A Pest and Timber Management Model: Jack Pine Budworm and Jack Pine

J. K. Rawat, K. L. Belli, S. M. Smith and J. C. Nautiyal

Faculty of Forestry, University of Toronto, Toronto, Ontario M5S 1A1.

Received 17 November 1986, accepted 6 May 1987

A simple illustrative mathematical model for integrating forest pest control decisions with timber management is developed for a hypothetical jack pine forest infested with jack pine budworm. Subject to several assumptions made in the model, optimal quantities and timings of pesticide application and optimal rotation ages of the forest are determined under various sets of parameters such as cost of pesticide, stumpage price, pest population growth rate and age of the forest at the time of pest infestation. The sensitivities of the optimal values to these parameters are examined. In general, the rotation age and hence harvesting schedule is affected under different pest situations, site conditions and economic parameters. In addition, immediate pest control action following noticeable pest infestation in young crops may not always be the most profitable decision, particularly when only one pesticide application is permitted and when net return expected from a crop is low. These findings have implications for effective pest and timber management.

Nous avons élaboré un modèle mathématique simple intégrant les décisions de lutte contre les parasites forestiers et la gestion du bois d'oeuvre pour une forêt de pins gris hypothétique infestée de tordeuses du pin gris. Nous avons ainsi déterminé les quantités optimales et l'échéancier pour l'épandage de pesticides ainsi que l'âge optimal de rotation de la forêt, compte tenu de divers groupes de paramètres (par exemple, coût des pesticides, prix du bois sur pied, taux de croissance et date de l'infestation), en vertu de diverses hypothèses de départ intégrées dans le modèle. Nous avons examiné la sensibilité des valeurs optimales face à ces paramètres. En général, l'âge de rotation et, par ricochet, l'échéancier de la récolte changent en fonction de l'ampleur de l'infestation, de l'état du peuplement et des paramètres économiques. En outre, l'application de mesures immédiates de lutte dès les premiers signes d'une infestation dans les jeunes peuplements risque de ne pas toujours être la décision la plus profitable, en particulier lorsqu'on ne permet qu'un seul épandange et que le revenu attendu d'une récolte est faible. Ces résultats ont une incidence sur les mesures de lutte antiparasitaire et sur la gestion du bois d'oeuvre.

INTRODUCTION

Increasing demand for Canadian forest products and nontimber uses of forest lands during the last few decades had led to a higher investment and a greater emphasis on intensive forest management than in the past (Smyth et al 1984). Effective pest control measures are part of intensive forest management. The economic importance of pest control both in forestry and agriculture has been dealt with by a number of authors, including Morris (1951), Eaton (1962), Johnson (1963), Headley (1972b), Waters and Cowling (1976), Waters and Stark (1980), and Mumford and Norton (1984). In Canada, where more than 90% of the productive forests are owned by the Crown and where the provinces have sole responsibility for protecting them, damage to forests by pests and diseases is seen with great concern by the government and, to some extent, by the public.

Effective methods of detection and control of harmful pests have been developed over the years. Of the various pest control methods, silvicultural techniques are environmentally more appealing and also are found to be potentially successful. However, pesticides have been most commonly used and remain the most reliable immediate solution to the problem at hand (Huffaker and Smith 1980). The pesticide may be chemical (such as DDT, malathion and arsenicals) or microbial (such as *Bacillus thuringiensis* or *Baculovirus* spp., a nucleopolyhedrosis virus). The effects of chemicals on insects are relatively better known, and chemical control methods have been found to be more practical and economical to use, compared with biological control methods (Blais 1976 and Bartsch 1978).

Pest control decisions require knowledge of the behavior of pest populations, current and potential losses due to them, and the effectiveness and cost of control measures. Several models describing the growth of pest populations are reviewed by Shoemaker (1973). Studies have been conducted to assess the role of pesticides in controlling various pests and of damages to different forest species caused by these pests (Waters and Stark 1980, Markin and Johnson 1983, Cadogan et al 1984, Hall 1984 and MacLean 1984).

Most crop pests, including those associated with forests, are highly adaptive and are not likely to be eradicated. Containment of their population rather than prevention or eradication should be the logical objective of management (Huffaker and Smith 1980). On economic grounds, pest control is desirable only if the cost of control is lower than the potential loss caused by the pest. This principle has led to the concept of economic threshold, which is generally defined as the pest population level at which controls should be initiated (Headley 1972a, Stern 1973 and Hall and Norgaard 1973).

Of course, variables other than those dealing with economics also influence the threshold. These variables include local climatic conditions, time of year, stage of plant development, the crop involved, plant variety, cropping practices, the purpose for which the crop is to be used, and the desire of man.

Given the pest population growth rate and other information mentioned above, the most important decisions to be taken in chemical or microbial control of pests are the optimal quantities and timings of pesticide application. Several mathematical models to answer some of these questions have been developed for both agricultural and forest pest management (e.g., Morris 1963, Watt 1964, Campbell

1967, Becker 1970, Mann 1971, Headley 1972a, Chatterjee 1973, Hall and Norgaard 1973, Hueth and Regev 1974, Talpaz and Borosh 1974, Coulson 1979, and Cuff and Baskerville 1983). These models try to determine the pest control strategy that will minimize damage or maximize net returns from a crop.

In the case of intensive forest management, another important decision to be taken by a forest manager is when to harvest the trees to obtain maximum net returns over a long planning horizon. Once a forest crop has been affected but not completely destroyed by an insect outbreak, the optimal age to harvest the damaged crop may need modification (Rose 1973). Several models (Bible 1981, Nyrop et al 1983, and MacLean and Erdle 1984) have been developed, using various programming techniques, to take into account the effect of insect outbreaks on forest growth and yield. These models determine revised harvesting (and thinning) regimes to minimize the economic impact of pest damage. However, they are not designed to deal with pest control decisions. Since pest infestation affects growth and yield, the necessary determinants of economic rotation age, pest control and timber management decisions are interlinked. Therefore, there is a need to develop a more comprehensive model to couple crop protection and crop production decisions (Luckmann 1982).

In this paper, an optimization model for integrated pest and timber management is developed. It is then applied, for purposes of illustration, to a hypothetical jack pine (*Pinus banksiana* (Lamb.)) forest infested with jack pine budworm (*Choristoneura pinus* (Freeman)). The pesticide used is assumed to be *Bacillus thuringiensis*, or B.t. For the sake of simplicity the model presented here deals with an even-aged forest stand only and not with an entire management unit composed of various age classes. Although this has the effect of eliminating direct, practical application of the results, developing a simpler model will open the way to more realistic and comprehensive models. Numerical search methods are used to determine optimal control treatments and to investigate the sensitivities of decision variables to certain important parameters. Development of the model also demonstrates the inadequacy of our knowledge in the field of pests and their economic impact on forest for determining optimal control activities.

THE MODEL

The model is an application to forestry of the principles discussed by Hall and Norgaard (1973). In adapting this approach, harvest date must become a decision variable to accommodate the multi-year time frame not found in the management of annual crops. This constitutes the only conceptual dissimilarity from the Hall and Norgaard model. The following five basic functions are used as a model framework: pest population growth function, kill (of the pest) function, timber damage function, pesticide cost function and timber production function. These functions are briefly discussed in the following paragraphs in the context of hypothetical situations employed for analysis in this paper.

It is postulated that endemic pest populations remain at more or less constant levels and that they threaten to grow to epidemic levels only when (because of some environmental factors) the reproductive rate is increased and/or natural mortality is reduced. If the endemic population levels are known, any increases in them beyond the expected bounds can be considered to be potentially threatening. This model is meant to be used only when such a threat is perceived.

Empirical evidence (Shoemaker 1973) shows that pest population growth rate at any time t depends on the population density $P(t)$ at that time and on the density-dependent birth-minus-death rate $F(P)$. This growth process can be expressed as:

$$\partial P/\partial t = F(P)\,P(t) \tag{1}$$

If $F(P)$ is assumed to be a linear function of $P(t)$, the solution of Eq. 1 yields the pest population growth function, given by the following expression, known as the logistic equation (Clark 1976):

$$P(t) = \frac{E}{1 + \left(\frac{E}{P_0} - 1\right) e^{-rt}} \tag{2}$$

where

E = carrying capacity (i.e., maximum attainable population size),
r = intrinsic rate of natural increase (i.e., the rate at which the population grows if resources are unlimited and if the individuals do not affect one another), and
P_0 = initial pest density (Ruesink 1976).

The control measures against defoliators are usually of the kind where pesticide is sprayed on the affected crop during an appropriate season. Several factors, such as concentration, season, temperature, time of the day, insect behavior, spraying technique and equipment, affect the performance of the pesticide. The size of particles and the proportion of pesticide reaching the target pests have a very important bearing on the efficiency of a control operation. It is assumed that the forest manager has adequate knowledge of these factors (Williams and Shea 1982, Akers and Nielsen 1984, and Hall 1984) and that the pesticide is utilized in a technically efficient manner. In such utilization, the overall effectiveness of a pesticide is generally given in terms of a fraction of the pest density it is able to kill (Markin and Johnson 1983 and Cadogan et al 1984). This fraction itself may be a monotonically increasing function, $f(X)$, of the amount X of active ingredients of the pesticide used (Talpaz and Borosh 1974) expressed as litres per hectare, with formulation, g/L, held constant. Though little is known about the kill function for forest pests, it is assumed that in general it can be expressed as:

$$K = f(X)\,P(t) \tag{3}$$

such that $f(X) \longrightarrow 0$ as $X \longrightarrow 0$ and $f(X) \longrightarrow 1$ as $X \longrightarrow \infty$. Also, because of the diminishing marginal impact of an additional dosage of pesticide, $f(X)$ should increase with X at a decreasing rate.

The following exponential function satisfies these conditions and is therefore used as a factor in the kill function:

$$f(X) = 1 - e^{-aX} \tag{4}$$

where

a = a measure of the effectiveness of the pesticide.

The greater the value of a, the more effective the pesticide. Pests surviving the pesticide application are assumed to grow again according to their growth function in Eq. 2.

The reduction of volume in a forest or stand is partially due to direct losses from mortality (excluding salvage of dead trees) and partially due to lower growth rates of stressed trees. A pest could be incorporated into the production function of a forest crop as a negative input, and the reduction in volume due to the increase in the pest population could be seen as damage. In the absence of adequate yield and growth data from controlled experimental plots, this is not easy to do. Alternatively, potential damage in the shape of merchantable volume destroyed by an infestation could be determined directly, if past records of damage and the corresponding pest population are used and if the damage is assumed to be proportional to the pest density. Such proportionality has been employed in describing damage functions in agricultural pest models (Chatterjee 1973, Hall and Norgaard 1973 and Talpaz and Borosh 1974).

In the case of forest pests, it is not obvious that such proportionality is always justified. Several experiments have been conducted to study the effects of insect defoliation on growth and mortality of trees (Kulman 1971). Though it may not be possible to determine a general damage function for all forest pest situations, some approximate relationships can be estimated for specific pest-host combinations. In this paper, it is assumed that damage is directly proportional to pest density (later this assumption is approximately justified on the basis of some data available for jack pine and jack pine budworm).

The damage function can then be expressed as:

$$g(t) = b\,P(t) \tag{5}$$

where

$g(t)$ = the instantaneous rate of stand damage in physical units due to pests and

b = a parameter denoting rate of stand damage per unit pest density.

The total damage, $G(t_2 - t_0)$, accumulated at the time of harvest t_2, since the time it is recognized as capable of taking epidemic form, t_0, is the sum of damage caused prior to time t_1 when the pesticide is applied, and that caused after it:

$$G(t_2 - t_0) = \int_{t_0}^{t_1} g(t)\,dt + \int_{t_1}^{t_2} g(t)\,dt \tag{6}$$

In a general form, this can also be expressed as:

$$G(t_2 - t_0) = b \int_{t_0}^{t_1} P(P_0, t)\,dt + b \int_{t_1}^{t_2} P(P_1, t)\,dt \tag{7}$$

where $P_1 = (P(t_1) - K)$, the pest density at time t_1 remaining after pesticide application.

Using the logistic equation, Eq. 2, the cumulative damage function in Eq. 7 can be written as:

$$G(t_2 - t_0) = \frac{bE}{r}\, ln \left[\left[\frac{P_0}{E}(e^{r(t_1 - t_0)} - 1) + 1 \right] \cdot \left[\frac{P_1}{E}(e^{r(t_2 - t_1)} - 1) + 1 \right] \right] \quad (8)$$

The cost of control C can be assumed to be linearly related to the effective quantity of pesticide applied. It may or may not include the initial set costs, as these affect only the net revenue and not the optimal control levels (Chatterjee 1973 and Hall and Norgaard 1973).

A simple cost function can thus be expressed as:

$$C = \alpha X \quad (9)$$

where
α = the cost of purchasing and applying one unit of active ingredient of the pesticide.

It may also be assumed to include the rent of the equipment used if the rent is charged on the basis of usage. This will obviate the need for including initial fixed cost in the cost function.

A timber production function is of a complex nature (Nautiyal and Couto 1984) but, for the sake of simplicity, the volume of timber, $V(t)$, produced on each hectare of an even-aged forest stand can be treated as a function of age only (Payandeh 1973).

Assuming the forest is managed for timber production only, the net yield per hectare, $Y(t)$, can be expressed as:

$$Y(t_2) = V(t_2) - G(t_2 - t_0) \quad (10)$$

It is assumed that at no stage does the cumulative damage exceed the volume of growing stock; that is, $Y(t_2) > 0$ for all ts and t_0s.

In view of the long duration of time involved between various costs and benefits, present net worth of a forest plantation is the only logical objective function of a forest enterprise. By discounting different costs and revenues with the real rate of interest i, these values can be brought to a common point in time, say, at $t = 0$. In this model, revenues and costs during a single rotation only are considered. The occurrence and time of pest infestation for the subsequent rotations cannot be known; thus the planning horizon of the forest manager is restricted to one rotation only.

The expected present net worth W per hectare for a forest can be expressed as:

$$W = \frac{\beta Y(t_2) - Ce^{i(t_2 - t_1)}}{e^{it_2}} \quad (11)$$

where
β = the stumpage price.

Substituting Eq. 9 and Eq. 10 into Eq. 11 will give:

$$W = (1/e^{it_2}) \left[\beta\,[V(t_2) - G(t_2 - t_0)] - \alpha\, X e^{i(t_2 - t_1)} \right] \tag{12}$$

Optimal levels of the three decision variables X, t_1 and t_2, denoted by X^*, t_1^* and t_2^*, respectively, are those that maximize the objective function W in Eq. 12. These optimal values are obtained by solving the following three first-order conditions for maximization of W:

$$\beta\, \partial D/\partial X = -\alpha\, e^{i(t_2^* - t_1^*)} \tag{13}$$

$$\beta\, \partial D/\partial t_1 = i\, \alpha\, X^*\, e^{i(t_2^* - t_1^*)} \tag{14}$$

$$\beta\, \partial Y/\partial t_2 = i\, \alpha X^*\, e^{i(t_2^* - t_1^*)} + i\, W e^{it_2^*} \tag{15}$$

In economic terms, the condition in Eq. 13 means that optimal intensity of pesticide application is achieved when the value of damage saved by an additional unit of active ingredients of pesticide just equals the cost, with both values measured at the time of pesticide application. Similarly, the condition in Eq. 14 implies that the optimal time of pesticide application is when the value of damage caused by one year's delay in the application just equals one year's interest earned on the cost of control. Finally, Eq. 15 describes the condition for optimal harvest age. At optimal t_2, the value of marginal net yield from the forest, by delaying the harvest for one more year, equals the sum of additional interest to be paid on the control costs and one year's interest lost on the value of growing stock.

Despite several simplifying assumptions used in the model, solving these conditions analytically is difficult since the expression for cumulative damage in Eq. 8 is quite complex. Moreover, the solutions obtained from the first-order conditions is valid only if the second-order conditions for maximization are satisfied. These require that (Allen 1938):

$$\partial^2 W/\partial X^2 < 0 \tag{16}$$

$$\begin{vmatrix} \partial^2 W/\partial X^2 & \partial^2 W/\partial X \partial t_1 \\ \partial^2 W/\partial t_1 \partial X & \partial^2 W/\partial t_1^2 \end{vmatrix} > 0 \tag{17}$$

$$\begin{vmatrix} \partial^2 W/\partial X^2 & \partial^2 W/\partial X \partial t_1 & \partial^2 W/\partial X \partial t_2 \\ \partial^2 W/\partial t_1 \partial X & \partial^2 W/\partial t_1^2 & \partial^2 W/\partial t_1 \partial t_2 \\ \partial^2 W/\partial t_2 \partial X & \partial^2 W/\partial t_2 \partial t_1 & \partial^2 W/\partial t_2^2 \end{vmatrix} < 0 \tag{18}$$

The condition in Eq. 16 is a simple inequality and can be readily understood in practical terms. For instance, it can be shown that when the cost function is linear with respect to X (as in Eq. 9), a kill function that increases at a decreasing rate (as assumed in Eq. 3 and Eq. 4) adequately satisfies the condition in Eq. 16. However, the determinants in Eq. 17 and Eq. 18 yield complex expressions on expanding and it is not easy to interpret them for any physical meaning. Therefore, no further analytical treatment of this model is attempted and the numerical approach to its solution is taken. A simple numerical search computer program can be used to solve the model for a hypothetical but realistic pest-host situation in the field.

ANALYSIS

For the analysis, an even-aged stand of jack pine on site class-3 in Ontario being managed for timber production is considered. Its gross merchantable volume[1] per hectare in cubic metres at various ages, as shown in normal yield tables (Plonski 1974), can be mathematically expressed as:

$$V(t) = 367.3 + 24.6\,t - 0.083\,t^2 - 186.2\,t^{0.5} \tag{19}$$

where

t = the age of the crop.

It is further assumed that the forest is infested with jack pine budworm (hereafter abbreviated as JPBW) whose population in the epidemic stage grows logistically. The model is applied to the above pest-host combination and the values of X^*, t_1^* and t_2^* for various pest situations and economic conditions are determined.

To begin, it is necessary to quantify various constants and parameters employed in the model. The values for parameters P_0, E and b can be estimated from experimental observations related to JPBW infestation and the corresponding timber damage (Kulman et al 1963, Foltz et al 1972, Rose 1973, and Clancy et al 1980). There are several potential indicators of pest population density P_0, such as counts of egg masses, early larvae, late larvae or pupae, to consider. The late larval count comprising principally fifth and sixth instars appears to be the most appropriate estimator for three reasons. First, maximum defoliation and hence damage is done by these larvae (Batzer and Millers 1970 and Prebble 1975). Second, survival factors in these age intervals have little effect on population change (Foltz et al 1972) and, therefore, pest population in the subsequent generation can be more accurately predicted. Finally, sampling techniques for larval counts are well standardized.

Recording the number of larvae observed on specific sizes of midcrown branch tips of affected trees is a common sampling technique for budworms (Sanders 1980). For JPBW, the average total number of larvae found on six 38-cm-long midcrown branch tips per plot is taken as a pest population indicator (Clancy et al 1980). These average late larval counts (hereafter abbreviated as LL) are used in this analysis to represent pest densities. A prediction model developed for JPBW in northwestern Wisconsin (Clancy et al 1980) indicates budworm status as follows: 5 or fewer LL very low; 6 to 10 LL low; 11 to 20 LL medium; 21 or more LL outbreak. The same levels have been used in Ontario to classify the degrees of budworm infestation.

Based on the classification mentioned above, it is assumed that pest infestation is recognized as threatening only when the larval count exceeds about 10 LL. In other words, the initial pest density in epidemic stage P_0 is taken as 10 LL. It may be noted that pest densities at endemic levels (i.e., P is fewer than 10 LL) are present in all the forest crops and in themselves are not a cause for concern. It is presumed that pest populations are monitored regularly and that fluctuations in endemic population levels in a normal stand are known.

Kulman et al (1963) classifies pest infestation of JPBW as low, medium, heavy and very heavy on the basis of degree of defoliation. Defoliation is termed as very heavy when all the new and old needles are consumed, while heavy defoliation is said to occur when only the new and some old needles are consumed. By definition, the pest status associated with very heavy defoliation is equivalent to the carrying capacity, E, of the forest stand. Strictly for the purpose of the present analysis and presuming that pest densities with larval counts within 21 to 30 LL cause heavy defoliation, a conservative estimate[2] for the value of E is taken as 50 LL; which is approximately twice the level of heavy defoliation.

Defoliation by JPBW causes timber damage in the form of growth loss, mortality and top-killing (Kulman 1971). In Minnesota studies (Kulman et al 1963), the percentage reduction in summerwood and springwood rings in the sections of stems from a 30-year-old jack pine forest caused by defoliation in 1956 were recorded for a period of three years. Growth, expressed as area of the annual rings, was reduced in light, medium, heavy and very heavy defoliation classes in 1956 summerwood by 32%, 60%, 83% and 99%, respectively, in 1957 springwood by 54%, 76%, 99% and 99%, respectively, and in 1957 summerwood by 27%, 44%, 77% and 91%, respectively. The effect on growth two years later was found only in the case of heavy (51% and 20% reduction in springwood and summerwood, respectively) and very heavy (86% reduction in both types of wood) defoliation. This information is used here to provide rough estimates of the damage parameter b.

The ratio of springwood to summerwood, though dependent on the height of the section of stem from the ground, is estimated as approximately 1:1 (Kulman et al 1963). The average annual growth of a site class-3 jack pine forest aged 30 to 35 years is 2.8 cubic metres per hectare (Plonski 1974). Therefore, light, medium, heavy and very heavy defoliation may be expected to cause, respectively, a loss of 1.7, 2.5, 4.6 and 6.4 cubic metres per hectare in growth.

Attributing annual volume loss caused by mortality of trees to the pests is quite complex. It is reported (Kulman 1971) that medium and heavy defoliation in a young pole-sized stand cause 2% to 6% mortality in dominant trees. However, trees generally die because of the cumulative effect of repeated defoliations. In managed forests where pest control actions are taken, the affected trees have a greater probability of recovering, and mortality is expected to be low. Moreover, dead trees do not represent a complete loss of volume, as they yield some timber, though it is of a poor quality. It is suggested that, in jack pine forests, top-killing is the most visible form of damage caused by JPBW (Prebble 1975, and Knight and Heikkenen 1980). The affected trees develop rounded or flat tops and cause reduction in merchantable volume.

The loss in volume caused by mortality and top-killing should be treated as an aggregate effect and must be accumulated over the period of infestation to estimate annual loss. Thus, the growth loss computed above must be inflated by a certain factor to get the actual cumulative volume of timber damage. For low pest densities, this factor is almost negligible but, for very heavy pest infestations, it may range from moderate to extremely high values for managed and unmanaged forests, respectively.

Because of a lack of quantitative information regarding the accumulation of growth losses, the following estimates for the inflation factor for growth losses are arbitrarily used in the analysis: 10% for medium, 15% for heavy, and 25% for very heavy defoliation. Hence, the total damage due to low (mean larval count, 8 LL), medium (15 LL), heavy (25 LL) and very heavy (40 LL) pest infestation during any year becomes approximately 1.7, 2.8, 5.4 and 8.1 cubic metres per hectare, respectively. Damage is nearly directly proportional to the pest density (as assumed earlier in describing the damage function in Eq. 5, and the value of the damage parameter b works out to be 0.2 cubic metres per LL, which will be used in this analysis.

The effectiveness of a particular pesticide, given by parameter a in Eq. 4, in the case of a chemical insecticide, depends on the type of chemical employed and its formulation. In the absence of any quantitative information describing the effect of any particular pesticide on JPBW densities, the results of experiments conducted on spruce budworm, *Choristoneura fumiferana* (Clem.), are used. Morphologically, this budworm is sympatric with JPBW (Knight and Heikkenen 1980) and any readily available data for one can therefore be used as an approximation for another (Clancy et al 1980). For aerially applied Matacil 180F (a chemical pesticide), where an application of 1.5 litres per hectare is reported to have killed 90% of spruce budworm larvae (Cadogan et al 1984), the value of parameter a is estimated to be about 1.5. If similar information is available on the effectiveness of a biological pesticide such as B.t., it can be easily incorporated in this model. However, for this analysis, it is assumed that the behavior of B.t. is similar to Matacil 180F. Hence, the value of parameter a is taken as 1.5.

The choice of real discount rate i is difficult but crucial (Harou 1985 and Nautiyal and Rezende 1985). When discounting over long periods, as in the present case, the decision becomes very sensitive to the choice of this rate (Lind 1982). Long-term, real, risk-free rates of return on Canadian treasury bills are reported to be about 1.5%, whereas short-term rates are closer to 9% (Adamo and Martin 1984). Teeguarden (1974) suggests that a relatively low rate of discount be used for long-range investment decisions. Since a forestry enterprise requires long-term investments, a real discount rate of 5% appears to be reasonable and is used in the analysis presented here.

Stumpage price β of standing trees largely depends on the location of the forest and on the value of the end products that can be manufactured from the trees. Stumpage rates are usually higher for older crops, since mature trees cross diameters, which sharply increases the value of the best product produced from them (Nautiyal 1983). Therefore, stumpage price can be assumed to increase with age (Nyrop et al 1983).

For this analysis, the stumpage rate per cubic metre is presumed to be constant for crops aged less than 30 years, but increases steadily for those at higher ages. Three stumpage regimes, low, medium and high (see Figure 1), depending upon the location and accessibility of the forest and quality of wood, are considered. The stumpage rates at these scenarios are 25%, 50% and 75% of the price[3] attributed to wood at the mill gate.

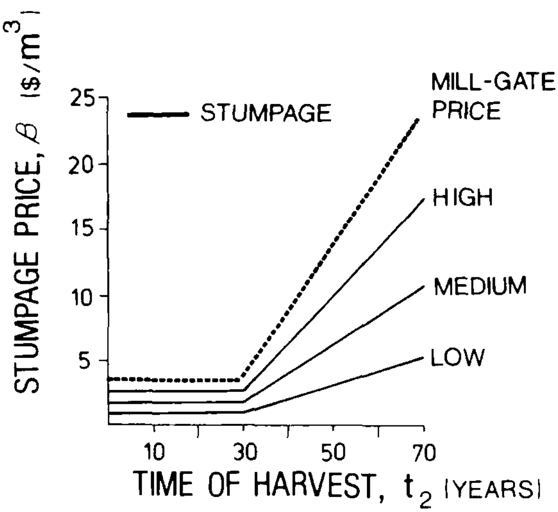

Figure 1. Effect of low, medium and high stumpage regimes.
Source: Nautiyal and Innes (1984).

The remaining exogenous parameters are the age of the forest at the time when threatening infestation begins, t_0; intrinsic growth rate of pest population, r; and cost of each unit of pesticide, α. Reasonably wide ranges of 15 to 45 years for t_0, 0.03 to 0.07 for r, and \$10 to \$30 per litre per hectare for α are selected for these parameters.

RESULTS AND DISCUSSION

Using the estimates of the parameters discussed above, the values of X^*, t_1^* and t_2^* and their sensitivity to changes in t_0, α, r and β are determined for the previously mentioned even-aged jack pine stand. In this exercise, other parameter values of $E = 50$ LL, $P_0 = 10$ LL, $b = 0.2$ cubic meters per LL, $i = 0.05$ and $a = 1.5$ are held constant with changes in the variables analyzed.

In Figure 2a, the sensitivity of optimal time of pesticide application t_1^* is shown with respect to changes in t_0. When a threatening pest infestation is noticed, the intuitive response would be to take immediate control action (i.e., to make $t_1^* = t_0$). Results from this model, however, show that when t_0 is low, control action is delayed (i.e., $t_1^* > t_0$). This is due to the fact that only one pesticide application is made during the life of the crop and total eradication of pests is considered to be impossible in the model. In such circumstances, the forest manager must optimize pest damage over the entire rotation period. Thus, the prescription that pests be controlled as soon as an infestation occurs (Fisher 1983) is not economically justifiable for the conditions assumed in our model.[4] Notice in Figure 2b that lower quantities of X^* are applied for higher t_0, that is, when an epidemic starts at a later stage in the life of a stand.

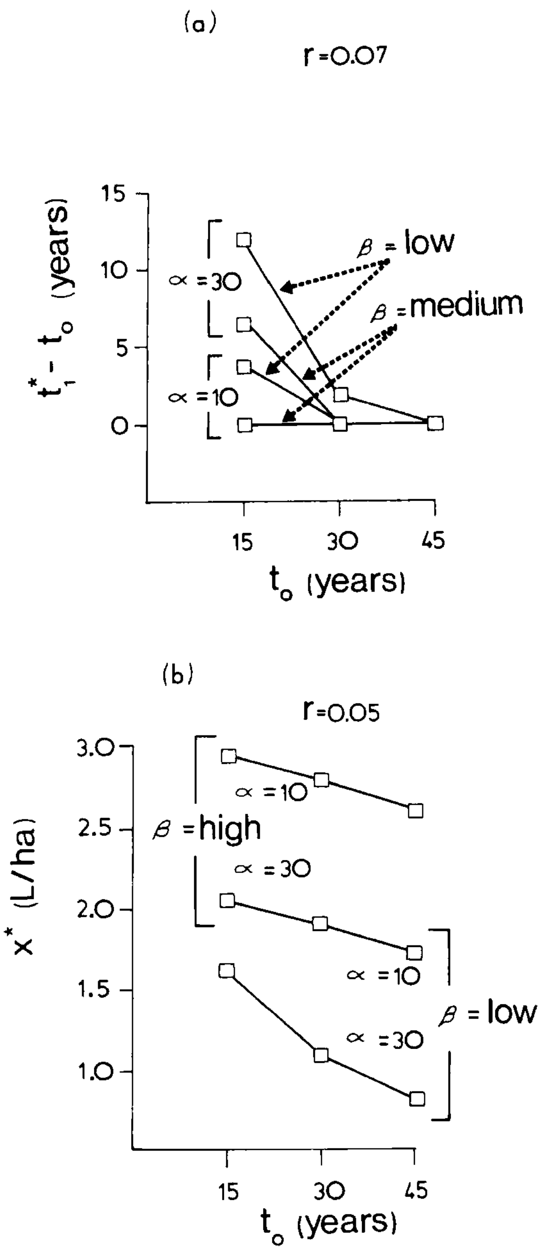

Figure 2. Effect of age of forest when infestation is recognized t_0 on (a) timing of pesticide application $t_1^* - t_0$ and on (b) amount of pesticide used X^*.

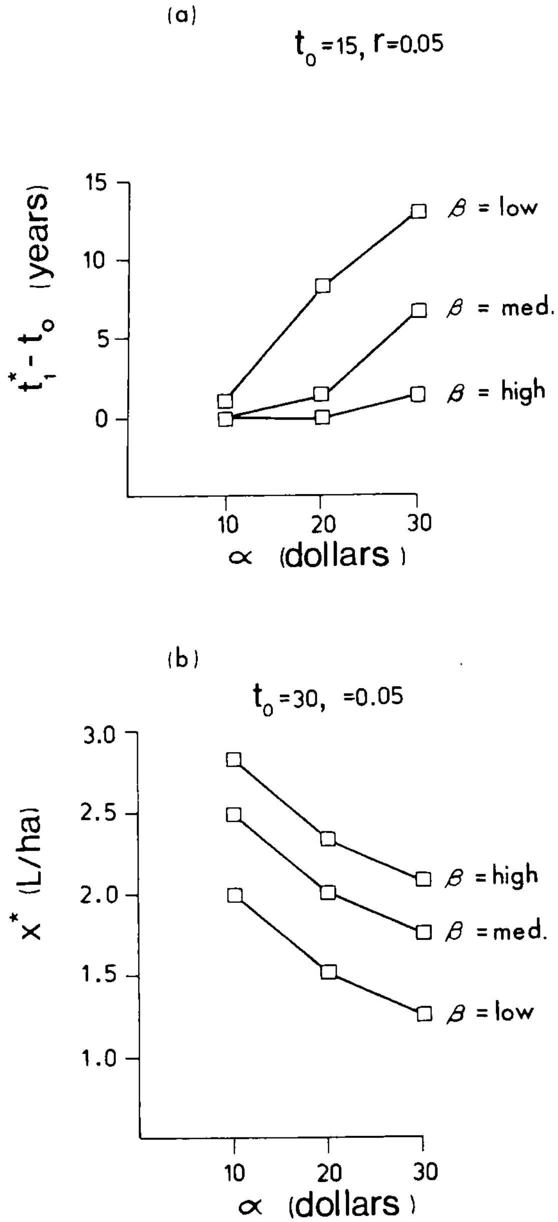

Figure 3. Effect of cost of active ingredient α on (a) timing of pesticide application $t_1^* - t_0$ and on (b) amount of pesticide used X^*.

In Figure 3a, the optimal time of treatment t_1* is delayed for higher α so that interest charges on this expenditure are carried over a shorter period (t_2* – t_1*). Also, as would be expected, the optimum amount of active ingredient X* falls as the pesticide becomes more expensive (Figure 3b).

Figure 4 shows that if intrinsic rate r is faster, X* is larger (for all stumpage price regimes) and t_1* increases (except within the high stumpage price regime). This can be interpreted as a general recommendation for stronger, but delayed, treatment when pest outbreaks are more eruptive and damaging.

In Figure 5, if stumpage price β is higher, X* is larger and t_1* is lower. This demonstrates that if the forest is more valuable, it is appropriate to take a stronger action at an earlier age. Furthermore, the decision variables, as illustrated in both Figures 4 and 5, appear to be quite sensitive to β, indicating that the anticipated characteristics of future wood markets play an important role in the current pest control decisions.

It is apparent from the results that optimal rotation age t_2* changes appreciably under various pest situations (rotation ranged from 56 to 63 years). In the absence of any pest infestation, t_2* is 61 years. In general, the introduction of pests reduces the optimal harvest age. The expenditure on pest control, in addition to the vast capital blocked in the form of growing stock, induces the forest manager to hasten the recovery of revenues from the stand.

The degree by which a pest infestation influences t_2*, however, depends largely on the timber production function. For instance, when a similar analysis[5] is conducted for jack pine forest on site class-1, the change in optimal rotation under similar pest scenarios is much less. Apparently, a forest on a good-quality site generates relatively higher revenues than the pest control costs. Therefore, pest infestation does not appreciably affect net revenue and hence the harvesting schedule.

Similar results (larger change in optimal rotation at a poor site than at a good site) are obtained by Nyrop et al (1983) from their simulation model for jack pine. However, in cases where a significant change in economic harvest age is warranted, the problems facing the manager involve not only when to apply control measures but also when to harvest each even-aged stand in the management unit.

CONCLUSION

From the simple illustration presented in this paper, it is apparent that numerous variables and functions are involved in developing an optimization model for pest and timber management. Most of the quantitative information required for such an exercise are either lacking or inadequate. Therefore, there is a need to build a strong data base to quantify various relationships, which will aid in the development of more robust and practical management models. It is also clear that a separate model for each pest-host situation is likely to be required.

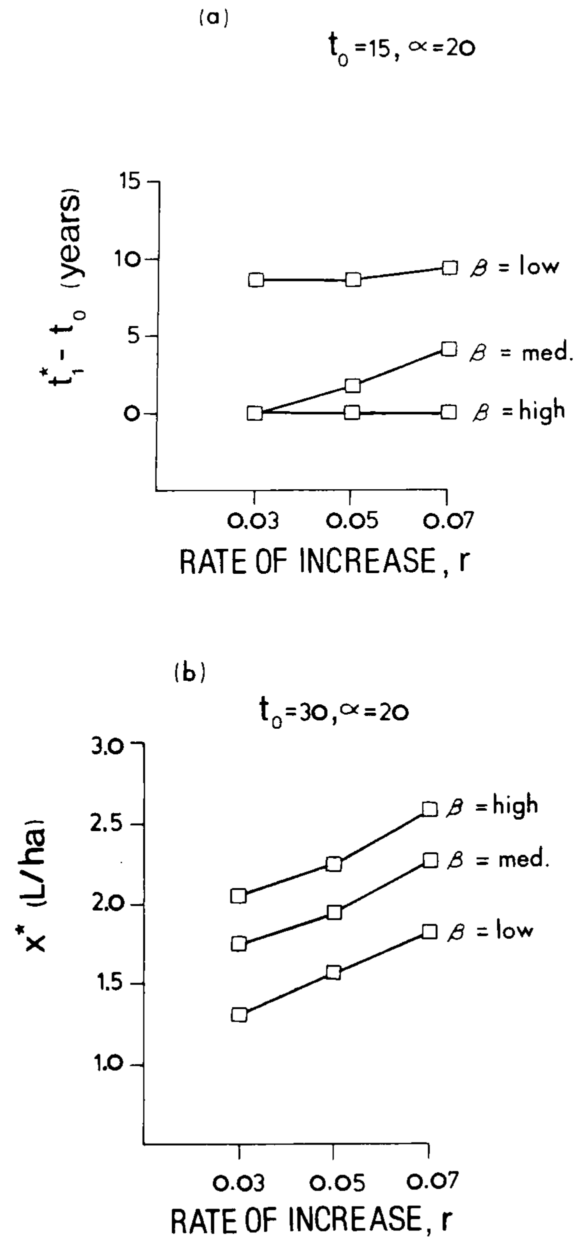

Figure 4. Effect of intrinsic pest population increase rate r on (a) timing of pesticide application $t_1^* - t_0$ and on (b) amount of pesticide used X^*.

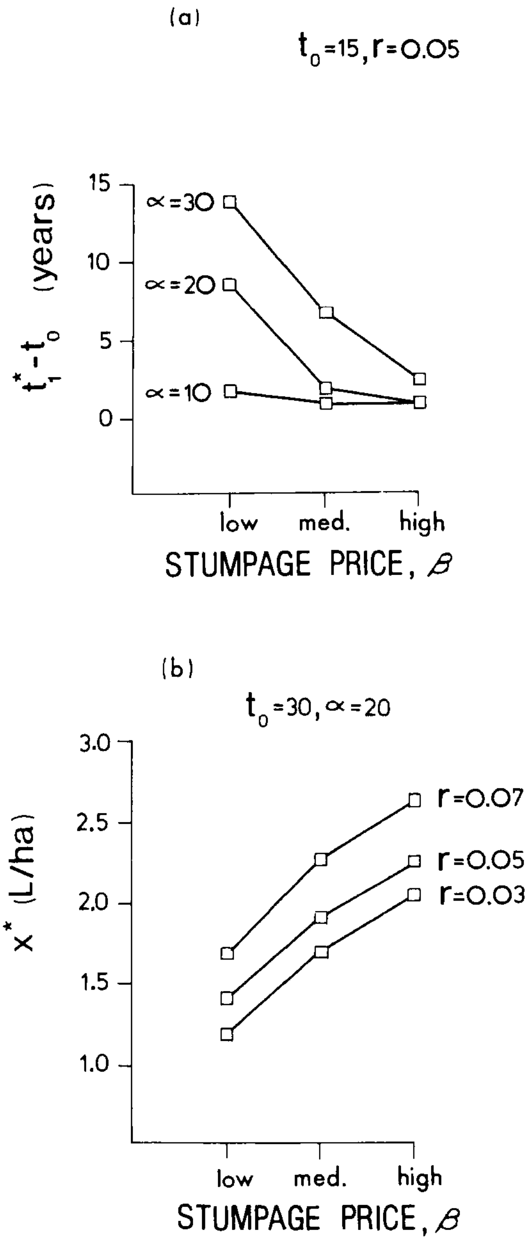

Figure 5. Effect of stumpage price β on (a) timing of pesticide application $t_1^* - t_0$ and on (b) amount of pesticide used X^*.

Subject to the assumptions made in the model presented here, the results provide some helpful insights into the economics of jack pine forest management. For example, immediate pesticide application may not be the most profitable course of action to take. Also, certain combinations of pest and forest conditions may change the economic rotation age significantly. This may warrant a substantial readjustment of cutting schedule for the entire forest management unit. Therefore, the use of optimization models such as presented here may be desirable for the identification of the need to reschedule annual cuts.

The development of this model is intended to provide a first step in an ongoing effort to better understand the effects of pest infestation in a forest management context. One major limitation of the model is that it incorporates only one pesticide application during a rotation of forest crop. It should be extended to consider more than one application. However, under such conditions there can be two forest pest control strategies:

- a remedial one, where control actions are contemplated after each abnormal infestation occurs, and
- a preventive one, where low levels of control activities are undertaken periodically with the aim of forestalling any major outbreaks.

Research is needed to determine under what set of circumstances one of these strategies may be more economical than the other.

In the model presented here, types of pesticide, spraying equipment and technology link the kill and cost functions and determine the parameter a. Research should be undertaken to develop models that can take account of the increase in costs of control due to different methods of application and of the corresponding changes in effectiveness. Also, in the formulation of the model, the dual nature of volume losses due to both mortality and growth decline is not addressed. The framework of the model can easily be modified to include functions describing both types of loss. However, this cannot be accomplished until more basic research is carried out to provide data to calibrate these functions.

Finally, the model needs to be extended to include stochastic functions. Considering the long planning horizon of any forestry enterprise, there is a large uncertainty associated with occurrences of pest infestation, with costs of control operations, and with future timber prices. Furthermore, the planning horizon of a forest manager is presumed to be one rotation long. A longer horizon and its effects on decision variables must be considered.

NOTES

[1]Yield data for a stand aged 30 to 80 years were used and ordinary least squares method was applied to estimate Eq. 19. Economic harvest age was found to lie within this period.

[2]The carrying capacity also depends upon the age of the crop (i.e., quantity of food for insects). The value used here is only for mature stands of jack pine aged more than 30 years.

[3]The wood prices used here are commensurate with the mill-gate prices used by Nautiyal and Innes (1984) for jack pine in Ontario.
[4]A change in the assumption that only one pesticide application be made per rotation would, of course, alter the optimal solution.
[5]The yield of merchantable volume (Plonski 1974) is estimated as $V(t) = -533.1 - 7.2t + 153.8t^{0.5}$. Assuming $E = 100$ LL and other parameters are unchanged, the optimal rotation is found to vary between 49 and 52 years. Optimal rotation under no-pest situation is 52 years.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support for this research from the Natural Sciences and Engineering Council of Canada (Grant A6205) and from the Human Resources Development Fund of the Canadian Forestry Service.

REFERENCES

Adamo, D. and P. Martin. 1984. *1983 investment returns.* McLeod Young Weir Ltd.
Akers, R. C. and D. G. Nielsen. 1984. Predicting *Agrilus anxius* (Coleoptera: Buprestidae) adult emergence by heat unit accumulation. *Journal of Economic Entomology* 77(6): 1459–63.
Allen, R. G. D. 1938. *Mathematical Analysis for Economists.* New York: St. Martin's Press.
Bartsch, R. 1978. Economic problems of pest control: Examined for the case of Gezira/ Sudan. Munich: Weltforum Verlag.
Batzer, H. O. and I. Millers. 1970. Jack-pine budworm. Forest Pest Leaflet 7. Washington, D.C.: USDA, Forest Service.
Becker, N. G. 1970. Control of pest population. *Biometrics* 26: 365–75.
Bible, T. D., J. D. Brodie and C. Kao. 1981. Optimal harvest and thinning regimes for stands subject to episodic insect damage. *Proceedings of Society of American Foresters.*
Blais, J. R. 1976. Can *Bacillus thuringiensis* replace chemical insecticides in the control of spruce budworm? *Forestry Chronicle* 52: 57–60.
Cadogan, B. L., B. F. Zylstra, P. de Groot and C. Nystrom. 1984. The efficacy of aerially applied Matacil to control spruce budworm *Choristoneura fumiferana* (Clem.) in Bathurst, New Brunswick. Information Report FPM-X-64. Forest Pest Management Institute.
Campbell, R. W. 1967. The analysis of numerical change in gypsy moth populations. Forest Science Monograph 15.
Chatterjee, S. 1973. A mathematical model for pest control. *Biometrics* 29: 727–34.
Clancy, K. M., R. L. Giese and D. M. Benjamin. 1980. Predicting jack-pine budworm infestation in northwestern Wisconsin. *Environmental Entomology* 9: 743–51.
Clark, C. W. 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* Toronto: John Wiley and Sons.
Coulson, R. N. 1979. Population dynamics of bark beetles. *Annual Review of Entomology* 24: 417–47.
Cuff, W. and G. Baskerville. 1983. Ecological modelling and management of spruce budworm infested fir-spruce forests of New Brunswick, Canada. In *Analysis of Ecological*

Systems: State-of-the-Art in Ecological Modelling, edited by W. K. Lavenroth, G. V. Skogerboe and M. Flug, pp. 93–98. Amsterdam: Elsevier Scientic Publishing.

Eaton, C. B. 1962. Entomological considerations in the economics of forest pest control. *Journal of Forestry* 60: 309–11.

Fisher, R. A. 1983. Two decades of budworm simulations: A retrospective view of comprehensive simulation models. In *Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling*, edited by W. K. Lavenroth, G. V. Skogerboe and M. Flug, pp. 107–11. Amsterdam: Elsevier Scientific Publishing.

Foltz, J. L., F. B. Knight and D. C. Allen. 1972. Numerical analysis of population fluctuations of the jack pine budworm. *Annals of the Entomological Society of America* 65: 82–89.

Hall, F. R. 1984. Pesticide application techniques for optimizing efficiency. *Journal of Arboriculture* 10(4): 104–7.

Hall, K. K. and R. B. Norgaard. 1973. On the timing and application of pesticides. *American Journal of Agricultural Ecnomics* 55(2): 198–201.

Headley, J. C. 1972a. Defining the economic threshold. In *Pest Control Strategies for the Future*, pp. 100–08. Washington, D.C.: National Academy of Sciences.

Headley, J. C. 1972b. Economics of agricultural pest control. *Annual Review of Entomology* 17: 273–68.

Harou, P. A. 1985. On a social discount rate for forestry. *Canadian Journal of Forest Research* 15: 927–34.

Hueth, D. and U. Regev. 1974. Optimal agricultural pest management with increasing pest resistance. *American Journal of Agricultural Economics* 56: 423–552.

Huffaker, C. B. and R. F. Smith. 1980. Rationale, organization, and development of a national integrated pest management project. In *New Technology of Pest Control*, edited by C. B. Huffaker, pp. 1–24. Toronto: John Wiley and Sons.

Johnson, N. E. 1963. Some economic considerations in planning control of insects affecting young forest trees. *Journal of Forestry* 61: 426–29.

Knight, F. B. and H. J. Heikkenen. 1980. *Principles of Forest Entomology.* 5th ed. Toronto: McGraw-Hill.

Kulman, H. M. 1971. Effects of insect defoliation on growth and mortality of trees. *Annual Review of Entomology* 16: 289–324.

Kulman, H. M., A. C. Hodson and D. P. Duncan. 1963. Distribution and effects of jack pine budworm defoliation. *Forest Science* 9: 146–57.

Lind, R. C., ed. 1982. Discounting for time and risk in energy policy. Washington, D.C.: Resources for the Future Inc.

Luckmann, W. H. 1982. Pest management and future. In *Introduction to Insect Pest Management*, edited by R. L. Metcalf and W. H. Luckmann, pp. 557–60. 2nd ed. New York: John Wiley and Sons.

MacLean, D. A. and T. A. Erdle. 1984. A method to determine effects of spruce budworm on stand yield and wood supply projections for New Brunswick. *Forestry Chronicle* 60: 167–73.

MacLean, D. A., A. W. Kline and R. L. Lavigne. 1984. Effectiveness of spruce budworm spraying in New Brunswick in protecting the spruce component of spruce-fir stands. *Canadian Journal of Forest Research* 14(2): 163–76.

Mann, S. H. 1971. Mathematical models for the control of pest populations. *Biometrics* 27: 357–68.

Markin, G. P. and D. R. Johnson. 1983. Carbaryl applied at reduced dosage rates for control of western spruce budworm. Research Paper PSW-170. City: USDA, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Morris, R. F. 1951. The importance of insect control in a forest management program. *Canadian Entomology* 83: 176–81.

Morris, R. F., ed. 1963. The dynamics of epidemic spruce budworm populations. Mem. Entomological Society of Canada 31.

Mumford, J. D. and G. A. Norton. 1984. Economics of decision making in pest management. *Annual Review of Entomology* 29: 157–74.

Nautiyal, J. C. 1983. Towards a method of uneven-aged forest management based on the theory of financial maturity. *Forest Science* 29: 47–58.

Nautiyal, J. C. and L. Couto. 1984. The nature and uses of the timber production function. *Forest Science* 30: 761–73.

Nautiyal, J. C. and M. R. Innes. 1984. Optimal economic rotation for a mixed species even-aged forest. *Canadian Journal of Agricultural Economics* 32: 526–38.

Nautiyal, J. C. and J. L. Rezende. 1985. Forestry and benefit cost analysis. *Journal of World Forest Management* 1: 189–98.

Nyrop, J. P., J. T. Olson, D. G. Moshel and G. A. Simmons. 1983. Simulation of how jack pine budworm (Lepidoptera: Torticidae) affects economic returns from jack pine timber production in Michigan. *Great Lakes Entomologist* 16: 157–65.

Payandeh, B. 1973. Plonski's yield tables formulated. Canadian Forest Service Publication 1318. CFS.

Plonski, W. L. 1974. Normal yield tables (metric) for major forest species of Ontario. Toronto: Ontario Ministry of Natural Resources, Division of Forests.

Prebble, M. L. 1975. Jack pine budworm. In *Aerial Control of Forest Insects in Canada*, edited by M. L. Prebble, pp. 152–53. Ottawa: Department of the Environment.

Rose, D. W. 1973. Simulation of jack pine budworm attacks. *Journal of Environmental Management* 1: 259–76.

Ruesink, W. G. 1976. Status of the systems approach to pest management. *Annual Review of Entomology* 21: 27–44.

Sanders, C. J. 1980. A summary of current techniques used for sampling spruce budworm populations and estimating defoliation in eastern Canada. Canadian Forestry Service Report O-X-306. Ottawa: Department of the Environment.

Shoemaker, C. 1973. Optimization of agricultural pest management. I: Biological and mathematical background. *Mathematical Biosciences* 16: 143–75.

Smyth, J. H., K. L. Ramsay and D. E. Barron. 1984. Forest management expenditures in Canada: 1977–1981. Canadian Forestry Service Information Report 2918 (F-11). Ottawa: Department of the Environment.

Stern, V. M. 1973. Economic thresholds. *Annual Review of Entomology* 18: 259–80.

Talpaz, H. and I. Borosh. 1974. Strategy for pesticide use: Frequency and applications. *American Journal of Agricultural Economics* 56: 769–75.

Teeguarden, D. E. 1974. Comments and viewpoints. In *Timber Policy Issues in British Columbia*, edited by W. McKillop and W. J. Mead, pp. 233–39. Vancouver: University of British Columbia Press.

Waters, W. E. and E. B. Cowling. 1976. Integrating pest management: A silvicultural necessity. In *Integrated Pest Management*, edited by J. L. Apple and R. F. Smith, pp. 149–77. New York: Plenum.

Waters, W. E. and R. W. Stark. 1980. Forest pest management: Concept and reality. *Annual Review of Entomology* 25: 479–509.

Watt, K. E. F. 1964. The use of mathematics and computers to determine optimal strategy and tactics for a given insect pest control problem. *Canadian Entomology* 96: 202–20.

Williams, C. B. Jr., and P. J. Shea. 1982. Computer simulation for integrated pest management of spruce budworms. Research Paper, PSW-159. USDA, Forest Service, Pacific Southwest Forest and Range Experiment Station.