of Prince George British Columbia, a model incorporating a small amount of age selectivity fit historical data better than a model without any age selection.

2.3 Spatial Structure

One of the areas of investigation in this study is the relationship between landscape structure and disturbance. Dominance (Equation. 2.2) is a measure of the degree to which a particular type of land dominates the landscape. Contagion (Equation. 2.3) is a measure of the tendency of land to form clusters rather than be fragmented (O'Neill et al. 1988). Contagion and dominance are given by

$$D = \ln n + \sum_{i=1}^n p_i \ln p_i \quad (2.2)$$

and

$$C = 2n \ln n + \sum_{i=1}^n \sum_{j=1}^n p_{ij} \ln p_{ij} \quad (2.3)$$

where, $n = 9$ (the number of land classifications), p_i is the probability that a given cell is of type i and p_{ij} is the probability of land type i being adjacent to type j . For each index, the summation term represents a divergence from the theoretical maximum represented by the logarithmic term.

It is important to keep in mind that these indices are abstractions and are subject to interpretation. Frequently, a particular cover type is of interest, as would be the case when studying organisms that depend on old growth forest. A totally homogeneous old growth landscape will have the highest possible dominance *and* contagion values. If it is all of the same type, it stands to reason that it must be totally clustered into a single patch. This does not mean that combinations of dominance and contagion represent unique situations. On the contrary, it is possible for clusters to form in any land cover type for a single dominance value. Additionally, a landscape can be completely dominated by any one of the possible land cover types. Interpretation sometimes requires the addition of a map or histogram to show *which* cover types dominate. An example of this would be a forest age-class distribution plot.

Dominance and contagion indices are not comparable when different landscapes have different land cover types. However, this is not a problem when they are used in a sensitivity analysis of a single landscape with the same cover types. Provided that the portion of land types of interest are the same, landscapes with high levels of contagion

show higher probabilities of forming connected patches across the landscape than those with lower contagion (Gardner and O'Neill 1990). In the case of forest fire, this should translate to a reduction in fire size at lower contagion values.

3 Methods

In this section, I will outline the logic used to build the individual sub-models and the simulation model as a whole. The model was designed to approximate how a real system behaves. It was formulated to capture the more significant elements of a forest system involving fires and insect outbreaks. Sub-models were reduced to a series of processes that performed predetermined tasks. In the model trees are killed, beetles reproduce, fires are started and forests are grown. Each process is called upon according to its own set of rules to produce behaviour and/or change in the system. Changes either alter the landscape directly or produce results for other processes that depend on them. Most processes are performed in each time step. Some processes, however, occur only if random chance permits.

3.1 Framework

3.1.1 Spatial Context

Spatial extent was required to be as small as possible with the largest grain size possible. A 20km by 20 km area was modeled as a raster grid with 1km² cells. The size of the cells reflects a reasonable cut block size (100 ha) and represents the approximate upper range of beetle flight. 400 km² was chosen because it was sufficient to allow large fires (up to

40,000 ha) to occur while still being small enough not to be too computationally demanding.

Simulating disturbance propagation and species migration on a small area has problems. If the area is so small that movement is hampered because of frequent encounters with the edge of the landscape, results can't be expected to extend through their full possible range. One possible solution for this is to use an area large enough so that edges represent only a small part of the landscape. Unfortunately, this approach inherently involves more computation. Instead, I designed the landscape grid to treat an edge encounter as a transition to the mirror image of the grid (i.e., upper left goes to lower right, etc.). In this way, the landscape could be considered a snapshot out of a larger system while still allowing spatial behaviour enough room to operate. "Wrap around" propagation can be considered to be simultaneous entrance and exit events. What leaves the system is compensated for by what enters it and events are not "cut off".

3.1.2 Temporal Context

Procedures operated in one-year time steps. This does not imply that all processes had time scales of one year. Stochastic procedures generated random numbers each year but their effective time scales were determined by their probability distribution functions. A 512 year period was chosen to encapsulate periodic behaviour feasible in a management context. The choice of exactly 512 years is an artifact of the analysis technique used, and will become clear in later sections.

Beetle populations were modeled with two distinct deterministic time steps in one-year intervals. Forest fire was modeled so that lightning strikes and ignitions occurred with

frequencies determined by probability functions. Fire size and frequency varied but the cumulative frequency tended to converge to a rate representative of the fire return interval. Harvest was modeled deterministically such that a percentage of the area, determined by the rotation age, was removed each year.

3.1.3 Control Variables

The system involves forest growth, forest decay, fire, bark beetle population dynamics, climatic variability and harvest. Only two factors were varied for sensitivity analysis: simulated fire suppression and simulated rotation age. By keeping all other factors constant, it was easier to isolate the effects of management on system performance. Fire suppression was simulated by lowering ignition rates, thereby producing smaller fires. Harvest was simulated by removing grid cells each year. The number of cells harvested each year corresponds to a fixed area that theoretically translates to a rotation age. Four levels of each control variable were chosen totaling 16 combinations. Each combination represented one possible management scenario.

Harvest was simulated with a percent cut each year that represented a feasible range of harvest intensities for a boreal forest. It was set at 0% (no harvest), 0.75% (133 year rotation), 1% (100 year rotation) and 1.25% (80 year rotation). Lightning strikes cannot be stopped, but fires that do start can be suppressed and reduced in size. I reduced fire sizes by lowering the ignition probability, which limited the size of fires. Experimental manipulations were performed to reproduce approximate fire size distributions consistent with fire regimes in the boreal (Andison 1996, Cumming 1997). I assumed that the ignition rate that best estimated the historical data would likely include some degree of

suppression so I extended the range beyond that value. Probabilities were set at 15%, 18%, 21% and 24%. 15% represents a highly suppressed landscape and 24% is theoretically unsuppressed.

3.1.4 Response Variables

A detailed accounting record of forest characteristics was maintained throughout simulations at one-year time intervals. The record included total landscape live biomass, total beetle population, dominance, contagion, harvested volume and individual fire sizes. The goal was to see if manipulating variables changed system behaviour. Three kinds of responses were examined: non-spatial, spatial and temporal. Non-spatial response variables describe the landscape without saying anything about its geometry or spatial relationships. Spatial response variables describe the arrangement of patches on the landscape. Temporal responses are not so much a yearly measure as they are a measurement of variation throughout the years. It only becomes evident when a time series of a spatial or non-spatial response variable is viewed as a sequence of observations that there is some sort of pattern in time.

Besides producing indicator time series, I considered that single simulations do not adequately represent system behaviour. For example, a single large fire can coincidentally kill the majority of beetles on a landscape. If it also happens to have burned most of the older forest, the landscape may not have much left to allow further activity by either beetles or fire. Such a run may be anomalous but it could happen and would not necessarily represent a likely outcome. To get an idea how the system behaved on average, I chose to simulate each scenario 30 times. This made it possible to calculate

average performance and variation for each response variable for 30 simulations. From this, I calculated the variation in means. I calculated the mean, the standard deviation and the standard deviation of the mean for each response variable in each scenario.

3.1.5 Initialization

Simulations can exhibit behaviour that is a product of initial conditions. I wanted to ensure that the behaviour I observed was a product of both the model and the imposed management. I ensured that when a simulation was run, it was initialized with forest conditions that evolved from the same management regime that was being tested. Additionally, I ensured that each simulation of a given management alternative began with exactly the same conditions.

To accomplish this I randomly initialized a landscape, simulated it for 500 years under a given management alternative, saved an image of the landscape, and used this image for all 30 simulations of the same type of management. The same strategy was used for all 16 scenarios. This way each scenario had its own unique initial conditions.

3.2 Stand Dynamics

This section discusses the construction of a model that approximates a forest. A stand model was constructed to approximate the behaviour of a forest system of white spruce in the Yukon. It was designed to provide information pertinent to fire behaviour, beetle population dynamics and harvest in such a forest.

Growth rates were inferred from volume, dbh and height curves produced by the Variable Density Yield Prediction (VDYP) model of the British Columbia Ministry of Forests.

VDYP is an empirical yield prediction system for natural stands. I implemented the program with a 100% white spruce forest and a uniform site index of 15 at base age 50. The volume curve can be seen in Fig. 3.2.1. It reaches a maximum of 565 gross cubic meters per hectare at 250 years, after which there is no further growth. Maximum height and dbh are approximately 33 m and 30 cm respectively, and each has a sigmoidal curve similar to volume.

Stands were initiated as bare ground when they burned or when all trees were killed by beetles. In the first 20 years of stand growth, fires and beetle attacks were prevented from occurring. Stand characteristics in this age range were determined directly from a table lookup of VDYP data. After 20 years, disturbances were allowed to occur. Annual growth rates in dbh, volume and height were calculated from VDYP data and used to increment actual stand values. In events of significant tree loss (>50%), the remaining trees grew as a younger stand of equivalent biomass.

Dead biomass accumulated for two reasons: natural mortality and beetle attack. The VDYP volume data accounts for death but only produces values for live biomass. I determined how many trees died each year and the corresponding biomass. I found that the portion of volume dying decreased over time. Between 80 and 250 years, roughly 0.08% of volume was lost each year. Death rate was varied randomly between 0.05% and 0.1% of live biomass.

BarkArea, calculated as $6 \times Volume / dbh$, was based on the assumption that trees have the shape of a cone. I calculated this each year as a requirement of beetle population dynamics and attack behaviour.

Stress in host trees is known to facilitate insect outbreak (Rykiel et al. 1988). Trees can become stressed as a result of age and random perturbations such as drought or windstorm. These perturbations can be widespread or isolated. Some years large areas may be affected and other years only a small area. I attempted to capture this spatial and temporal variation in stress levels by generating a stochastic function each year. I generated a random number for each cell to represent variation between cells and another random number to represent variation year to year for the entire landscape. Yearly random variation (rnd1) ranged from 0 to 0.08 and cell variation (rnd2) from 0 to 0.2. Since the cell variation factor is larger, it has a more significant effect than the yearly variation.

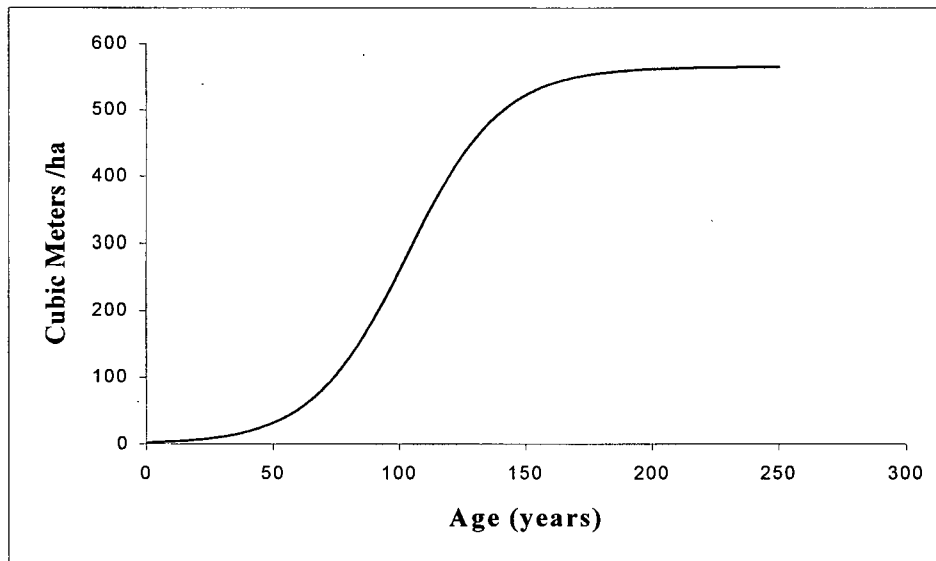


Figure 3.2.1 Volume of white spruce.

Additionally, I made denser stands more susceptible. Stress,

$$S = \text{rnd2} \times \text{rnd1} \times \text{biomass} / \text{maximum biomass} \quad (3.1)$$

is shown in Figure 3.2.1.

Resistance to beetle attack was modeled as a function of age, competition and stress (Reynolds and Hard 1991, Hawkes 1983, Berryman et al. 1984). Young trees demonstrate high resistance to beetle attack. Until age 20, resistance (R) was modeled to be 100%. After age resistance was

$$R = (1-S)(1-(age-20)^7/(maximum\ age-20)^7) \quad (3.2)$$

Where the maximum age is 250 years and S is the stress. The choice of a power of 7 was to ensure that significant decreases in resistance only occurred when dbh reached about 25 cm near 120 years (fig 3.2.2). Stands allow a portion of 1-R of beetles to be successful

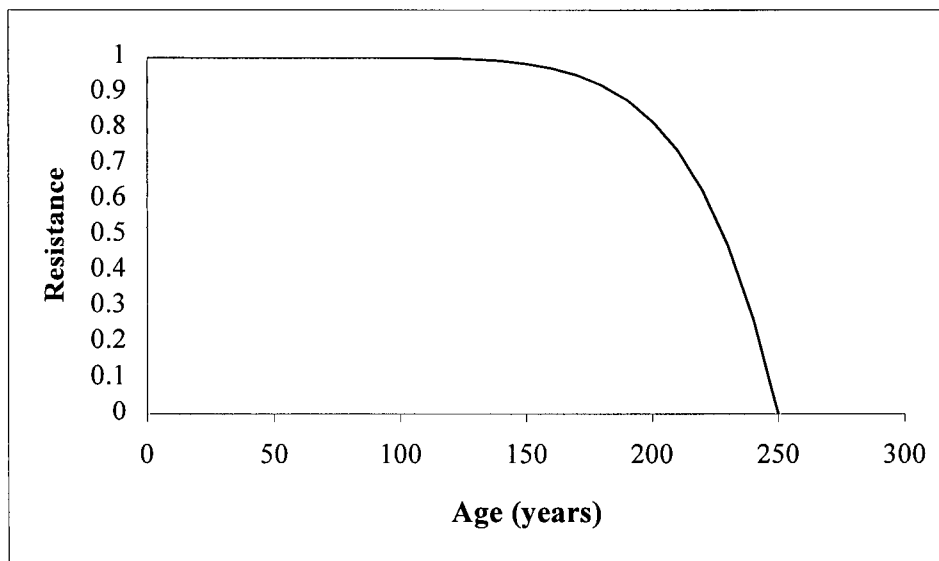


Figure 3.2.2 Tree resistance to beetle attack.

in attacking trees. Those beetles are distributed throughout the stand and succeed in killing trees according to how close their density approaches the carrying capacity of the bark (see section 3.3).

Equation 3.2 does not allow for significant variation in young stands. I did not consider this a problem since young stands are not usually noted for high risk to attack. When beetles migrate to highly resistant cells, they are mostly killed, but if they arrive in large enough numbers, the surviving population can still succeed in killing a small amount of wood. Since biomass and age are generally closely correlated, resistance tends to vary more significantly in older stands.

3.3 Beetle Dynamics

In this section a simulated population of beetles is formulated to approximate a population of spruce bark beetles as outlined in section 2. Beetle dynamics depend on beetle populations, forest stand characteristics, tree resistance and random factors that affect tree stress. To kill trees, beetles aggregate and invade bark up to its carrying capacity (CC). The number of beetles determines the lower limit of the amount of area that can be attacked and the CC determines the upper limit. I set the maximum density at 120 beetle attacks per m² of bark area (Shore et al. 1990, Reynolds 1992). Multiplying this by the amount of bark area in a cell gives the CC of the cell (eqn. 3.3). The number of offspring was set at 35 beetles per adult based on a generalization of results in Holsten and Werner (1990).

$$CC_i = \text{Maximum density} \times \text{Total Bark Area}_i \quad (3.3)$$

Beetle life cycle occurs over two years. Beetles emerge from trees attacked two years previously in two separate waves. The proportion of beetles emerging in the first wave was set at 25%. These beetles attack only within their cell. Of these, *luckybugs* successfully attack recently dead wood. Remaining beetles are forced to *pioneer* an

existence in live trees. *Luckybugs* fill dead wood to carrying capacity. Remaining *pioneers* make up the balance of first wave beetles not lucky enough to find dead wood, or carrying capacity of live wood, whichever is smaller. If *pioneers* find no live wood to attack they are available to participate in the second wave attack.

$$LuckyBugs_t = \min \{ .25 Pop^n_t, CC_t, xRandom\ death\ rate_t \} \quad (3.4)$$

$$Pioneers_t = \min \{ (.25 Pop^n_t - LuckyBugs_t) \times (1 - Resist), CC_t \} \quad (3.5)$$

In the second wave of the attack, beetles migrate and attack live trees, though they will seek out fallen dead trees if any exist. Beetles potentially attack all eight surrounding cells. The assumption is that beetles tend to attack nearby trees, although they are capable of flying for several miles without stopping (USDA Forest Service, 1992). Dispersal is limited to adjacent cells, but beetles are also given the option to remain in their cell of origin if it is more desirable. A measure of attractiveness determines if cells receive immigrant beetles. This depends on how many first wave beetles occupy the cell as well as the carrying capacity. Attractiveness (equation 3.6) increases with the presence of pheromone emitting first wave beetles and decreases as carrying capacity is approached, at which point the production of disaggregation pheromones makes the cell unattractive (Fig. 3.3.1).

$$Attractiveness_t = (Beetles_t) / CC_t (1 - (Beetles_t) / CC_t) \quad (3.6)$$

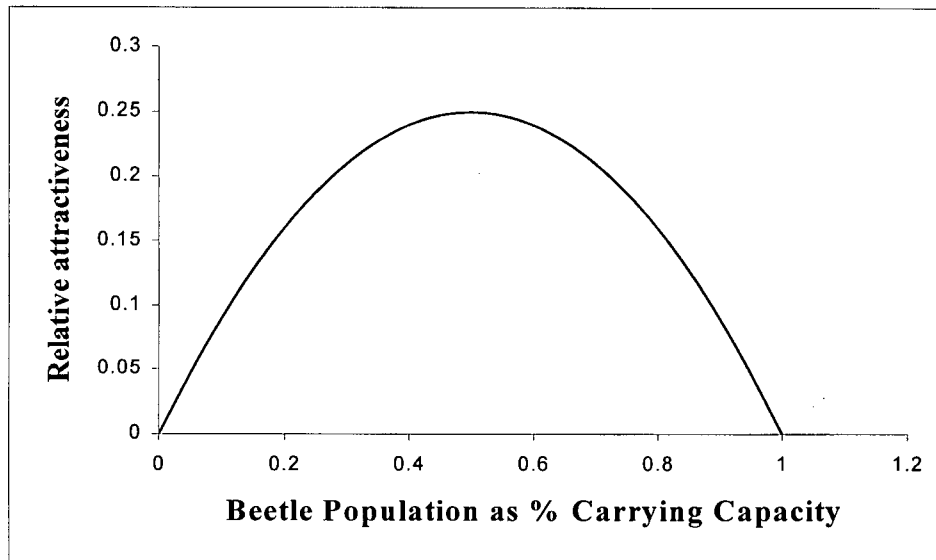


Figure 3.3.1 Relative attractiveness of a pixel to beetle migration.

In each neighbourhood of nine cells, the total attractiveness was calculated. The relative attractiveness of each cell was calculated as the weighted portion of total attractiveness. Beetles distribute according to weights of attractiveness. The result was that beetles tend to aggregate in attractive cells. Cells containing older trees tend to be more attractive. Lower resistance and larger amounts of fallen wood allow beetle populations to increase more easily.

Beetles aggregate on trees to overcome resistance. First, the beetles are distributed evenly over all bark area in the cell. The resulting density of beetles was divided by the maximum density of bark to give the success rate of beetles (Eqn. 3.9). The success rate determined how much bark is killed (Eqn. 3.10). Bark area is killed and translated into a corresponding volume loss. The amount of bark area killed was recorded and translated into an emerging beetle population two years later.

The number of beetles emerging from trees is a product of the amount of wood successfully attacked two years previously and productivity of beetles per unit of bark area attacked. Productivity is the product of maximum density and fecundity (120 beetles m^{-2} and 35 beetles per adults). Once beetles emerge from trees and migrate, dead wood is added to the record of dead biomass. The following equations were used:

$$Beetles_t = Attacked\ Bark\ Area_{t-2} \times Productivity \quad (3.7)$$

$$Dead\ Bio._t = Dead\ Bio._{t-1} + Attacked\ Bio._{t-2} + Deathrate \times Live\ Bio._{t-1} \quad (3.8)$$

$$Success\ Rate = (Beetles_t / Bark\ Area_t) / Maximum\ Density \quad (3.9)$$

$$Attacked\ Bark\ Area_t = Bark\ Area_t \times Success\ Rate \quad (3.10)$$

The model assumes no predatory effects on beetles, although beetles are known have vertebrate predators. I assumed that production levels of beetles incorporated predation. Eight species of birds are, however, known to prey on *Dendroctonus rufipennis* during flight (Stallcup 1963 as cited in Dahlsten 1982) resulting in approximately 10% reduction in population. I also assumed that productivity was the same at all forest densities when in fact forests may attract beetle predators at the same time as they attract beetles. Woodpecker populations and predation rates of beetles both increase during epidemic levels (Dahlsten 1982).

I also assumed that beetles emerged and attacked trees before fire occurred. There does not appear to be any reason to assume that a bias would arise from this assumption. Random fires would simply randomly hit or miss a beetle population. There certainly seems to be no reason to wait until later in the season since temperatures are high enough for beetles to emerge before the fire season begins.

3.4 Fire Dynamics

Fire behaviour depends on forest fuels, weather and topography (Perry 1987). Beetle outbreaks increase fuel sources and have the potential to increase probability of ignition (Geisler et al. 1980, Holsten et al. 1995). I modeled the landscape to be topographically uniform with constant weather conditions. Lightning strikes occurred at random, and cells ignited (or not) according to the state of the forest and rules governing ignition. In a single time step, all cells had a chance of being struck by lightning. Fire was spread to adjacent neighbours, which ignited according to the same set of rules as lightning strikes. In other words, cells burn either because they were struck by lightning or because neighbouring cells caused them to ignite. Once cells burned, they were reduced to bare land and left to regenerate according to forest growth rules.

Two probabilities were associated with fire: 1) the probability of a lightning strike and 2) the probability of ignition. Lightning was modeled to occur randomly with a probability of 0.003 in each cell. Ignition probability, an age dependent base rate, was augmented by dead biomass accumulation. The base value changed under different management alternatives as it was used to simulate fire suppression by limiting how big fires became. Forests younger than 20 years did not burn. Between 20 and 40 years, the base ignition probability increased linearly to the maximum, which occurred at 40 years. After 40 years no further increase occurred. The base ignition probability was further modified by dead biomass accumulating from beetle outbreak as well as natural mortality.

Accumulation of dead biomass modified the probability of ignition by at most 25% of the maximum base rate. For example, if the maximum base ignition probability was 24%,

and the dead biomass accumulation at its maximum, then the effective dead biomass modified ignition rate was $24\% + 0.25 \cdot (24\%) = 30\%$.

Detailed fire behaviour with respect to topography is well documented (Rothermel 1972, Perry 1987, Pyne et al. 1996). Slope, aspect, wind and fuels all play vital roles in how fires spread. However, given the evidence that large fires tend to ignore these factors and operate according to fire weather rules, it seemed logical to omit this detail. Fire, as modeled in this project, was not specifically age selective like a Weibull distribution. It was, however, less likely for very young aged stands to ignite from lightning strikes. Since lightning strikes cannot be prevented, I assumed that fire suppression had the effect of reducing the average size of fire. Fire suppression was emulated by decreasing the probability of fire ignition.

3.5 Harvest

A model of a harvest regime was built to remove a fixed number of entire pixels of trees each year. Harvested area corresponded to specific rotation ages of 80, 100 and 133 years. It was implemented such that the cells with the most biomass were logged first. The model assumed no logging slash was left behind from harvest. All live biomass was considered merchantable and nothing was left behind for beetles.

3.6 Landscape Ecology

At the end of each year, I calculated dominance and contagion of the landscape. Each forest cell was reassigned a code corresponding to one of nine age class of the BC MOF

age classification system. Dominance and contagion were calculated on age classifications rather than actual ages to speed up computation.

3.7 Spectral Analysis

Spectral analysis is concerned with estimating the spectral density of time series. Fourier analysis assumes time series functions can be expressed in either the time domain as a function of t or in the frequency domain as a function of f . It also assumes that you can transform between the time and frequency domains using the fourier transform pair equations (Chatfield 1984, Press et al. 1992). A perfect continuous periodic function will transform exactly between time and frequency domains. Natural systems are not perfect continuous periodic functions and usually incorporate some high frequency “noise”. Nevertheless, periodic behaviour can still be detected and the contributions of different periods can be extracted from the signal. The Fast Fourier Transform (FFT) separates time series into discrete sinusoidal components. It assumes that periodic time series can be expressed as finite sums of periodic components.

Figure 3.7.1 shows two separate periodic functions plotted over time. Both have amplitudes of 1 but they have different periods. One has a period of 256 years and the other has a period of 2048 years. In other words, one has 16 cycles and the other only 2 cycles in 4096 years. The two functions are added together to give the function shown in figure 3.7.2. The resulting amplitude is the combined amplitude of the two original functions. Using the FFT technique over 4096 years, the spectral density of this function can be generated. The power spectrum estimate shows how much amplitude is contained in each periodic component in the frequency domain. The term “power” is inherited from

the field of engineering where Fourier techniques were developed to estimate spectral properties of passing current through resistors. The power spectrum estimate shows how the variance is distributed among frequencies. Figure 3.7.3 shows power at only two frequencies, which confirms that only two periods existed in the original signal in time domain. One periodic signal is at 2 cycles in 4096 years and the other is at 16 cycles. They also have the same power, meaning both signals contribute equally to the variance,

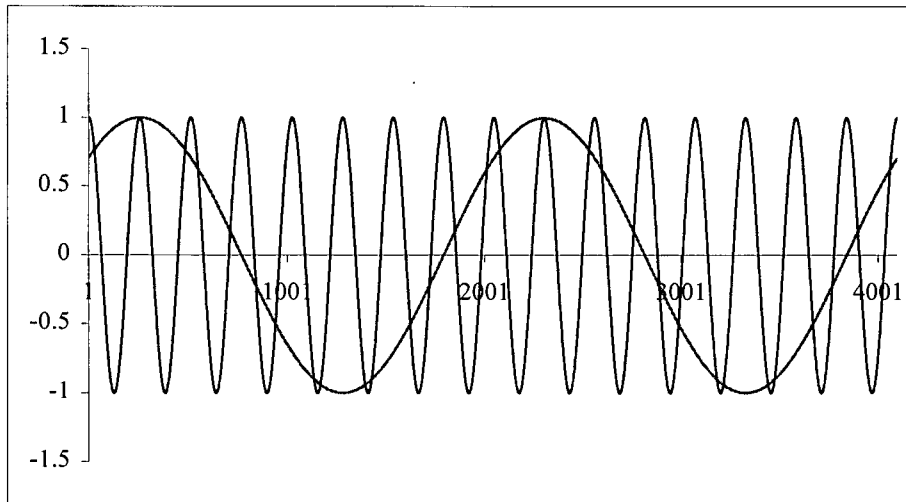


Figure 3.7.1 Plot of two periodic signals, which was evident in figure 3.7.1

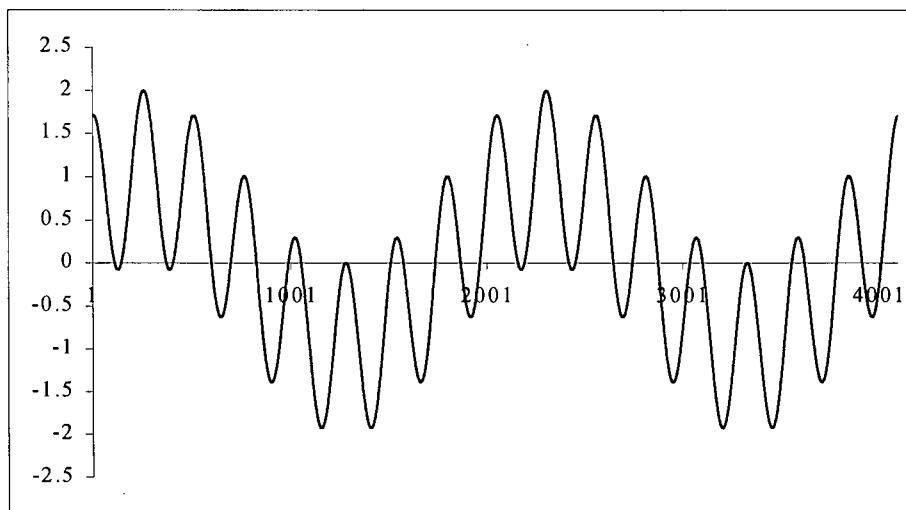


Figure 3.7.2 Plot of combined periodic signals.

but not in figure 3.7.2. This method of separating signals was applied to each response signal produced by simulation.

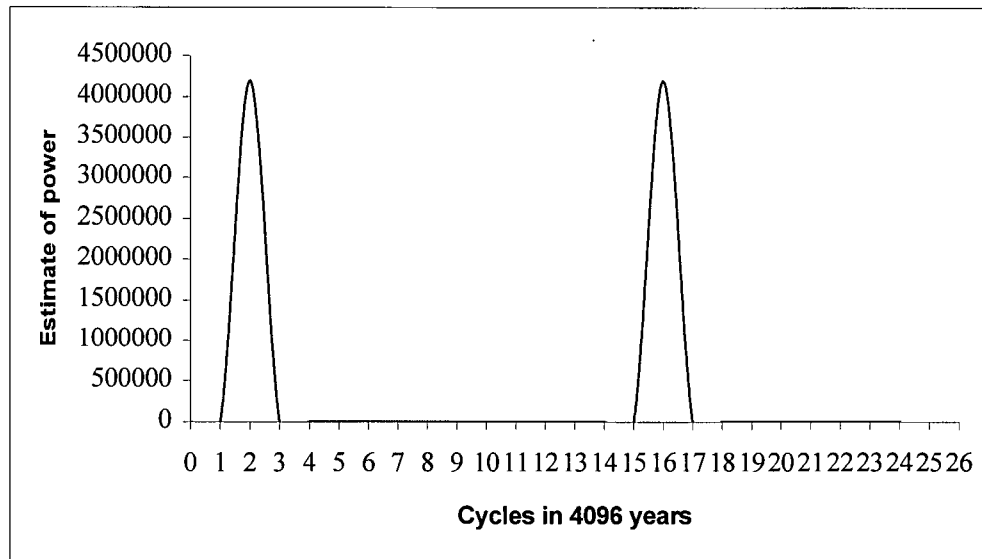


Figure 3.7.3 Power spectrum estimate of Figure 3.7.2.

In natural systems, and in simulated natural systems, interacting components cannot be separated. We can only look at combined responses as illustrated in figure 3.7.2. The Fast Fourier Transform technique requires that the length of the time series be a power of 2 integer. 512 years seemed to be the minimum feasible length series to interpret for periodic behaviour of up to 250 years. Simulating 30 times and averaging the power spectrum estimate treated each simulation as a separate sample signal and the averaged power spectrum accentuated consistent behaviour and filtered inconsistent signals.

I aggregated power spectrum estimates over multiple simulations to reduce the variance of the estimate. The simulation produced 30 separate 512 year signals for each response variable. First, the mean value was subtracted from each value in the series. This ensured

that the mean would not dominate the power spectrum. Discrete sampling has the effect of allowing neighbourhood frequencies to “leak” into sampled intervals. A technique called windowing was used to lessen the impact of this phenomenon (Press et al. 1992). Each individual time series was smoothed using a Bartlett window to compensate for leakage. Finally, to accentuate the relative contributions of frequencies to the amplitude of the power spectrum, I normalized the power between 1 and 256 cycles by dividing each power value by the total power. This allowed visual interpretation of the relative contribution of frequencies, and allowed power spectral density (p.s.d) estimates to be displayed on a common plot.

4 Results

Throughout sections 4 and 5, I refer to management alternatives as the combination of rotation period and fire suppression intensity. The form (133, low) implies a 133 year simulated harvest rotation period and low simulated fire suppression. In section 4.1, I use the base model to illustrate how results were interpreted. I display system behaviour graphically by plotting the time series of response variables for the full length of a single simulation (512 years). This gives a sense of the variation in time, and periodicity in a single simulation. In section 4.2, I compare mean responses between and within control levels. I use an aggregated mean response signal to represent performance. In fact, since I use the 512 year mean of 30 simulations, it is an aggregate of an aggregate.

It is important to remember the hierarchy of data. For each of the 16 possible management alternatives, there are 30 simulations. Each simulation has a resulting mean and standard deviation over 512 years. The means are distributed with a mean and

standard deviation. The mean of the means is used to compare system performance and referred to simply as “the mean”. The standard deviation of the mean represents variation in the mean. Occasionally, I refer back to the mean of the standard deviations of the original response signals. This is the mean of 30 separate standard deviations, which are each based on variation in yearly responses over 512 years

4.1 Base Model

The base model was designed to emulate an unmanaged forest. It burned without being suppressed and grew without being harvested. It was used to see if the system behaved as intended. In this section I illustrate how the model was interpreted graphically. In most cases, I illustrate a single simulation response signal over 512 years. The other 29 simulations likely appear similar, but graphing them all simultaneously would make it difficult to distinguish periodicity and variation.

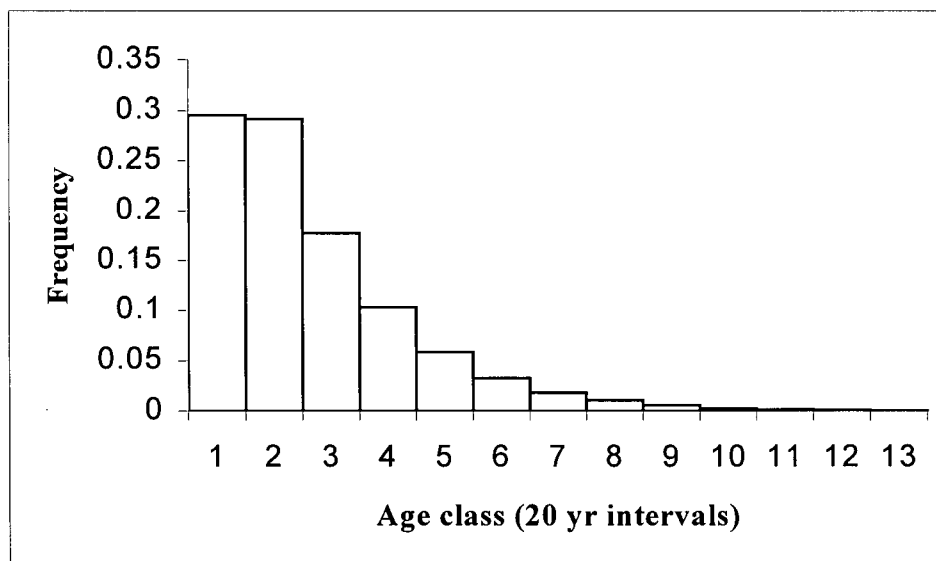


Figure 4.1.1 Age class distribution (base model).

The age class distribution (Fig. 4.1.1) reflects an age selective fire regime, as would be expected. The results were derived from an averaged yearly census of forest ages over the entire landscape for 30 simulations of 512 years each. This validates the intended fire regime as outlined in section 3.4. It shows an age selective curve characteristic of a Weibull distribution.

Figure 4.1.2 shows the total landscape biomass of three separate simulations over 512 years. Despite the fact that all three series begin with the same initial conditions (see section 3.1.5), each follows a different path as determined by random events. It is evident that despite following unique trajectories there is a common pattern in all three. Each series shows what appears to be periodic behaviour at two different periods. Live biomass appears to collapse and recover quite frequently every 40 years. At the same time these collapses and recoveries appear to part of another cycle with a longer period.

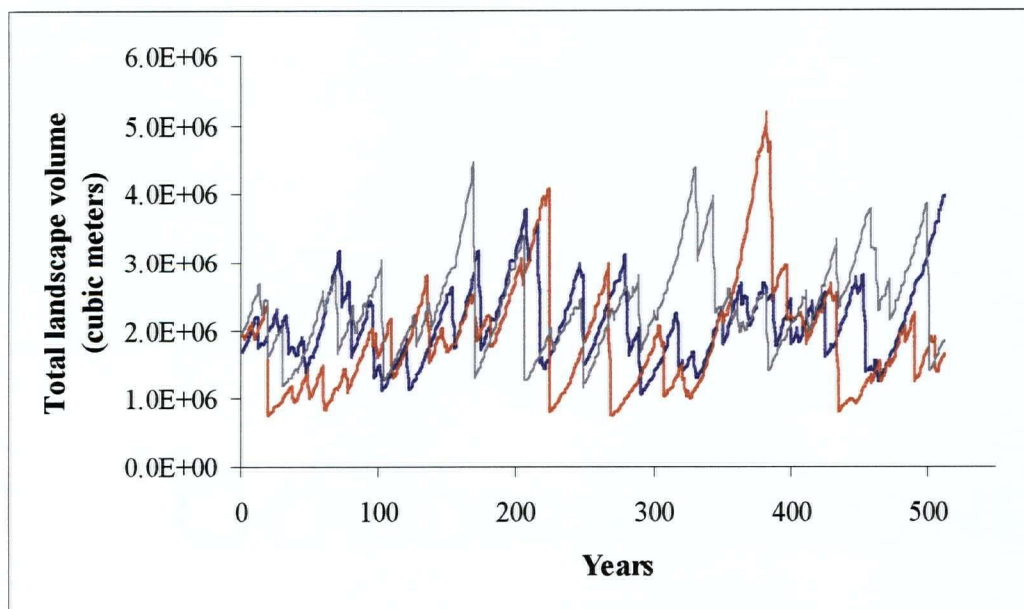


Figure 4.1.2 Total live tree biomass (base model).

Figure 4.1.3 shows a single beetle population time series for a single simulation. Periodic population explosions are evident at random intervals, although populations are low between explosions.

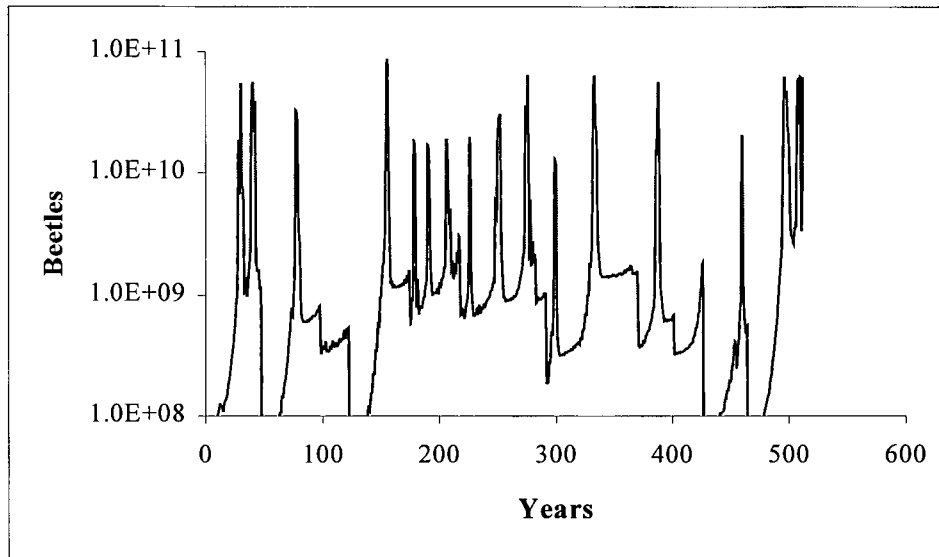


Figure 4.1.3 Total landscape beetle population (base model).

Figure 4.1.4 shows a normalized spectral density plot of five response indicator variables. The X-axis labels represent the number of cycles in 512 years, which is the frequency. A low frequency represents a long period. For example, if the original time series had only one signal with a period of 256 years, the spectral density plot would show 100% of the power at 2 cycles.

Each signal in Fig. 4.1.4 has its own spectra. Beetles show no significant power at any particular level. This is consistent with figure 4.1.3, where explosions appear to occur randomly. Live biomass shows significant amplitude at periods of 256 and 40 years, which is consistent with Fig. 4.1.2 and corresponds to 2 and 12 cycles in 512 years.

The power spectral plots are aggregates of 30 separate simulations. The FFT method of extracting individual spectra was applied to each simulation and averaged to produce figure 4.1.4. When a significant portion of its signal appears at a particular frequency, a cycle exists with a period corresponding to that frequency. A peak in the power spectrum indicates there is a consistent tendency among simulations to cycle at that frequency. If simulations showed different periodic behaviour for each different run, there would be no significant power in any particular frequency.

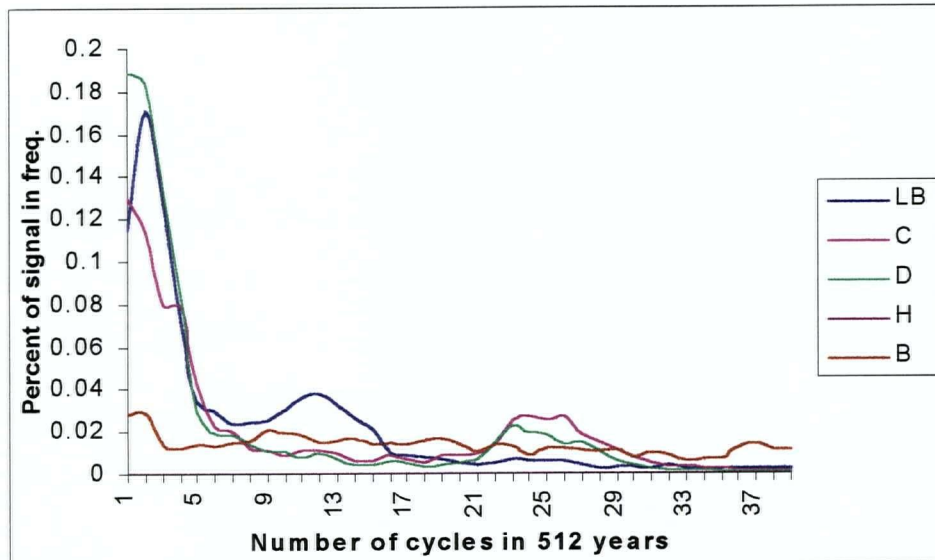


Figure 4.1.4 Normalized power spectral density (Base model).

LB = Live biomass, C = Contagion, D = Dominance, H = Harvest, B = Beetles.

The graph of the time series of dominance of a single simulation in Figure 4.1.5 shows a strong cycle with a 250 year period and more frequent cycles at about 20-year intervals (26 cycles in 512 years). These periods are evident in the plot of power spectral density in Fig. 4.1.4. The 20-year cycles are most likely a byproduct of the fact that dominance calculations were based on 20-year interval age classes. Trees get recruited into age

classes every 20 years, which causes the value of dominance to fluctuate. The age class distribution in Fig. 4.1.1 clearly shows that an insignificant percentage of trees exist at the 250+ year age class. Since the base model has a fire return interval of 67 years, the 250-year cycle cannot be a result of any significant recruitment in that class. What causes this cycle remains to be determined. This question will be addressed in section 4.2.

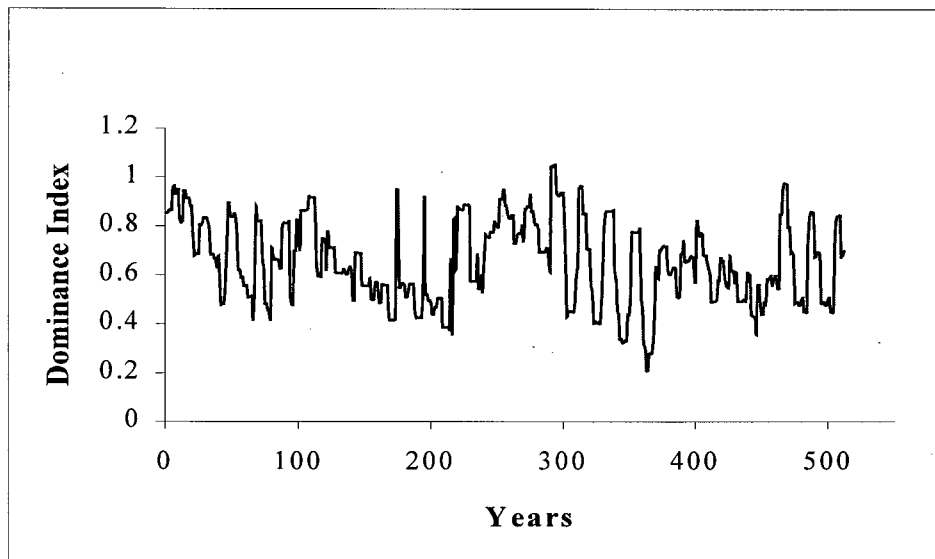


Figure 4.1.5 Dominance (Base model).

The time series plot of contagion in Figure 4.1.6 shows similar behaviour to dominance, except that the long period cycle does not have the same relative strength to its shorter period counterpart. This is confirmed in the spectral density plot (fig. 4.1.4) where it can be seen that the relative power of the signal at 512 and 256-year periods (1 and 2 cycles) are not as strong as for dominance and do not drop off as rapidly. This suggests that periodic behaviour is not as concentrated at these frequencies as it is for dominance. It is important to note that the time series for contagion and dominance show in figs. 4.1.5.

and 4.1.6 are single simulations whereas the spectral density plot is aggregated over 300 simulations.

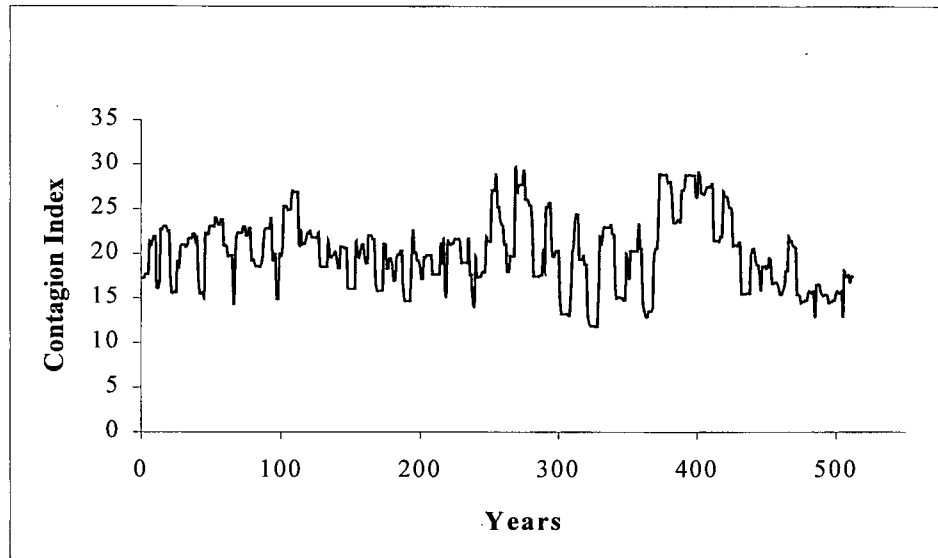


Figure 4.1.6 Contagion (base model).

Figure 4.1.7 shows fire size frequency. Notice that over 20% of fire ignitions resulted in fires in the vicinity of 100 ha. This graph is in log scale, so the peak at $\ln(\text{size}) = 5$ corresponds to $\ln(\text{size}) \leq 5$ which accounts for all single pixel fires. Pixels can be viewed as aggregations of land conditions where the pixel is at least 50% covered by fire. Single pixel fires, therefore, represent all fires 50-100 ha. 35% of fires were over 1000 ha. This portion of total area burned by the few large fires is shown in Fig. 4.1.8. This indicates that over 60% of fires are over 13,000 hectares. This does not agree with data in Anderson (1996), where fires over 10,000 hectares only accounted for 31% of the area. This is, however, expected since Anderson's results were based on historical analysis of forest inventory maps. Historical analysis counts patches as regenerated disturbances, whereas fires often re-burn previously burned areas.

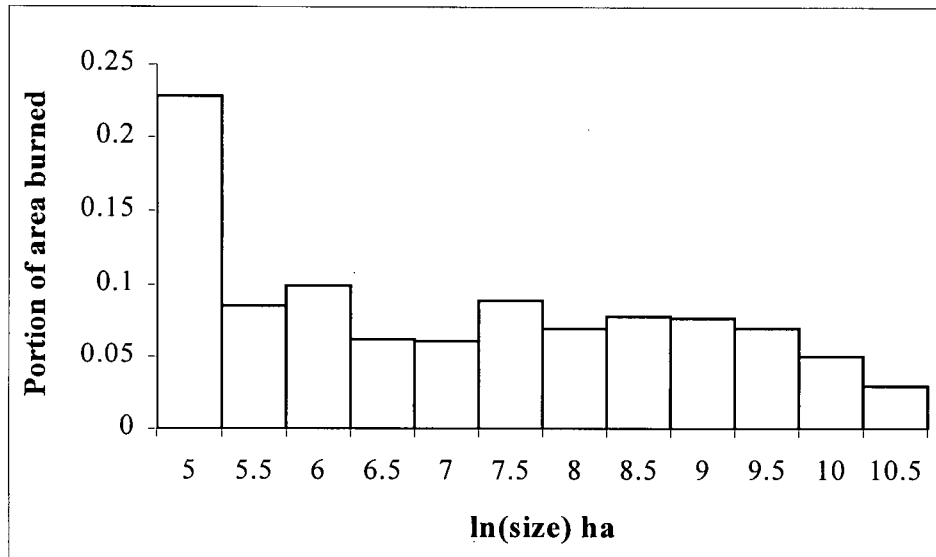


Figure 4.1.7 Fire size distribution (base model).

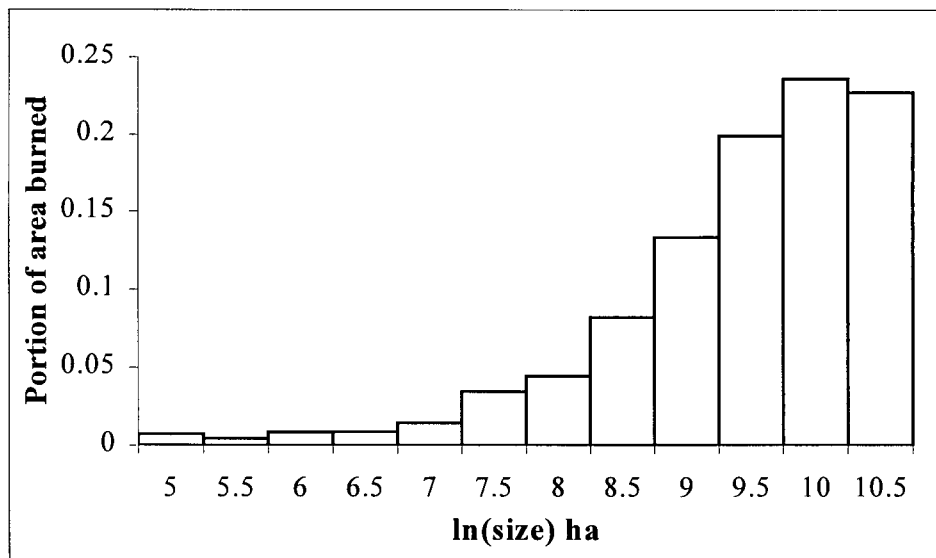


Figure 4.1.8 Distribution areas burned by size class.

The results discussed in this section are unique to the base model. Distinct management alternatives produced cyclic behaviour at different periods and different amplitudes. This applied to contagion, dominance, fire, harvest and forest growth, although in some cases there were similarities. A synergy between management and disturbance could lead to

unexpected system behaviour. The following section deals with isolating the conditions that lead to such an event.

4.2 Sensitivity Analysis

This section discusses the behaviour of the model as it is manipulated by changes in management. Graphs show behaviour at all combinations of simulated harvest rate and simulated fire suppression.

Figure 4.2.1 shows mean fire size by suppression level and harvest rate. In each case, the results are based on the combined fires from all 30 simulations. An increase in fire suppression effort leads to a decrease in the mean fire size across all rotation ages.

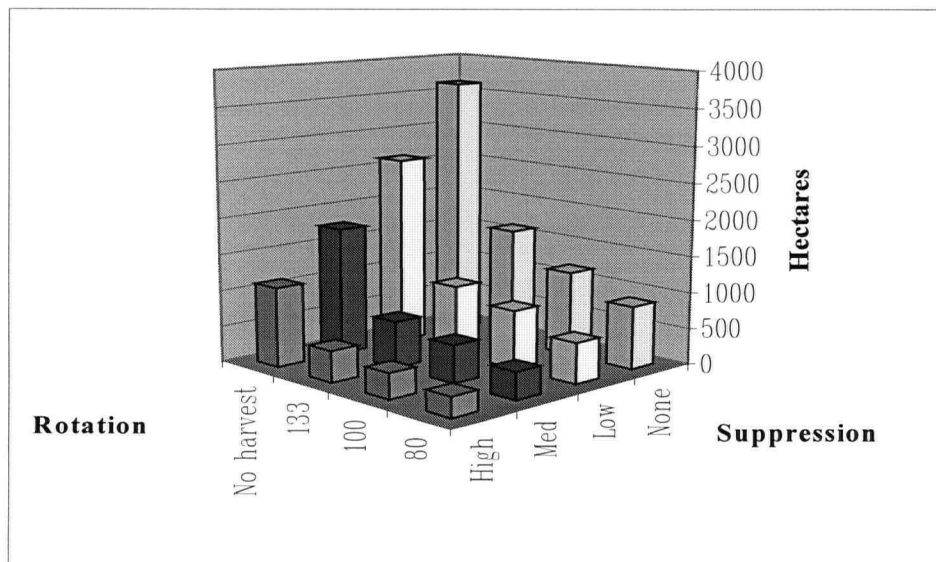


Figure 4.2.1 Plot of mean fire size against rotation age and suppression rate.

Similarly, an increasing harvest rate decreased mean fire size across all levels of suppression. The most significant decrease in mean fire size occurred when harvest was

first introduced into the system with a 133-year rotation. Subsequent increases in harvest intensity resulted in less significant changes.

The mean number of fires is illustrated in Fig. 4.2.2. The most noticeable effect is that fire suppression actually increases the number of fires when there is no harvest, which is the opposite of what happens with any level of harvest.

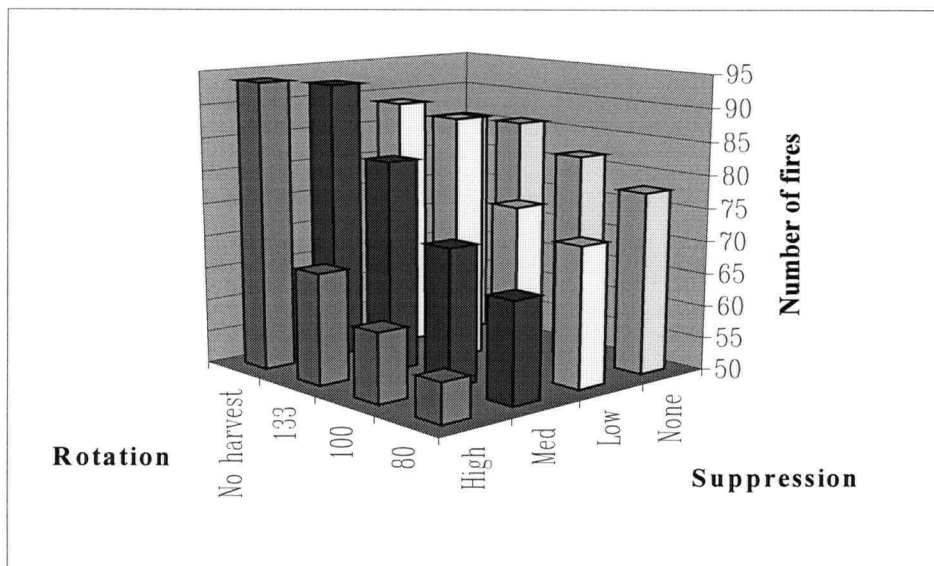


Figure 4.2.2 Plot of mean number of fires against rotation age and suppression rate.

Unmanaged forests produce more fires of significantly larger sizes. This may be due to the fact that the forest had no natural disturbance propagation barriers other than gaps created by disturbance. Without any kind of small-scale gaps such as rivers, lakes or other unburnable land, fires ignite more frequently and spread with less restriction. This is perhaps the reason for the sudden dramatic decrease in mean fire size with the addition of a moderate amount of harvest, as could be the sudden decrease in the number of fires. A small number of gaps distributed over the landscape significantly decrease the number of potential propagation routes.

Total landscape live biomass increases with reduction in harvest rate and increased fire suppression, with the exception of case (0, high) (Fig. 4.2.3). Perhaps more significant is how the means vary among different scenarios (Fig. 4.2.4). Without suppression, the

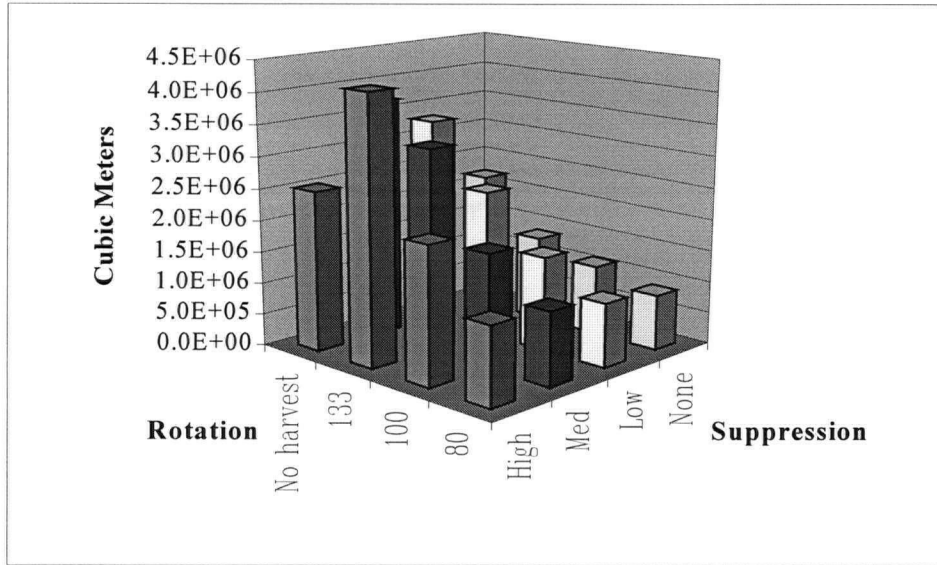


Figure 4.2.3 Mean live biomass.

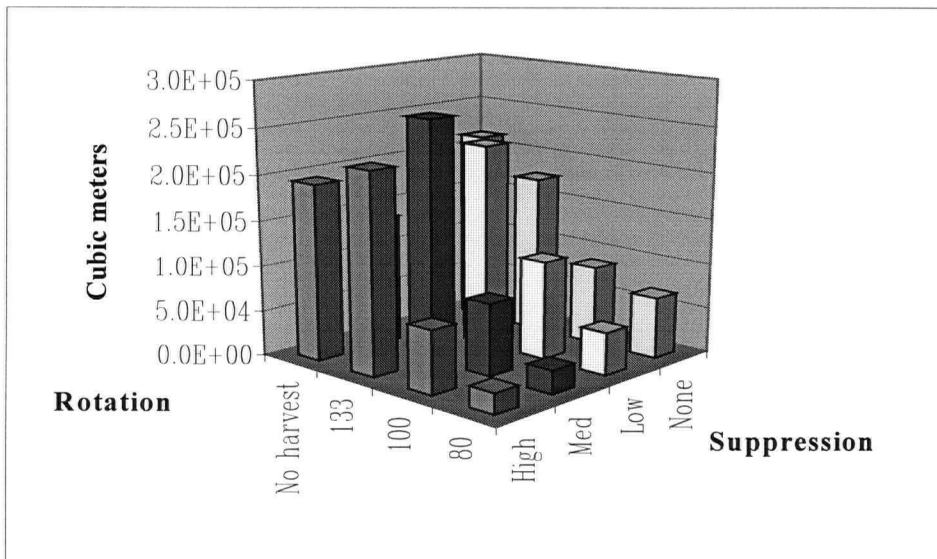


Figure 4.2.4 Standard deviation in mean biomass among simulations.

variation in simulation mean biomass increases as harvest is reduced. This is to be expected since it is clear in Fig. 4.2.1 that fire sizes increase with reduction in harvest. What is unexpected is that variation is highest at a 133-year rotation for levels of suppression. The variation is actually lower when there is no harvest and the highest variation occurs with a medium level of fire suppression.

Mean standard deviation of live biomass is shown in Fig. 4.2.5. Variation in this context implies variation over 512 years. In general, increased harvest activity lowers variation in simulations. It is interesting to note that there is no consistent trend in the way

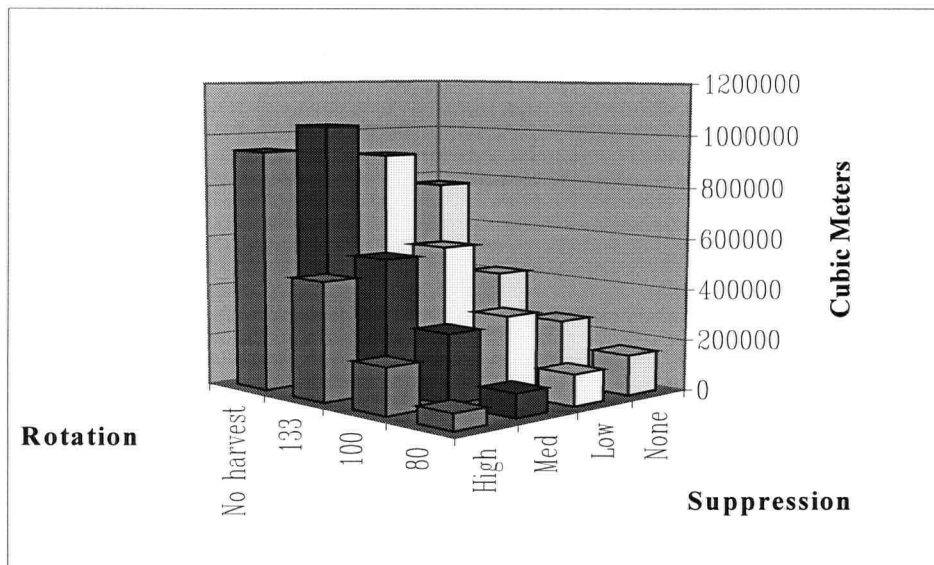


Figure 4.2.5 Mean standard deviation of live biomass.

variation changes across fire suppression levels. At an 80-year rotation age, it appears that increasing the level of fire suppression decreases the variability. The less intense the harvest regime, however, the more fire suppression appears to increase variation. At the same time, the highest level of suppression consistently has less variation than medium.

Beetle populations increase with an increase in suppression (Fig. 4.2.6). The beetle populations are shown in log scale so the actual increases are substantial. There are also substantial decreases in beetle populations with each increase in harvest.

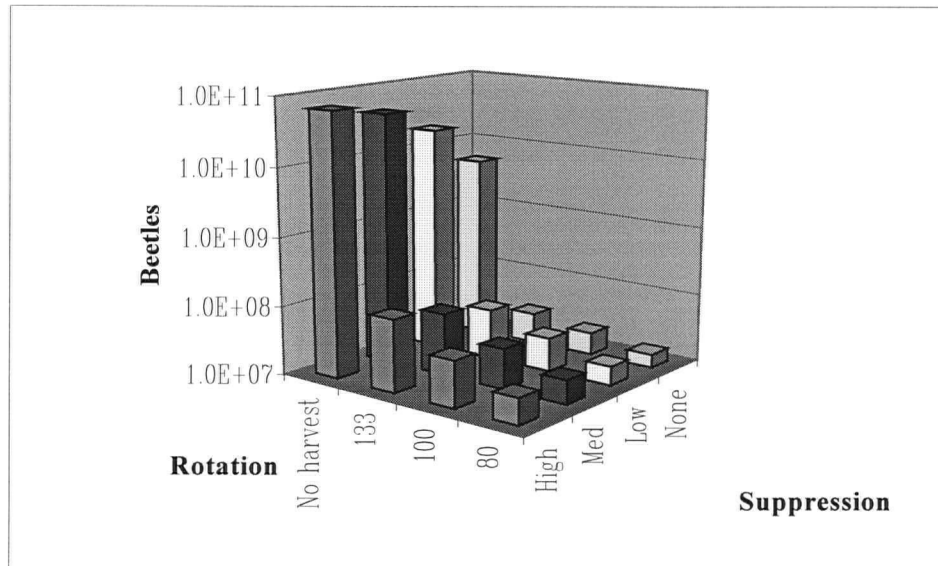


Figure 4.2.6 Mean beetle population.

Mean beetle population variation exhibits surprising behaviour. At low rotation ages, it decreases with increased levels of suppression (Fig. 4.2.7). At a 133-year rotation, and under no harvest, the trend is the opposite. It may be that increased fire suppression provides the necessary means for more beetle population explosions to occur on the more homogeneous landscapes of less harvested forests.

The more heavily the landscape was harvested the more evenly the land was proportioned into all possible age classes (Fig. 4.2.8). Fire suppression created smaller patches of more varied ages thereby lowering dominance.

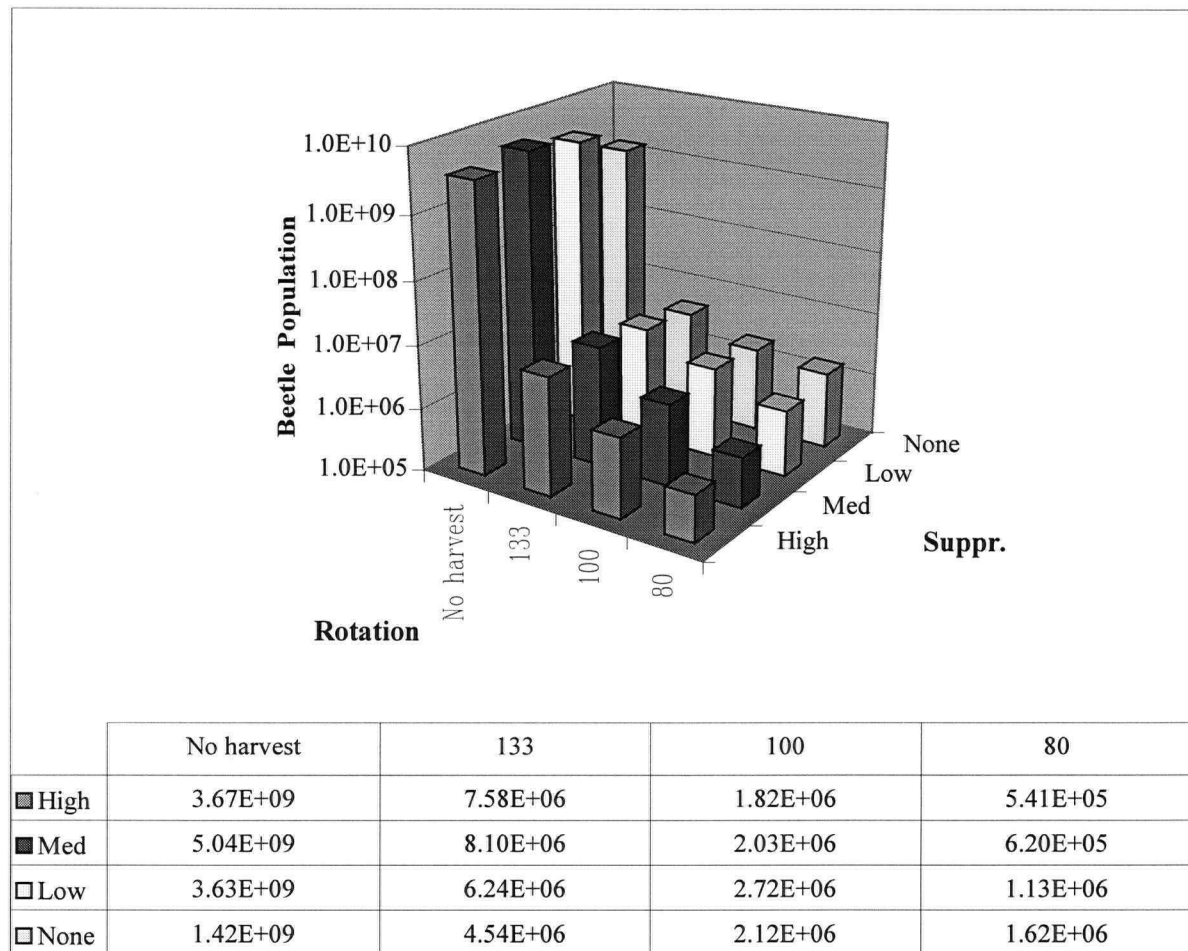


Figure 4.2.7 Standard deviation of beetle population means.

In the age class distribution graph (Fig. 4.2.9) we can see that as rotation changes from 133 to 100 the two lowest age classes increase at the expense of the highest age class. When the rotation age is changed to 80 years, age class 4 decreases significantly, accounting for the jump in dominance.

In general, variation in mean response levels of dominance is proportional to the mean values (Fig. 4.2.10). Intensely managed landscapes showed less variation among simulations.

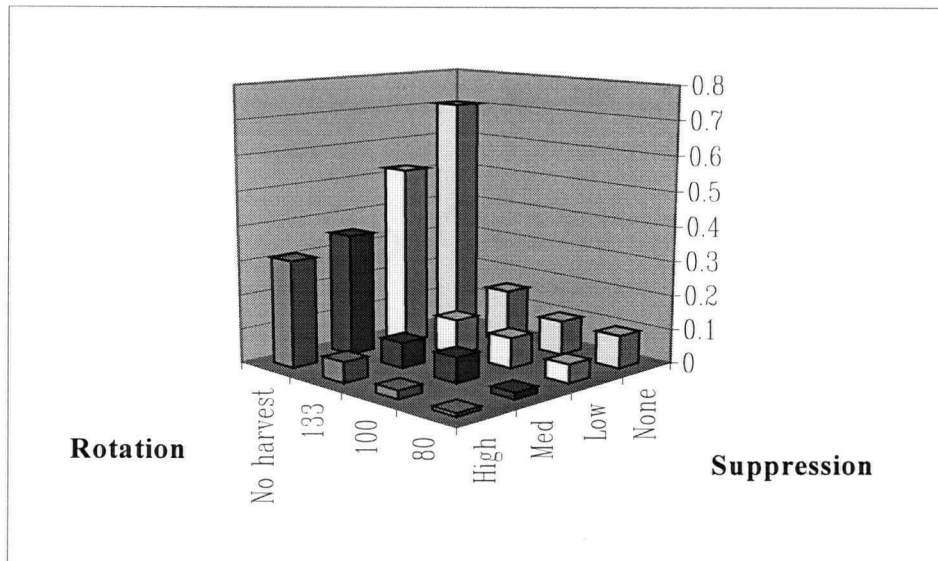


Figure 4.2.8 Mean dominance.

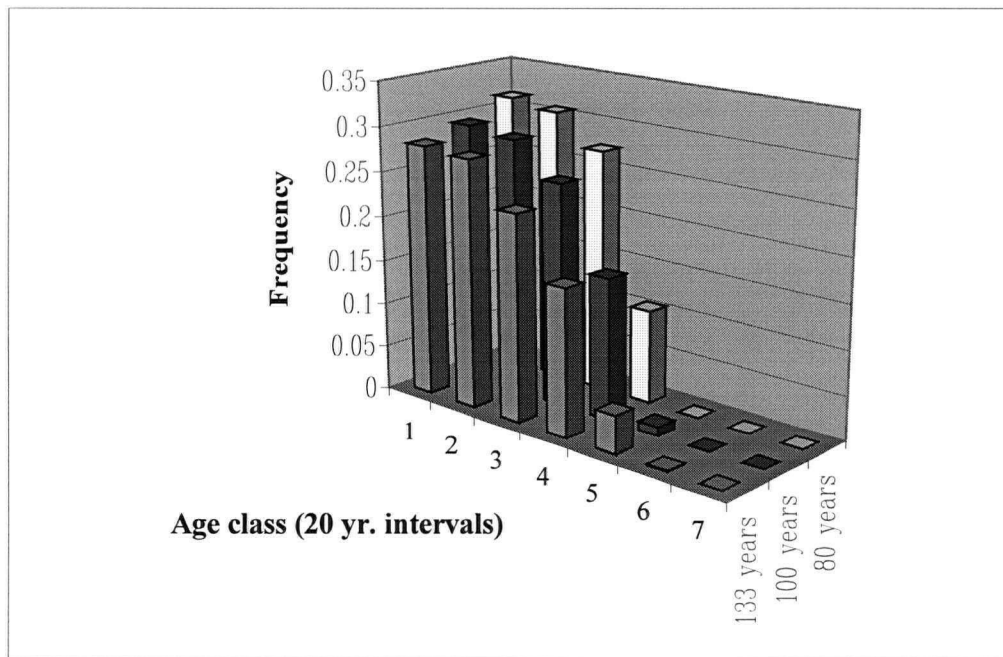


Figure 4.2.9 Age class distributions without fire suppression

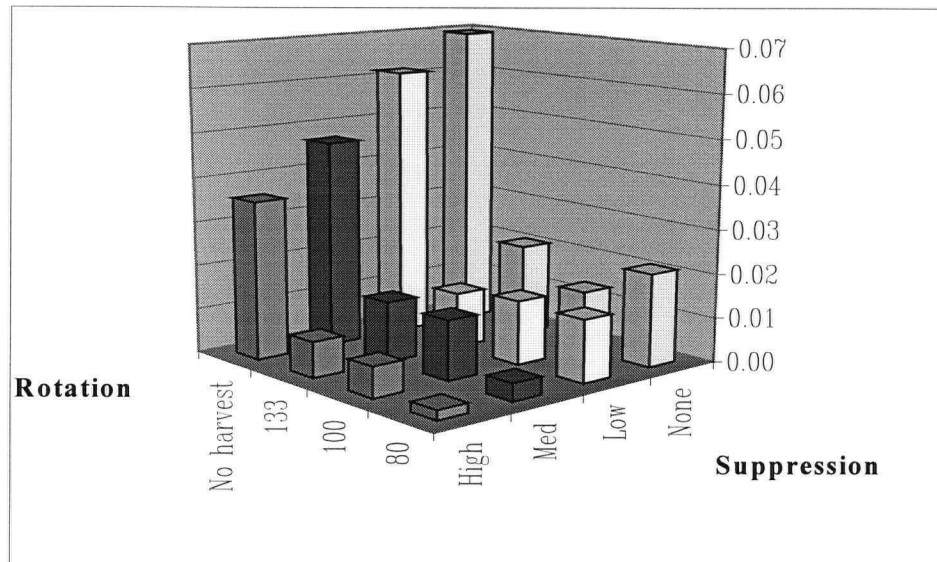


Figure 4.2.10 Variation in mean dominance.

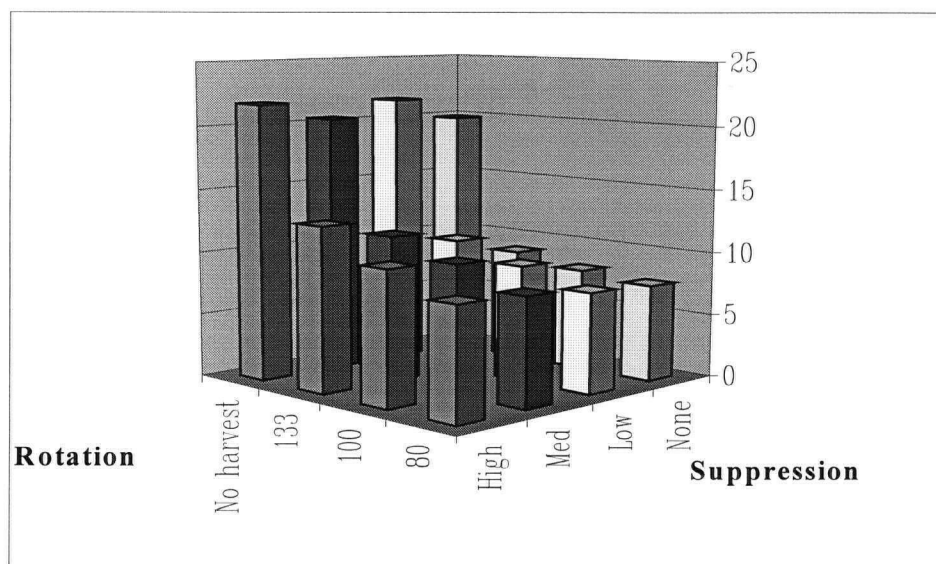


Figure 4.2.11 Mean contagion.

Behaviour of contagion mean is shown in Fig. 4.2.11. In general, at all levels of harvest, an increase in fire suppression causes an increase in contagion. Although this statement appears to be violated when there is no harvest, Fig. 4.2.12 shows high variation at

medium and no suppression, which may account for this fluctuation. Figure 4.2.13 shows the variation over 512 years, averaged for 30 simulations, for each scenario. The high variation at (0,low) and (0,none) seems to explain why the variation in means is high, and thus, why the mean levels were inconsistent with the trend in Fig. 4.2.11. The variation at (133,med) has a local low. For some reason, contagion does not change much over time for this scenario. In all cases, increased harvest stabilizes variation in time.

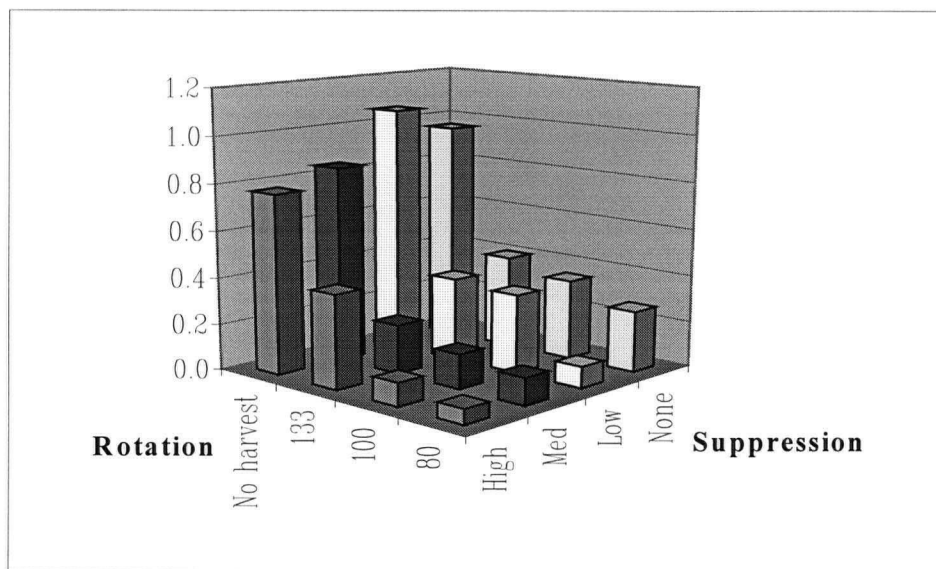


Figure 4.2.12 Standard deviation of Mean contagion.

I looked at the amount harvested per hectare (Fig. 4.2.14). Clearly, suppressing fires increases the amount per hectare whereas increasing the harvest intensity lowers it. It is interesting to note that the variation is lower in heavily managed conditions (Fig. 4.2.15). There also appears to be a bit less variation in an unsuppressed regime than one with a low amount of fire suppression.

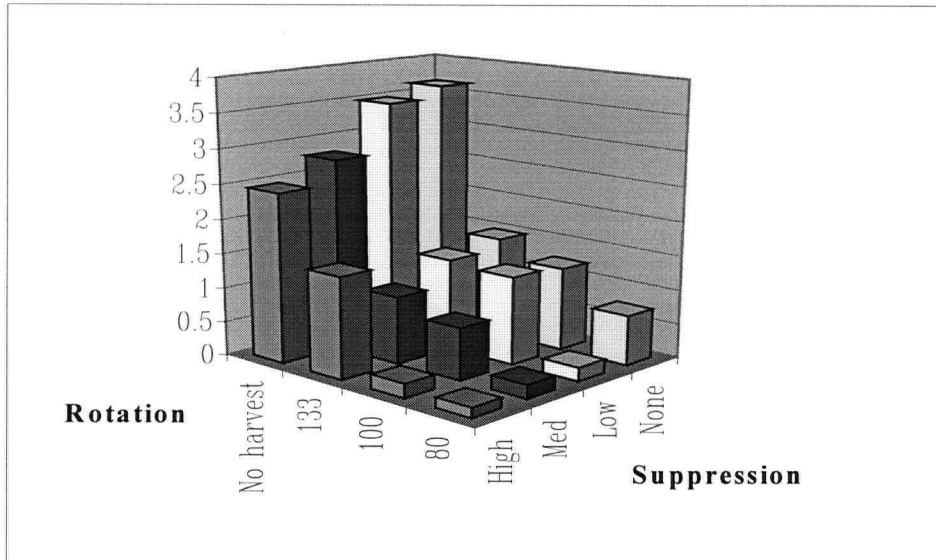


Figure 4.2.13 Mean standard deviations of contagion.

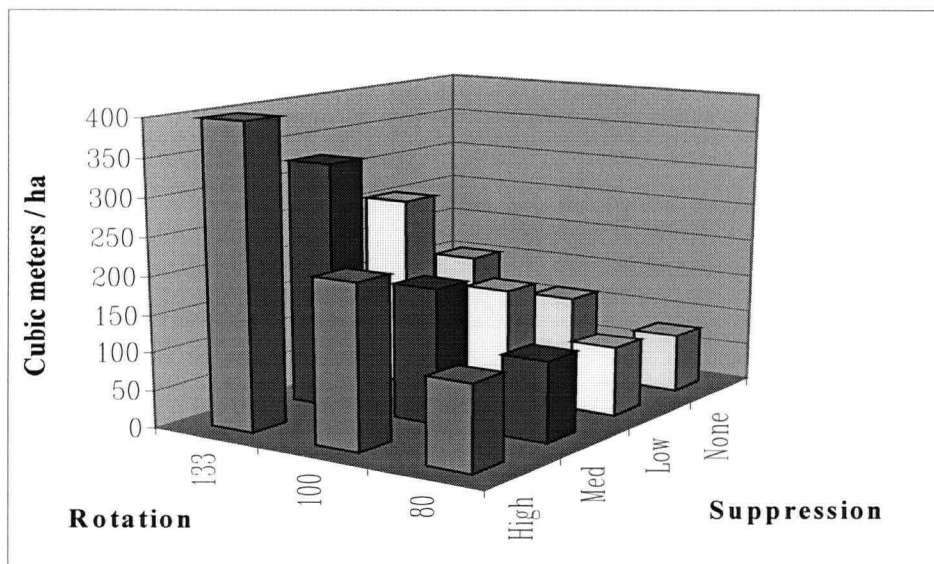


Figure 4.2.14 Mean harvest.

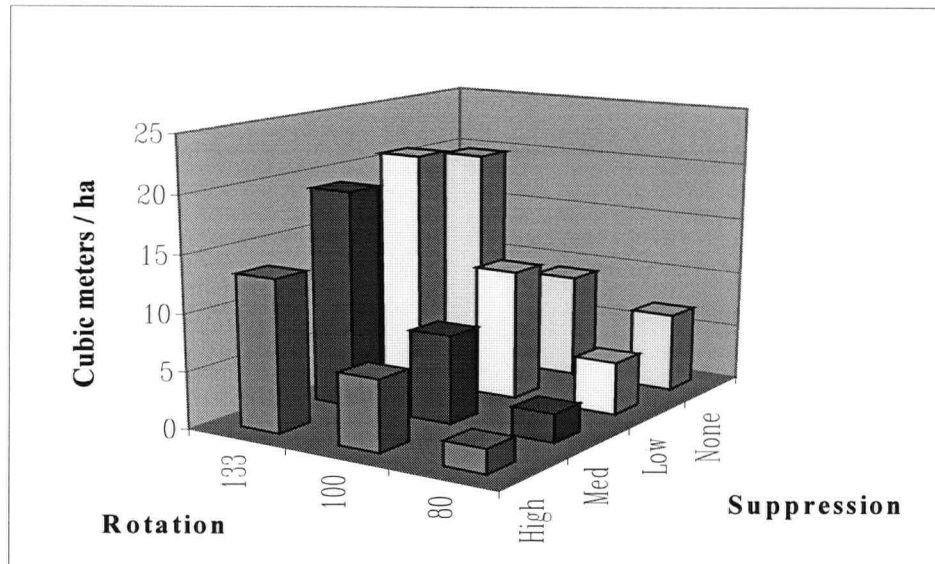


Figure 4.2.15 Standard deviation of mean harvest.

4.3 Spectral Analysis

Discussion in section 4.2 was limited to relationships between control and response variables. Response variables were examined at mean levels in relation to contrasting control variable levels. Both spatial and non-spatial responses were examined for variation between and among control levels. In this section I will examine the same response variables but in the time and frequency domains. Although spectra are plotted against frequencies, I will often refer to the corresponding period in the time domain.

Figure 4.3.1 shows spectral densities for all harvest levels with no suppression. Notice how the spectrum for dominance changes drastically when harvest is introduced. The power of the spectrum is no longer dominated by 1 and 2 cycles per 512 years. Further increases in harvest do little to change this. The power remains evenly distributed from 1 to 6 cycles (512, 256, 170, 128, 102 and 85 year periods) (figs. 4.3.1 (b), (c) and (d)).

Introducing suppression yields a different result (fig. 4.3.2) where the power remains relatively high at 1 and 2 cycles per 512 years. The only other significant frequency is 26 cycles (20 years), which is the effect of recruitment of cells into new age classes every 20 years. Harvesting appears to have a larger impact on the periodicity of dominance than fire suppression. Contagion, on the other hand appears to be respond more to fire suppression than harvest.

Harvesting appears to have an impact on the periodic behaviour of beetle populations. With harvest, the beetle population closely follows the same periodic pattern as live biomass. The harvested volume follows the same periodicity as live biomass as well (fig. 4.3.1 (b), (c) and (d)). These results may be explained by the fact that harvest eventually produces a forest of relatively young age classes.

Trees in young age groups are highly resistant to beetle attacks unless they are severely stressed. This forces beetles to live on fallen wood, which was calculated as a portion of live biomass (see section 4.2).

Live biomass show interesting behaviour. Without harvest, the addition of fire suppression, up to a medium level, shifts signal strength from 2 cycles (256 years) to 3 cycles (~171 years). Increasing the suppression intensity from low to medium strengthens the power at 171 years and decreases it at 256. Further increasing the suppression rate has the opposite effect. The power shifts back to a 256 year period at high suppression (fig. 4.3.2 (a)). What is lost when suppression is introduced are the high frequency signals visible between 10 and 15 cycles ((fig. 4.3.2 (d) and (c)). Higher levels of suppression reduce these signals significantly.

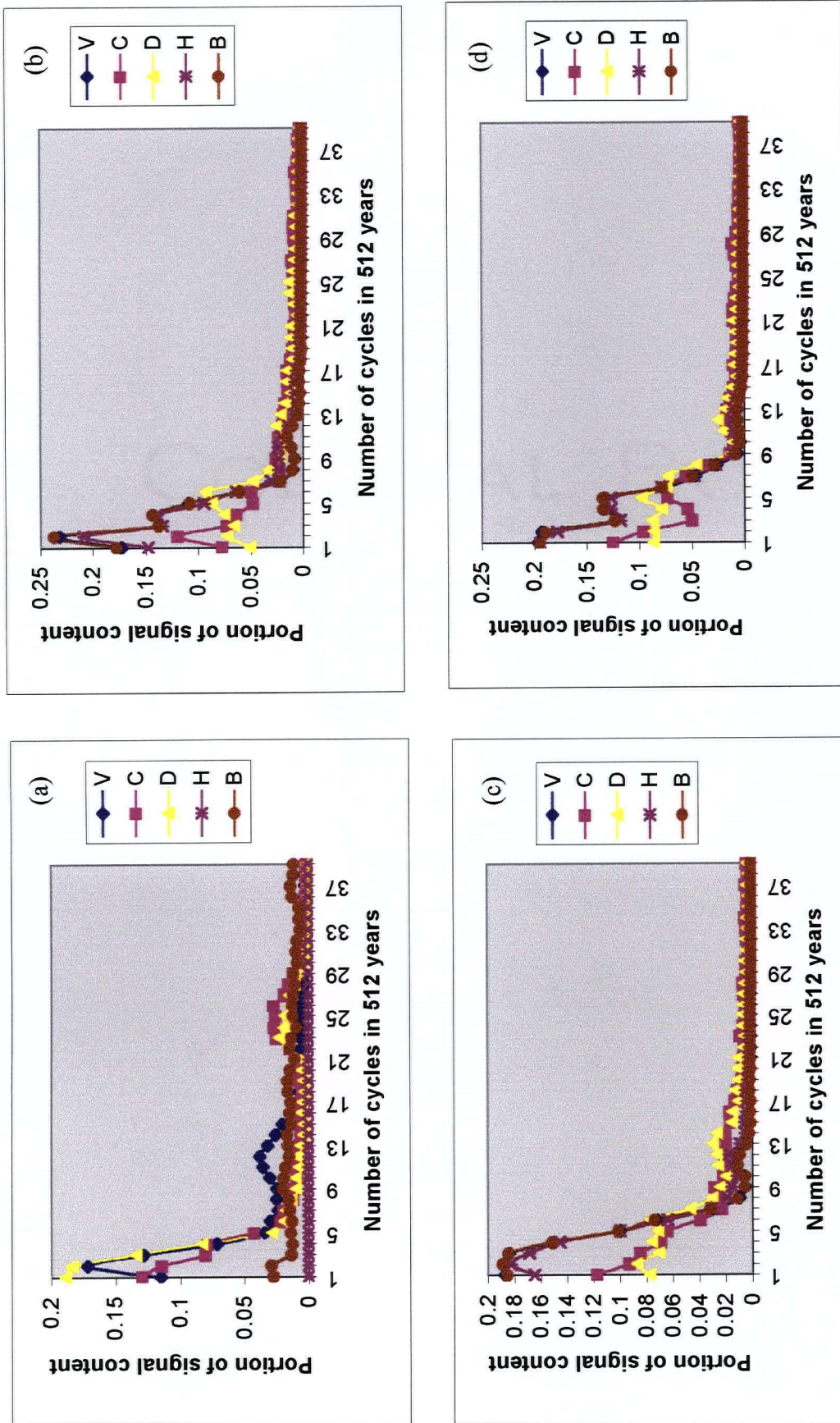


Figure 4.3.1 Normalized spectral density plot without suppression (V = Live biomass, C = Contagion, D = Dominance, H = Harvest, B = Beetles). (a) denotes the case with no harvest, (b) with a 133 year rotation age, (c) with a 100 year rotation age and (d) with an 80 year rotation age.

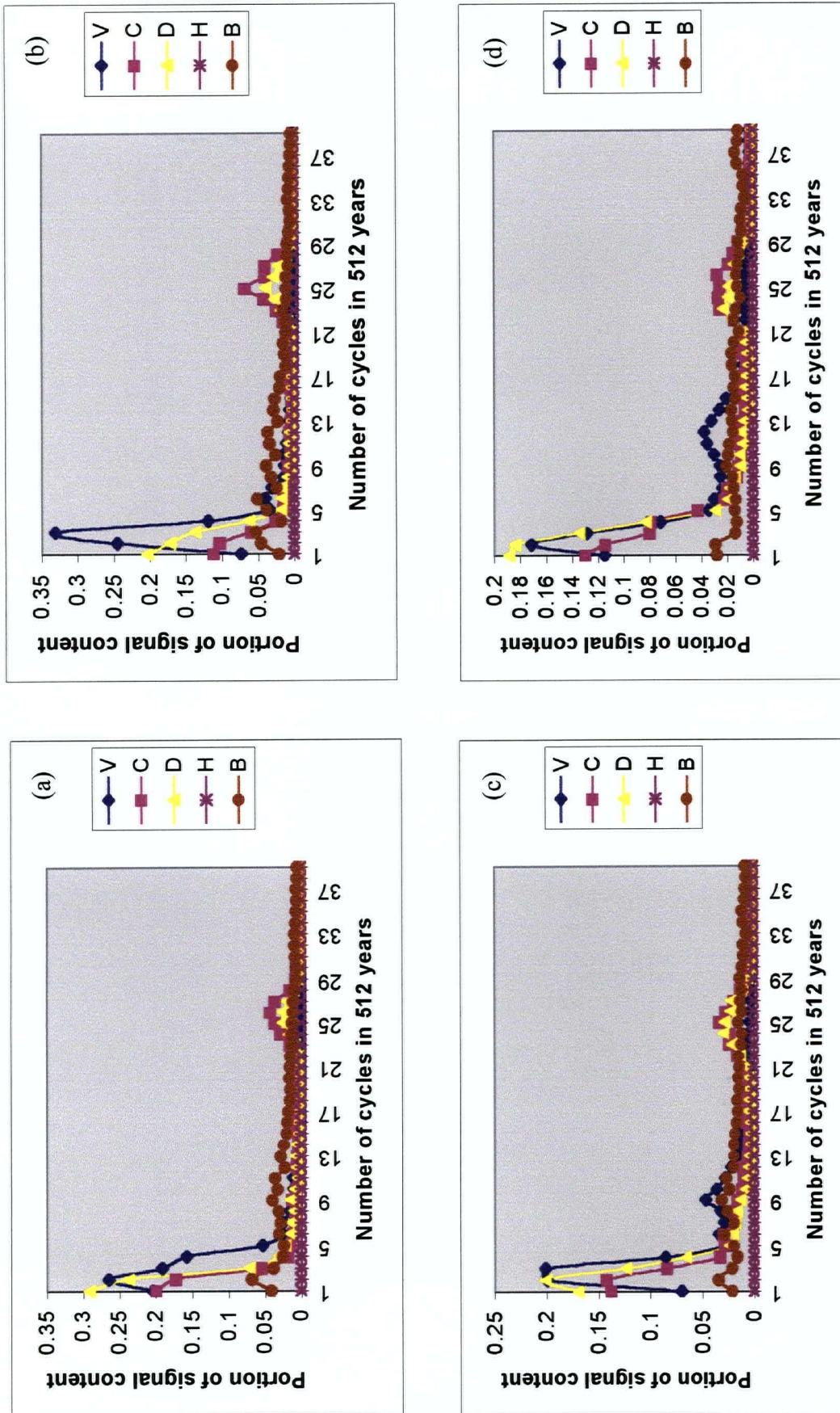


Figure 4.3.2 Normalized spectral density plot without harvest (V = Live biomass, C = Contagion, D = Dominance, H = Harvest, B = Beetles). (a) denotes the case where a high level of suppression is present, (b) medium, (c) low and (d) none.

5 Discussion

Since stand conditions were modeled to determine beetle resources, I attempted to find out what conditions most significantly affected beetles. Results showed that beetle populations were highly sensitive to the level of harvest. I attributed this to the fact that harvest effectively keeps forests young and that resistance (figure 3.2.1) is high at young ages. Additionally, other than the threshold of carrying capacity, no density dependence was modeled in beetle productivity so beetles never had a chance to thrive in the absence of within species competition or struggle in the presence of it. The result was that all harvest levels kept beetle net productivity low and beetle populations were insufficient to overcome tree resistance (except when stress was very high). Beetle populations merely existed at low levels living on fallen trees. Increasing the significance of stress kept beetle production up when forest age was reduced but still did not succeed in creating explosive populations. Harvest and fire both keep the forest at high levels of resistance by keeping it from growing old. It seems unlikely that beetle populations could be so vigorously controlled by a harvest regime of 133 years when 133 year old trees reach diameters known to have high beetle attack risk. Perhaps the answer lies in more detailed modeling of stress and resistance and density dependent factors of beetle productivity. Further investigation into the effects of beetle attacks on stress levels may show some insight into this behaviour.

Spatial scales are fundamental to system behaviour. I attempted to create a landscape large enough to represent the spatial extent of fires with pixels small enough to capture beetle migration scales. Computational limitations necessitated the choice of the largest

possible cell size and smallest possible area. This aggregated conditions over 100 hectares into a single 1 km^2 cell and limited the area to 400 km^2 . Aggregation may have resulted in loss of effective habitat, where habitat was dominated by the surrounding area in a cell. This may have had the effect of enclosing beetles in an unfavourable habitat, in a sense fencing them into unproductive cells to die. A smaller grain size may have allowed for escape by preserving some habitat that was dominated in a larger grain size. The choice of cell size may also have had an adverse effect on fire spread. Had fires been modeled such that partially burned cells were possible, they may have contributed to stress levels and increased beetle production rather than consistently inhibiting it.

Initialization was specific to each scenario. Forests evolving in one management regime can react strongly to having other management practices imposed on them. As discussed in section 3.1.5, I created a template initialization to use for all simulations of a given scenario. This way, initial conditions did not “clash” with the system. It allowed me to observe behaviour in a state normal for a system rather than record the way a system adjusted and overcame initial conditions. The drawback is that this provides no insight into the repercussions of changing from one management alternative to another.

Perhaps the most significant result found in the simulations was that harvest appears to determine many aspects of system performance in certain ranges of simulated management practice. Harvest lowered mean fire size for all levels of suppression and it decreased the number of fires that occurred as well. For the most part, increases in harvest lowered variation both in time and among mean simulated responses. Harvest also controlled beetle populations as did fire (Fig.4.2.6). It would seem that harvesting, and to a lesser extent fire, inhibit beetle populations from reaching epidemic levels.

It is interesting to note that there were cases where trends were inconsistent. For example, at all levels of suppression except the highest, increased harvest intensity lowered variation. At a high level of suppression, however, introducing harvest actually increased variation in mean biomass (Fig. 4.2.3). For low, medium and high levels of suppression, the introduction of harvest increased variability in time (Fig. 4.2.4), but then further harvest decreased it. This raises suspicion that critical points in system behaviour may exist in certain ranges of management practice. Further effort would be required to determine if anomalous behaviour observed in the model was more than just an artifact of model formulation.

6 Conclusions

The context for this study was the desire to develop a method to explore the way in which fire, insect outbreaks and forests interact. I wanted to do this both spatially and stochastically on a landscape level. I was particularly interested in developing a way to examine periodic behaviour without having to scrutinize reams of individual response signals. Simulations were designed to identify the effects of altering management practice. The stochastic nature of fire and environmental factors necessitated using a Monte Carlo approach, which provided an insight into the range of variation between and within control levels. Fourier analysis made it possible to look at average periodic tendencies across a range of control levels.

Despite the effort to initialize all simulations of a common management scenario the same way, it is obvious that simulations develop unique histories. It took 30 simulations of 512 years each to get a sense of how the system varied. Only through aggregation of

mean response levels and spectral signals was it possible to determine average behaviour and spectral density. There is a significant repercussion to this. Land managers faced with studying disturbance ecosystems must consider that data collected from a single time span may only represent one possible course of history. It may be dangerous to assume that behaviour observed in a single sample adequately represents the way the system can be expected to behave. In addition, since conditions change so rapidly it is difficult to assume that conditions would have been consistent over the time span of observations.

A problem, which was not addressed in this project, is that change inherently forces conditions onto a system that it may not be adapted to. All simulations were initialized with conditions that were products of the same management regime as the simulation. What managers need to consider is that management practices such as those modeled in this study may perform differently when applied to landscapes not pre-adapted to those practices. Considering that forest managers are currently looking for ways to reshape forests to meet a growing list of objectives, it would be interesting to see the effects of implementing different management plans in different landscapes. The consequences of harvesting and suppressing fires in a previously unmanaged forest would be of particular interest, as would be the consequences of leaving a previously managed forest unmanaged.

The model was not created with the intention of simulating detailed behaviour and predicting precise outcomes. It was created in order to explore the way the system performed in different management practices. Further development would include added detail in density dependent formulation of both stand growth and beetle productivity. It would also involve a study on the effects of altering grain and extent. We cannot, nor will

we ever, capture all the detail of natural systems subject to stochastic variation. The model can not predict what a landscape will look like in 50 years given its current conditions but it can estimate average behaviour over long periods under a constant management regime. Most importantly, the model has given credibility to the notion that forest conditions may be periodic and that land managers should ask whether forest conditions are rising or falling on a periodic trajectory. Spectral density estimates, although they tend to abstract the data, provide a useful way to view average periodic trends. They make possible a qualitative assessment of periodic trends in large amounts of data.

This thesis simulated a complex system of spatial and temporal scales and gave insight into system interaction and periodic behaviour. This study is a prototype method of dealing with the problems associated forest disturbance modeling and a first step at understanding the spatial and temporal processes that occur in managed forests.

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