The GSBGM Working Paper Series

WORKING PAPER 1/96

A dynamic simulation model for possum and gorse control on a farm woodlot

M.W. Lee, J. Bennett,
R.J. Taylor and R.Y. Cavana

ISSN 1173-4523
ISBN 0-475-11413-2

The GSBGM Working Paper Series 1/96 January 1996.
M.W. Lee, J. Bennett, R.J. Taylor and R.Y. Cavana* 'A dynamic simulation model for possum and gorse control on a farm woodlot.'

Please address inquiries concerning this paper direct to the author*
General enquiries concerning GSBGM publications to:
Monica Cartner
Research Co-ordinator
The Graduate School of Business and Government Management
The Victoria University of Wellington
PO Box 600
Wellington
New Zealand

Telephone: 64-4-495 5085
Facsimile: 64-4-496 5435
E-mail: Monica.Cartner@vuw.ac.nz

*R.Y. Cavana
Management Group
Victoria University of Wellington
PO Box 600
Wellington

Printed by The Victoria University of Wellington Printers.

A DYNAMIC SIMULATION MODEL FOR POSSUM AND GORSE CONTROL ON A FARM WOODLOT

M.W. LEE
Department of Internal Affairs
PO Box 805, Wellington, New Zealand

J. BENNETT
New Zealand Forestry Exchange
PO Box 10790, Wellington, New Zealand

R.J. TAYLOR
Powerbuy Group Ltd
PO Box 486, Wellington, New Zealand

R.Y. CAVANA
Graduate School of Business and Government Management
Victoria University of Wellington
PO Box 600, Wellington, New Zealand

ABSTRACT

Managers of farm woodlots in New Zealand are confronted by two major problems: possums and gorse. If these remain uncontrolled then they have a severe impact on the returns from farm woodlots. This paper presents a system dynamics model which has been developed to assist in the analysis of control measures for managing gorse and possums on a farm woodlot in the Makara Valley, Wellington. The model has four main sectors: a tree growth module for radiata pine; a growth module for gorse; a module for the stock of possums present in the habitat; and a module of financial indicators. A number of control experiments are presented which indicate the long term financial and physical consequences of different gorse and possum control measures. The model clearly demonstrates the complex nature of the dynamic behaviour of a system involving biological and environmental factors (ie possums, gorse and trees) and human intervention (in terms of silviculture, and possum and gorse control).

Keywords: farm forestry, woodlot management, radiata pine, possums and gorse control, system dynamics

TABLE OF CONTENTS

1. INTRODUCTION

Farm forestry in New Zealand is a thriving part of the forestry sector. The New Zealand Farm Forestry Association has about 6000 members whose motivation for their enterprises range from purely commercial to lifestyle aspects. For some of these forests (particularly if on steeper country or close to native bush), management is complicated by the impact of two problems: possums and gorse. It is the conflict created by these two problems on a farm woodlot based in Makara, Wellington, owned and managed by Jenni Bennett, one of the authors, that was the catalyst for this study.

This paper evaluates a range of measures for controlling possums and gorse, and examines their impact on the volume and value from a farm woodlot. A system dynamics model of the inter-relationships between gorse, possums and the woodlot was chosen as the means by which this evaluation would be carried out. A rich picture (Checkland, 1981) of the problem situation is provided in Figure 1. This picture, or situation summary, focuses attention on the main variables and issues involved in the system.

Makara is near the west coast of the Wellington Region, New Zealand. The topography of the property varies from river flats at sea level to steep hills rising to 300 m (metres) above sea level. The property is 73 ha (hectares) of which about half has been planted with trees. Radiata pine is on 25 ha, the rest is macrocarpa, acacia melanoxylon, several eucalypt species and small numbers of other species. The radiata pine was planted in 1991 and 1992. These plantings received different land preparation for gorse control; the 1991 block was just cut, while the 1992 block was aerially sprayed with Grazon, burnt and sprayed again with Grazon after planting. The model follows the management of the 1991 block. The hills on which the radiata is planted, are exposed to the prevailing wind, although two gullies provide protection to some areas of the woodlot. The site index (ie the mean height for the tallest 100 trees in the stand at age 20 years) for the woodlot ranges from 18 (ie 18 m) at the crest of the hills to 26 at the lower altitudes.

The management regime is a "low intensity" regime following Regime 2; the low management input, unpruned, sawlog regime described by Ministry of Forestry (1994). Such a regime is usually applied when there are obstructions, such as gorse, to the implementation of normal silvicultural operations. The regime consists of a single thinning to waste at between 10 to 14 years when the canopy has closed over, (shading out the gorse beneath) and no pruning. When gorse is shaded, it dries and becomes brittle making it much easier to work with. This regime produces sawlogs and pulplogs, although no pruned logs. This regime is often followed by woodlot owners who experience cash flow problems at the time when pruning should be undertaken, or who are not prepared to take the risk of higher outlays for pruning to gain the uncertain additional value of pruned logs at harvesting some 20-25 years later. Where these prices will be in 20 years time is not easy to predict. For example, new technology is making shorter lengths more useful with finger jointing and so forth which adds value to unpruned logs.

This paper is organised as follows. Section 2 provides a description of the structure and main sectors in the model. Section 3 describes the base case behaviour of the model. The sensitivity of the model to changes in the significant exogenous variables are discussed in Section 4. Section 5 considers the results of six control experiments with reference to both their physical and financial attributes. Finally, in Section 6 some conclusions are drawn about the applicability of this modelling approach to issues of this type. Appendix 1 contains the documented equations of the model and Appendix 2 provides the costs and revenues from the base case and the costs of the control measures.

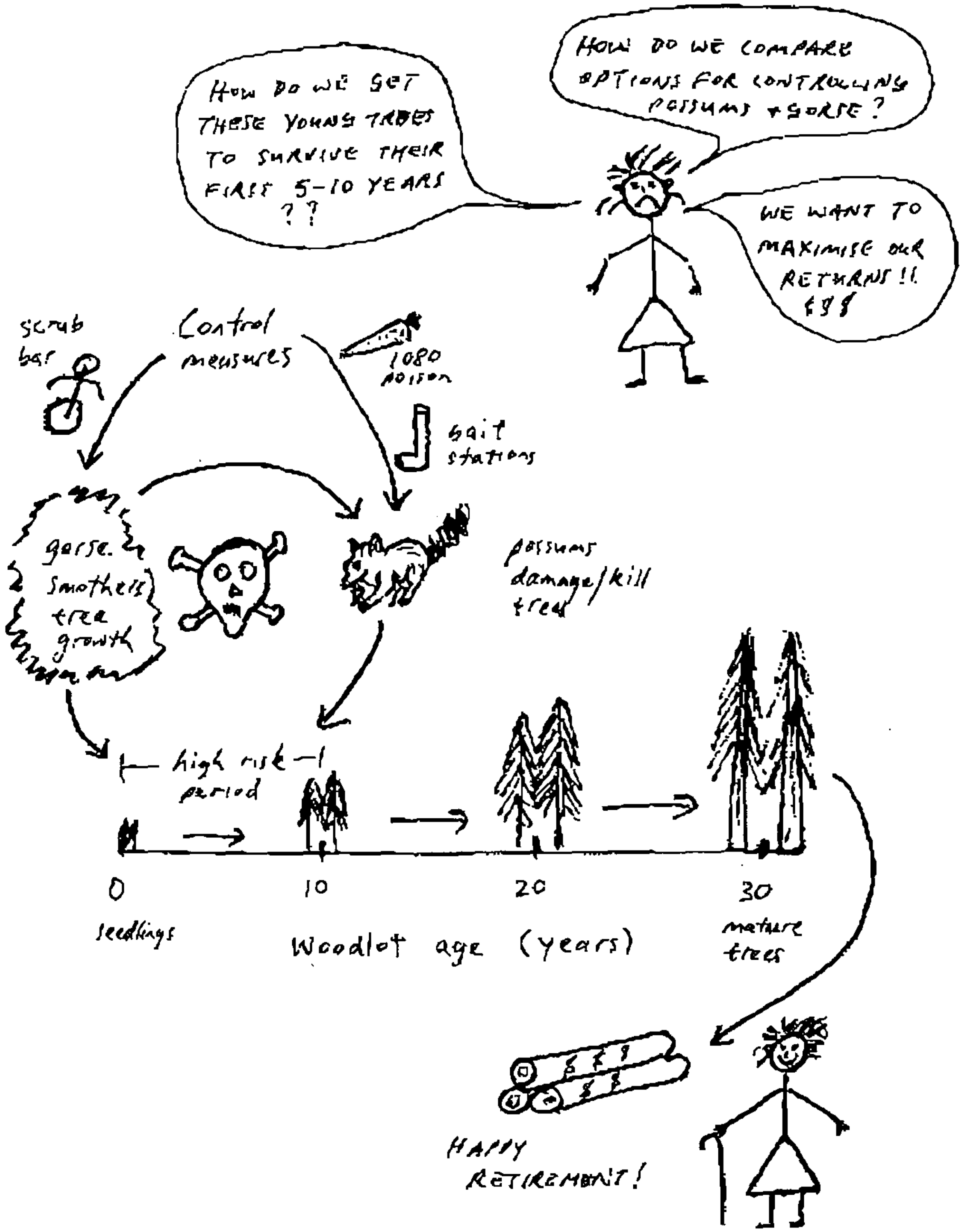

Figure 1. Rich Picture for the Makara Farm Woodlot

2. MODEL STRUCTURE

2.1. Overview of the Model

This model has been developed using the system dynamics methodology (Forrester, 1961 and Coyle, 1977) and the Stella II software package (Peterson and Richmond, 1994). For earlier work in New Zealand forestry using this methodology refer to Cavana and Coyle (1984).

The simulation has been set on a monthly basis, with a rotation length of 360 months (ie. 30 years). Simulation begins when the trees are "planted" at time zero, which equates to the month of June. All dollar values are constant 1994 dollars. Net present value is calculated on the pre-tax cash flows with a real discount rate of 8%[1]. The model's solution interval or 'DT'[2] value is set at 1 (ie 1 month). Most variables which relate to the woodlot are expressed on a per hectare basis. For example, stems per hectare, independent possums per hectare, wood volume per hectare, etc.

The model has four main sectors: a tree growth module for radiata pine; a growth module for gorse; a module for the stock of possums present in the habitat; and a module of financial indicators. The possum sector is made up of three sub-sectors relating to: the possum population; possum kills; and possum tree consumption. The gorse module is derived in the main from Bennett et al. (1994), while the possum module is related to Allen and Taylor (1994). In both cases the structure and data content of these modules have under gone some evolution throughout the period of the study.

A simplified influence diagram for the model is provided in Figure 2. This influence diagram indicates the direction by which one variable 'influences' or 'effects' another. For example, a '+' sign at the head of an arrow indicates that a change to the variable at the base of an arrow will 'influence' the variable at the head in the same direction. (Refer to Wolstenholme and Coyle (1983) for further explanation).

The major relationships in the influence diagram will be briefly discussed. In many instances the discussion of a relationship may be cursory. In such case readers should refer to Sections 2.2 - 2.5 which contains the Stella flow diagrams for the model and Appendix 1 which contains the model equations and additional documentation. References to variable names will be indicated by writing them in *italics*. The key relationships that drive the results from the model are those between:

possums --->$^+$ *tree deaths from possum* --->$^-$ *stems per hectare* --->$^+$ *wood volume*

possums --->$^+$ *damaged trees* --->$^+$ *growth delays* --->$^-$ *pine height* --->$^+$ *wood volume*

possums --->$^+$ *damaged trees* --->$^-$ *average wood price* --->$^+$ *wood revenues*

gorse height --->$^+$ *growth delays* --->$^-$ *pine height* --->$^+$ *wood volume*

gorse height --->$^+$ *tree deaths from gorse* --->$^-$ *stems per hectare* --->$^+$ *wood volume*

---

1 This discount rate was chosen as the most appropriate weighted average cost of capital for this particular investment. Major forest growers, such as Fletcher Challenge in their 1993/94 Interim Report (Fletcher Challenge Ltd, 1994), used a pre-tax real discount rate of 7.5% , while Carter Holt Harvey, New Zealand's largest forest grower, uses 8% (Carter Holt Harvey Ltd, 1994). Although in Ministry of Forestry (1994) a discount rate of 7% was used, Gorman (1995) suggests that a higher figure would be more appropriate.

2 The DT (Delta Time) value indicates how often calculations are made in the model. For instance, if the DT is equal to 0.25 then four calculations of the model variables are made per time unit. If the DT is equal to 1 then calculations are made each time unit. The rule of thumb in these models is that the DT should be one quarter of the shortest delay in the model system in order to produce well behaved dynamics from the model. In the case of the present model there are only small differences between the dynamics of the model when a DT of 0.25 or 1 is used.

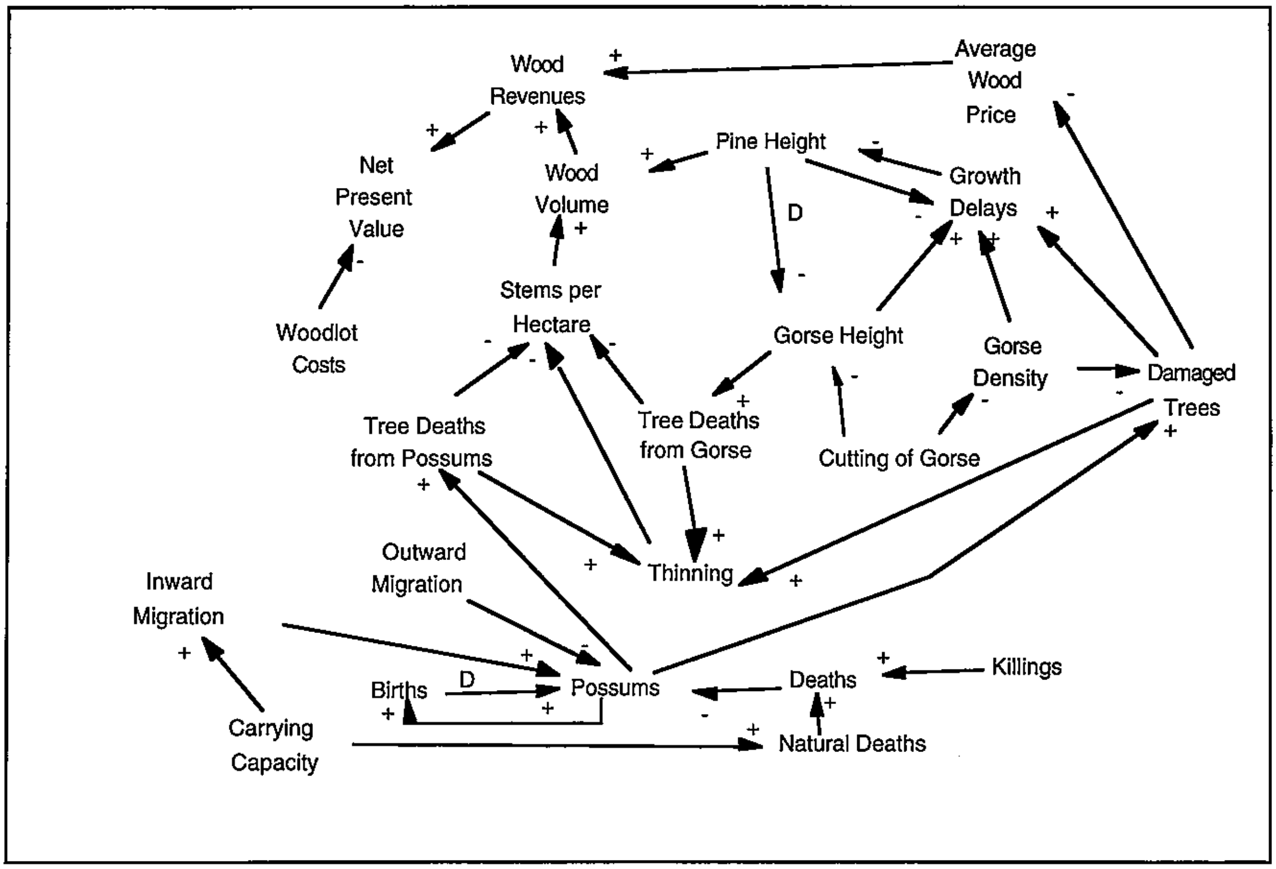

Figure 2. A Simplified Influence Diagram for the Farm Woodlot Model

There are two main paths by which *possums* activity affects the net present value of the woodlot. The first is via the actual death of pine trees as the result of possum damage. Tree deaths reduce the number of tree stems remaining in the woodlot which, if severe enough, affects the thinning decision, reducing the final stocking and ultimately the wood volume from the woodlot. Second, *possums* also cause damage to trees without killing them. There are two effects here, the damage leads to *growth delays* in the height of the trees, and it reduces the wood quality of the woodlot causing a reduction in the *average wood price* and revenues from the woodlot. Two factors are critical to these effects: first, the number of possums in the woodlot and, second, the age of the woodlot. Younger pine trees are more vulnerable to damage and death.

A similar description applies if the *gorse height* variable is the starting point. If the growth of gorse surpasses that of the young pine trees, then tree deaths can occur. Naturally, this reduces the *stems per hectare* and the final stocking in the woodlot. Alternatively, and perhaps more importantly, *gorse height* has a direct, positive effect on tree *growth delays* which inhibits *pine height* growth. As the height of gorse relative to the height of the pine tree increases, the variable *growth delays* increases and accumulates, and the potential height of the pine trees is reduced accordingly. The reduced tree height leads to a lower *wood volume* and *wood revenues*. These effects of gorse height on tree growth delays are modified by gorse density. Conversely, a positive side effect of gorse growth is that tree damage by possums and wind is reduced due to shielding by the gorse.

A major positive feedback loop in the model occurs between *pine height*, *gorse height* and *growth delays*. *Pine height*, after a delay, acts to limit the height to which gorse can grow, and thus the amount by which tree growth is delayed. *Pine height* also affects the *growth delays* variable directly and tends to dampen its effect.

2.2. Tree Sector

The growth module for radiata pine has three parts. The first describes the development of the height and girth of the tree, while the second shows the number of tree stems that remain at any point in time. Combining these allows the calculation of the volume of wood contained within one hectare. The third part models a way that gorse and possums have an effect on the growth of radiata pine. Figure 3 shows the Stella flow diagram for the tree sector. The model equations are provided in Appendix 1.

In the Stella flow diagrams: the boxes (rectangles) represent stocks or levels; the circles attached to double lines in or out of stocks represent flows or rates; the remaining circles represent converters containing other relationships, constants, parameters or graphs; and the clouds represent variables outside the system being modelled.

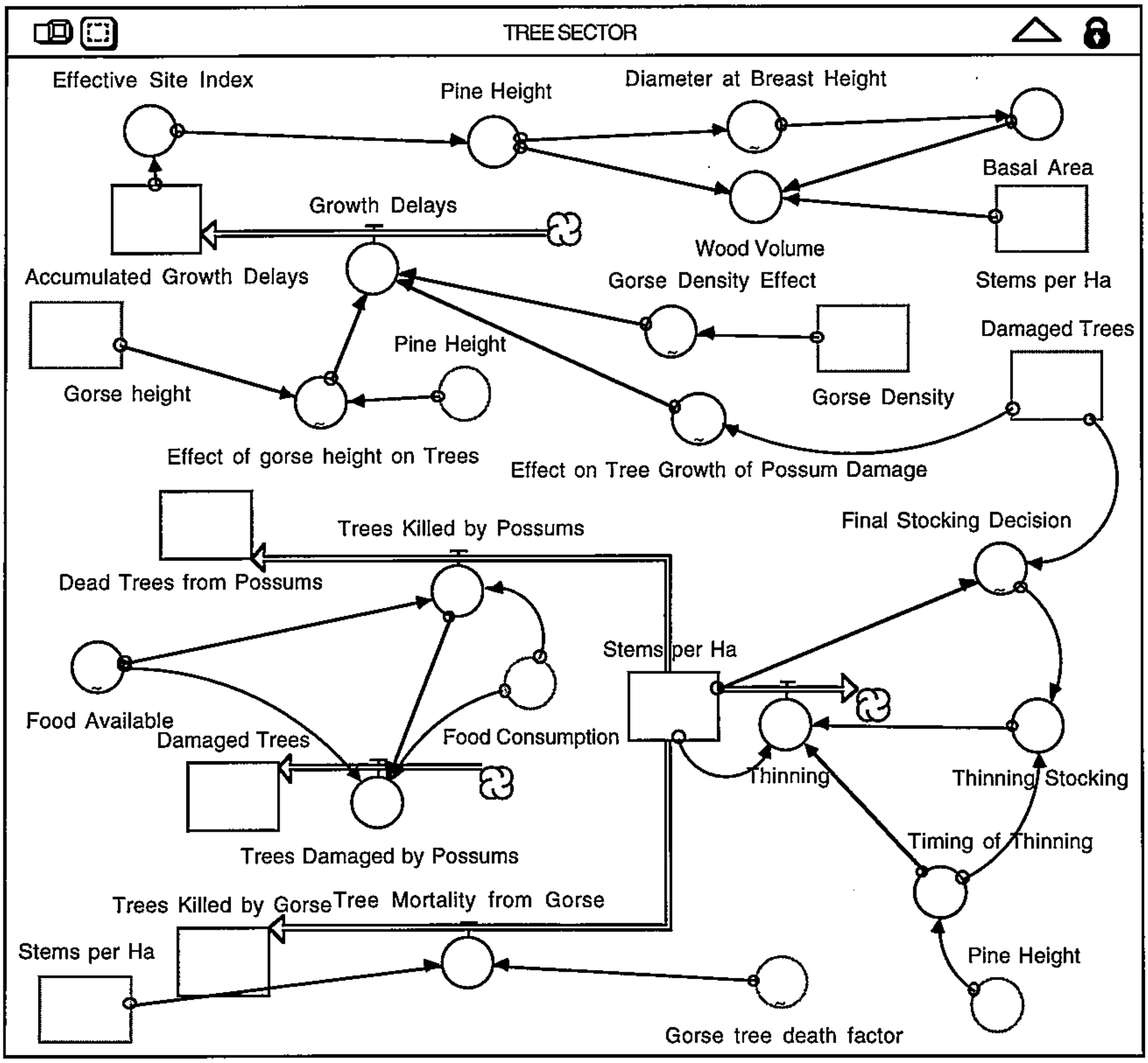

Figure 3. Stella Flow Diagram for the Tree Sector

2.2.1. Tree Growth

A site index is the mean height of the tallest 100 trees in a hectare at age 20 years. In terms of the functions describing the growth of the trees in this woodlot the *effective site index*[3] sets the height to which the trees will grow at age 20 years. This variable is affected by the density and height of gorse that may be growing in competition with the trees and by the effects of possum damage on tree growth. This is modelled by *gorse height, gorse density* and the *effect on tree growth of possum damage* variables feeding into an accumulator of *growth delays*. This reduces the *effective site index* and therefore simulates the delays to tree growth that gorse competition is thought to have (Richardson and West, 1994) and similarly for possums (Keber, 1988). The real site index would be less than the effective site index if gorse and possums have a significant effect.

The *effective site index* feeds into an equation that underlies the variable *pine height*. This equation defines the mean height of the trees at each point in time, dependent on the prevailing *effective site index*. The equation itself is drawn from work by Burkhart and Tennent (1977) and represents the growth path for trees in the Wellington Conservancy.

Next the height information is linked to a graph function which describes a height/dbh curve (dbh is defined as the diameter at breast height of the tree.) This height/dbh curve was taken from a computer run, supplied by Peter Gorman of the Ministry of Forestry, from STANDPAC, a forest analysis package (Whiteside, 1990). With the resultant dbh measurement a basal area calculation can be performed using a standard forestry formula (Levack, 1986). Lastly, the height and basal area information, as well as the number of stems per hectare remaining is used to calculate the wood volume in the hectare of woodlot. The volume calculation is also a standard forestry formula called the Stand Volume/Basal Area Ratio equation (Levack, 1986).

2.2.2. Stems per Hectare

This part of the tree sector defines the 'survival' of trees in the woodlot. The trees planted are represented here as a stock variable out of which there are three flows: *tree mortality from gorse*; *trees killed by possums*; and the silvicultural operation - *thinning*. The harvesting of the trees by clearfelling is not explicitly represented as it occurs in the final period of the rotation. In addition there is a stock-flow system which captures the damage that results from possums.

The variable, *tree mortality from gorse*, represents the mortality that arises when the growth rate of gorse is such that for some part of the pine tree's early life it is over-topped by the gorse. This process is driven by a graph variable, *Gorse tree death factor*, which relates the ratio of gorse height over radiata pine height to an output which is a number between zero and one hundred. The output from *Gorse tree death factor* is converted to a percentage which is applied to the remaining stems per hectare to give the number of tree deaths at that time. This impact is delayed in its effect by twelve months.

Trees damaged by possums and *trees killed by possums* are proxy relationships for the actual way that possums damage or kill pine trees. There are two main methods by which possums damage pine trees: by bark stripping, possibly ring-barking the tree and causing death; and by browsing, which may include the breaking or breaking off of the terminal leader causing either death or malformation. Surveys of the damage done by possums in plantation forests by Clout (1977) and Keber (1988) show that the damage experienced is variable. Damage has been assessed ranging from 7% through to 90%, while tree deaths have similarly varied between less than 1% and 50%. The average for these reports seems to be about 35% damage with 5% deaths (Clout, 1977). Within the damaged portion, between about 20% and 55% of trees which suffer leader damage become malformed (Keber, 1988). The main effect of malformation is to reduce the overall wood quality of the woodlot (see Section 2.5) and it also may reduce the final stocking in

---

3 There is a significant difference between the effective site index and the site index for this woodlot. This measure of forest productivity is an ex-ante measure, since it is typically assessed at the beginning of the rotation. This value, which could be called the expected site index, is the first component of the definition of the effective site index, which is then modified by accumulated growth delays.

the woodlot. In terms of the modelling of the woodlot we have taken the mid-point of these figures as the proportion of damaged trees that become malformed, ie about 38%, and applied this as an adjustment to the number of damaged trees where it affects the *pulpwood fraction* and the *final stocking decision* (these variables are detailed below).

The variable, *trees killed by possums*, tries to capture, in a simplistic way, possum damage and resultant deaths of pine trees. The mechanism employed simply combines the output of a graph, which is based on an estimate of the amount of leaf dry matter on a pine tree at different ages[4], with a figure for the amount of pine dry matter that a possum might eat in a month. By dividing the amount of food available into the amount of consumption activity occurring, an outcome is obtained which is interpreted as the number of damaged trees in the woodlot. Given information on possum damage, which was reviewed above, the number of tree deaths is one-seventh of the variable *damaged trees*. The number of damaged trees is also recorded and the model is calibrated to produce an amount of possum damage of around 30% of planted stems in the base case.

The thinning flow is a step function activated by *timing of thinning*. Thinning is dependent on the management regime being followed in the woodlot. In this case, a low intensity management regime is being followed, so the judgment as to when thinning occurs is partly a rule of thumb. This rule of thumb is to thin when the trees are taller than 12m. So thinning is dependent on the growth effects of possum damage or gorse competition. It could be between 10 to 14 years of age (Gorman, 1995).

The amount of the thinning is set by the *final stocking decision* variable which considers the number of trees which have survived and are not malformed due to possum damage. Generally, two to three trees are planted for each one which is finally selected. At the time of final thinning, the trees selected must have acceptable size and form. This leads to a rule of thumb that about 30% of the initial stocking is retained at thinning. However, where there is extensive damage to a stand of trees, the number of well formed trees is much reduced leading to both a reduction in the final stocking and the retention of trees which are not well formed. This has the effect of reducing the proportion of quality wood in the stand and reducing the number of trees retained to the end of the rotation.

To reflect these two aspects of the final stocking decision the *final stocking decision* variable considers the number of surviving trees at the time of thinning, subtracts the number of malformed trees due to possum damage and via a graph function determines the final stocking. This approach is conservative as it does not tend to reduce the final stocking much from the rule of thumb amount. Partly this is because it is difficult to know how any particular amount of possum damage reduces the quality of the woodlot and thus the number of trees which are sufficiently well formed to be retained.

Note that the variable *damaged trees* only has meaning until the trees are thinned. At this point the impact of possum damage is taken into account by the *final stocking decision* variable. By the time thinning occurs most of the damage that is going to happen to the trees has occurred. This also means that the impact on the *pulpwood fraction* and ultimately the *average wood price* has been set by this time. The variable *damaged trees* indicates the severity of damage suffered by the trees from possums prior to thinning.

2.2.3. Growth Delays

A site index measures the expected height for pine trees after 20 years of growth. If this growth is delayed, due to gorse competition or possum damage, then the trees will attain this expected height some time after 20 years. The amount of time required by the trees to reach this

---

4 The data upon which this graph is based (Madgwick, et al, 1977) has been adjusted in order to produce an expected number of 'damaged' trees and a time profile consistent with when the tree are most vulnerable. The young pine trees are thought to be particularly vulnerable to possum damage up to around 4 to 6 years.

expected height in excess of 20 years is the definition of the variable *growth delays*. This is modelled by a stock-flow mechanism which accumulates delays from gorse - both height and density - and possum damage. These growth delays alter the growth path of the woodlot through subtractions from the site index. This lowering of the *effective site index* simulates the growth delaying effect of gorse competition and possum damage because that variable determines the actual height of the trees at the 20 year mark. If the *effective site index* is reduced then the trees will not attain the expected site index height, in this case 24 metres, until they are over 20 years old.

Gorse competition has a strong effect on the growth path of the trees in this woodlot. This comes about within the variable *effect of gorse height on trees* which has as an input, the ratio of *gorse height* to *pine height*, and a set of values which are the growth delays from this source. These delays are such that when experienced for a period of 12 months they imply an 'x' metre reduction in height growth which translates into a time delay in growth.

However, these growth delays are modified by a scalar, *gorse density effect*, which simulates the effect of the density of gorse coverage. The argument here is that when the gorse ground cover is very dense, ie 60% and above, the level of light and nutrient competition is greater.

Possum damage also causes growth delays, particularly if leaders are damaged (Keber, 1988). To reflect this, the model checks each month the number of *damaged trees* until 181 months, ie about 15 years, and then applies a growth delay, defined by the graph variable *effect on tree growth of possum damage*, to the *effective site index* at that time.

2.3. Gorse Sector

The gorse module, illustrated in Figure 4, is one of the more straightforward parts of the farm woodlot model. The module consists of a single stock variable for *gorse height*, with an inflow defining the *additions to gorse height* and an outflow defining when and how *cutting of gorse* - or die-back - takes place. Supplementary variables are two possible gorse cut times, and a *gorse growth adjustment factor*.

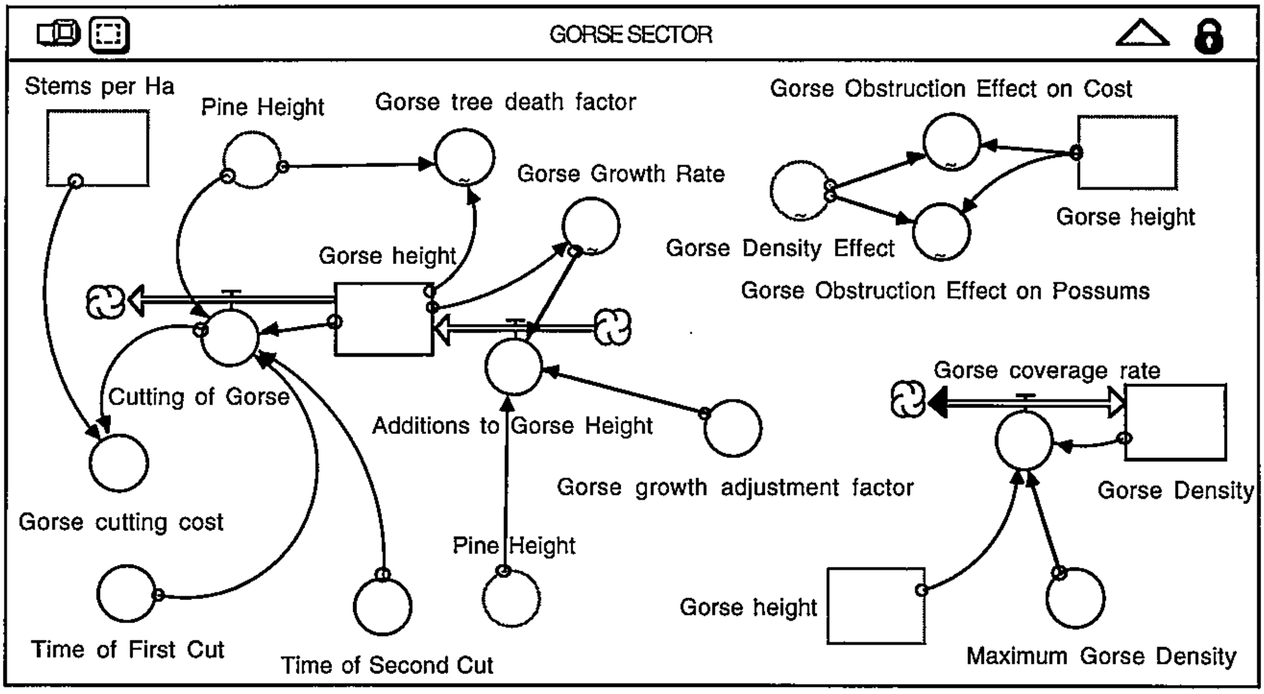

Figure 4. Stella Flow Diagram for the Gorse Sector

The *additions to gorse height* results from the variable *gorse growth rate*, adjusted by a *gorse growth adjustment factor*. There is also a logic statement such that the gorse will stop growing once the height of the radiata pine is over 10m reflecting the shade effect of the trees. A graph relationship describes the *gorse growth rate*; it denotes a monthly rate of growth that is applicable at each gorse height. The data underpinning the graph is from Lee, Allen and Johnson (1986) and is for the Dunedin area. Due to the lower temperatures in that area it was felt that an adjustment factor was necessary to reflect other growing conditions in a simple manner. The *gorse growth adjustment factor* is set at 2.6 times the growth path defined by the Dunedin data. At this level the adjustment factor causes some mortality from over-topping and growth delays from competition. Both these events have occurred with the Makara woodlot.

The *cutting of gorse* variable has two purposes. First, to represent the activity of releasing[5] the pine trees from the gorse by way of a 'scrub-bar'[6]. Second, to reflect the effect of the shading of the gorse by the pine trees. Releasing of the pine trees in this woodlot is achieved by two pulse functions whose timing is set by the two variables, *time of first cut* and *time of second cut*, and they are set to remove the current *gorse height*, that is, setting that variable to zero. The shading effect of the radiata pine trees is simulated by the *cutting of gorse* variable removing 7% of *gorse height* each month after the trees are greater than 10m in height. While in fact the gorse does not actually lose height in this manner, its ability to delay the growth of the trees or hinder silviculture operations within the woodlot is diminished, so that in around two years, or when the trees are about 12m, the canopy has closed over and the gorse is not as great an obstacle (Gorman, 1995).

Lastly, *cutting of gorse* initially generates costs at a rate of 60 cents per stem per hectare. However, as the gorse grows and spreads the ability of 'cutting' to release the trees becomes both physically and financially too expensive. To reflect this, after 48 months, 'cutting' cannot be done.

There are two further elements within the gorse sector. First is the calculation of the current *gorse density*. This is a stock-flow mechanism which adds to the percent coverage of the woodlot by gorse up to a defined maximum. Gorse cover does not occur all at once, it grows over a period of up to about three years. However, if the *gorse height* is cut the *gorse density* is reset so that it grows from zero again.

Finally, gorse has two obstruction effects. Gorse obstructs possums from getting at young pine trees and it obstructs the ability of workers to perform silviculture operations leading to higher costs. Both effects are handled by means of a simple index created from the product of the variables *gorse height* and *gorse density effect*. This becomes an input into two graph functions, whose output either reduces the consumption effects of possums or increases the costs of silviculture operations.

2.4. Possum Sector

The possum sector is divided into three sub-sectors: "possum population"; "possum kills"; and "possum tree consumption". The most important of these three is the "possum population" sub-sector, which simulates the population behaviour of the brushtail possum (*Trichosurus Vulpecula* Kerr). This sub-sector consists of three linked stock variables which describe the development and maturation of possums after birth. Also, there is an inflow and outflow representing birth and death behaviour, respectively, and two flow variables describing the inward and outward migration behaviour of juvenile possums.

---

5 Releasing refers to the action of, either physically or chemically, cutting back competing vegetation that is affecting the growth or survival of a target species, eg radiata pine.

6 A 'scrub-bar' is a motor driven 'weed-eater'-like machine with a circular blade at the end.

2.4.1. Possum Population

The development and maturation behaviour of the brushtail possum is represented by three stock variables and their connecting flows. *Births* are generated in a single inflow variable into the stock variable *pouch young*. Deaths are represented by three outflows, one from each of the main population stocks, *pouch young*, *juveniles* and *adult possums*. The development and maturation of the possum from pouch young through to adulthood is described by these three interconnected stock variables, and shown in Figure 5.

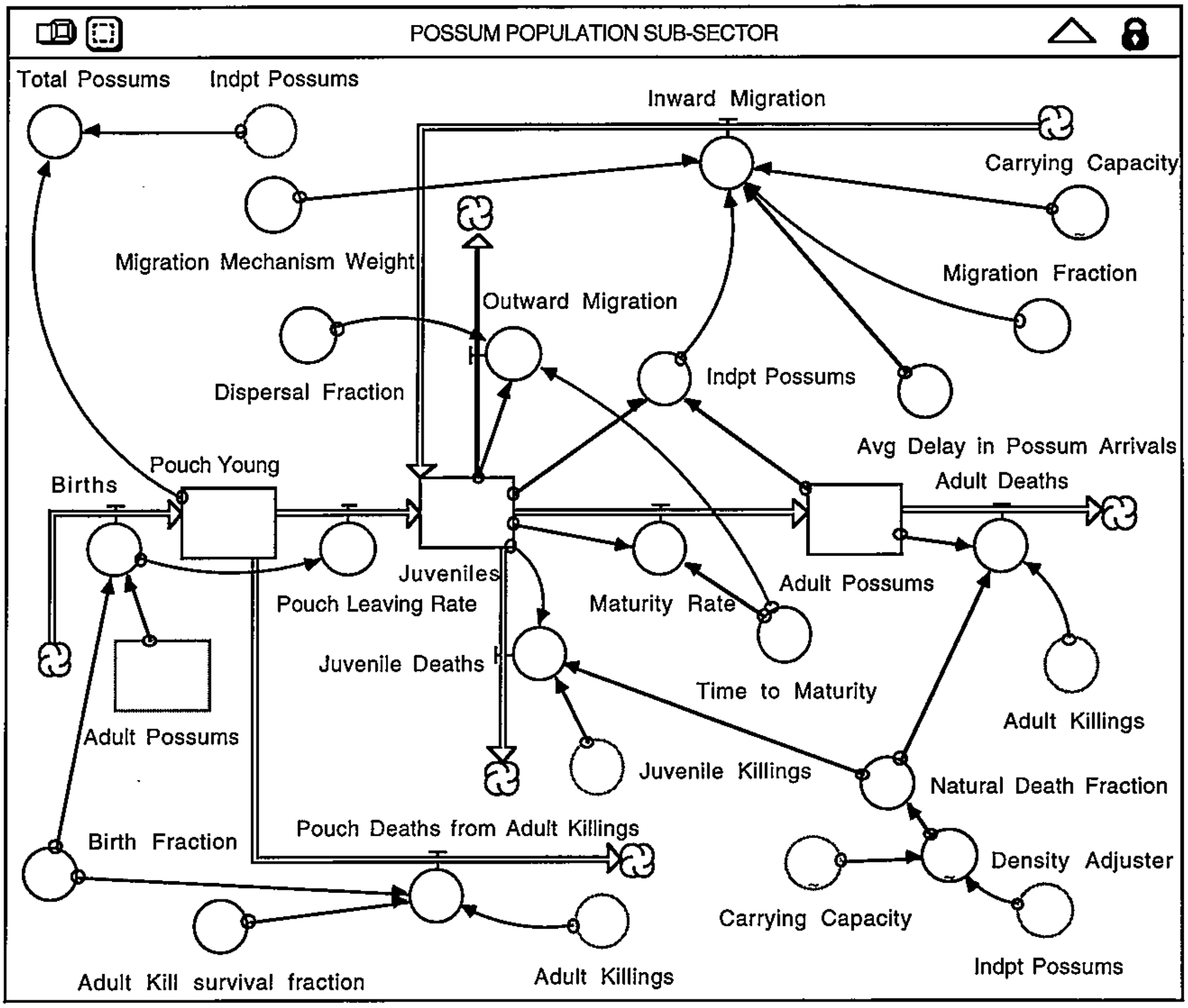

Figure 5. Stella Flow Diagram for the Possum Population Sub-sector

Births are described by a pulse function which adds to the possum population, a number of pouch young set by the *adult possums* times a *birth fraction*. These *births* are repeated every 12 months, starting in May following tree planting. The *birth fraction* is a number which represents the proportion of live young who would survive to become juveniles relative to the stock of adult possums - assuming an even sex ratio. In this model this figure is 0.3 which equates to about 60% of females bearing young who survive[7].

Deaths occur due to two separate causes: (a) Natural deaths, which happen at a rate of about 15% of adult possums per annum in normal conditions (Brockie, *et al.*, 1981). The average life expectancy for a possum is about 6 years (Brockie, *et al.*, 1981). (b) Possum killings which result from human action with devices such as 1080 poison drops or bait stations. For each of the stock variables, *pouch young*, *juveniles* and *adult possums*, there is a 'death' outflow, with both of the latter two stocks being affected by natural deaths and killings. Pouch young deaths depend on the number of adult female killings.

Natural deaths are modified by a *density adjuster* variable. This is used to simulate the effect of population density on the mortality of possums. If the population density is close to the carrying capacity of an area the condition of the animals present is reduced, leading to higher death rates (Gibbs, 1973). The *density adjuster* is a graph variable, which uses as an input the ratio of *indpt* (independent) *possums* to the *carrying capacity* of the woodlot. As the ratio increases, the value of the *density adjuster* falls. The *natural death fraction* is divided by the *density adjuster*, so the death rate rises as the population density rises.

Once possum births have occurred, they "flow" into a stock called *pouch young*. In this stock they are stored until released by the *pouch leaving rate*. The *pouch leaving rate* takes the births that occur and delays them for eight months before they flow out of the stock. This stock represents the development of the *pouch young* from birth until, after eight months, they become independent of their mother. Once the pouch young leave their mother's pouch they become *juveniles*; this being a state where they consume like adults but do not enter the breeding population. The *juveniles* remain in this state for about a further 16 months, until they are 2 years old, before entering the adult population (Cowan, 1990).

A variable which has an important role in setting the number of possums in the woodlot is *carrying capacity*. This variable, and the values it takes, represents the combination of different components. It represents the numbers in a population within the smallest geographical region for which a population can be considered; the availability of den sites and food, etc. One of those dimensions, food availability, suggests a feedback loop from the state of the woodlot to the numbers of possums in the woodlot. The idea is that as the woodlot ages, other factors remaining constant, the availability and palatability of the edible material in the woodlot changes and, overall, declines. With this decline, the number of possums that can be supported by the woodlot also declines. Such a mechanism, while not explicit in the formulation of the model, is implicit in the *carrying capacity* which is one of the main exogenous variables of the model.

Carrying capacity is thought to be high initially, at 18 per hectare, as the woodlot is close to a bush-pasture margin, which then declines to about 5 per hectare after 9 years. Our high initial possum stocking figure is from the Wellington Regional Council, however, this figure is reduced over the next nine years to reflect the much lower stockings found in mature pine forest by Clout (1977) and Keber (1988), who found stockings of about 3 per hectare.

Migration is also an important exogenous variable and has two aspects in this model of possum behaviour. First, juvenile possums begin to disperse from their maternal range once they leave the pouch. This dispersal can produce quite large movements with 10km typical, up to the

---

7 Various authors have discussed the productivity of possum reproduction - Clout (1977), Bell (1981). Clout (1977) indicates that births per female can vary between 0.7 and 1.8, while Bell (1981) shows that for adult females, over 3 years of age, 80-100% produce young each year. These authors also indicate that the survival rate of the young is greater than 90 percent. However, for females of less than 3 years, their rate of reproduction is much lower - see Bell (1981). Combining information in Brockie, Bell and White (1981) on the 'pooled' age structure of possum populations with the productivity estimates of Bell (1981) in the Orongorongo Valley, an estimate of overall productivity of about 20 percent of the population was derived. This seemed low given Clout's figures so a compromise of 30 percent of the population was choosen.

occasional 30km. It is thought that about half of the juveniles from a year's recruitment will disperse (Clout and Efford, 1984). This dispersal is captured in the flow variable *outward migration*. Second, there can be *inward migration*. There seems to be some debate as to what drives inward and outward migration, most of it being dispersal by juvenile possums. One view is that the dispersal is a genetically programmed event where the possum runs until it stops (Brockie, 1995). A simple mechanism of a fixed proportion of the carrying capacity of the woodlot migrating in each month can describe this process. Alternatively, the decision by a possum to stop could depend on external factors, such as the ability of the environment to support the possum, which for females, could be an important decision variable (Efford, 1995). A mechanism which compares the current stocking with the carrying capacity, adjusted for the rate at which possums arrive in an area could reflect this option. Both of these mechanisms have been implemented in the model with the user being able to choose one or other, or mix them.

2.4.2. Possum Kills

Two possum control techniques are used by the model (illustrated in Figure 6). These are 1080 poison drops and bait stations. A 1080 drop has a simple impact, it kills off 80% of independent possums plus some of the pouch young. Bait stations kill a steady 2.5% of independent possums per hectare per year (Allen and Taylor, 1994)..

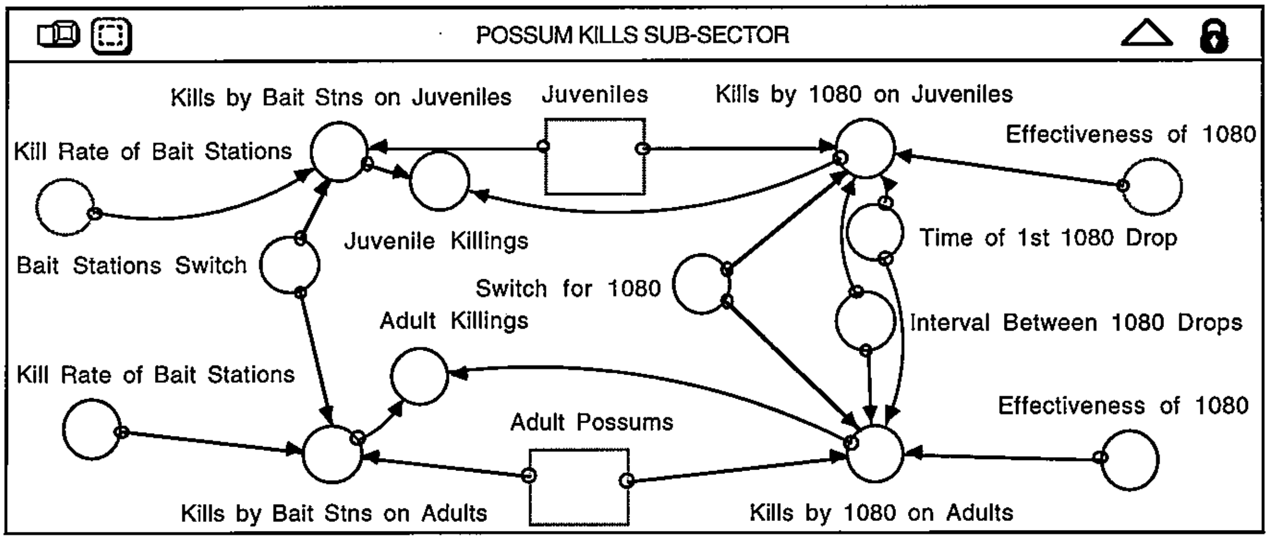

Figure 6. Stella Flow Diagram for the Possum Kills Sub-sector

Separate kill mechanisms have been set for *juveniles* and *adult possums*, as these groups are effectively different populations. For 1080 poisonings there is the option to set different times for the first 1080 drop and the interval between drops. However, these timings depend on decisions made by the Wellington Regional Council who control 1080 poison drops in the region. It is important to note that a pest management levy is paid by the land owner to the Wellington Regional Council whether any control measures are undertaken on the land or not. It is a flat rate of \$0.6653/ha (in 1993/94) on rateable properties over 10ha (determined with reference to Valuation NZ).

Another feature of the possum control mechanisms in this model is that they only operate for the first fifteen years. After fifteen years possums are not able to inflict much damage upon trees and so it was decided that there was no point, in terms of cost, to continuing the activities beyond that time.

2.4.3. Possum Tree Consumption

As part of the proxy mechanism for simulating the damage that possums do to the pine trees in our model a number of variables are combined. The critical variable is the *possum consumption factor* as it is this which is modified by the other variables. It was difficult to decide on a value for this variable due to the proxy nature of the relationship being described. In the end a figure has been used which reflects the amount of dry matter that a possum could eat in a month and the other side of the relationship specifying the damage done by possums has been calibrated to produce 'damage' of around 30-35%. The consumption factor refers to the effect of a single possum so it is scaled up by the number of independent possums in the woodlot.

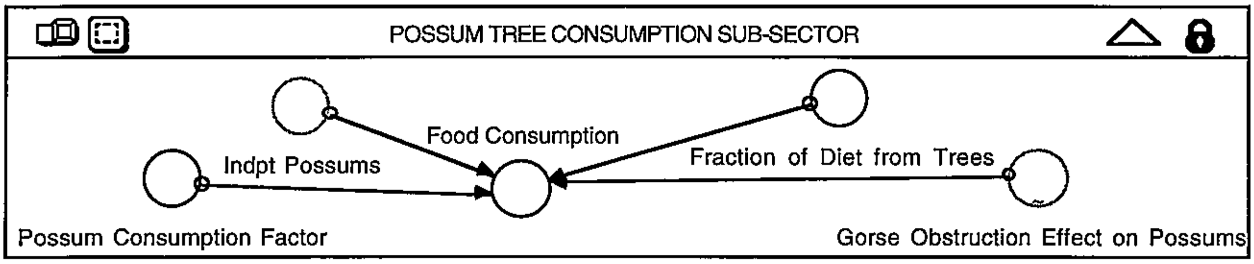

Figure 7. Stella Flow Diagram for the Possum Tree Consumption Sub-sector

Possum consumption is affected by two other variables, *gorse obstruction effect on possums* and *fraction of diet from trees*. First, the gorse obstruction variable suggests that a dense gorse cover tends to shield the young pine trees from the depredations of possum browsing and bark-stripping. A damage survey reviewed by Clout (1977) noted that a forest block with a dense covering of broom had about 90% less possum damage than two other blocks surveyed which were clear of obstruction. Second, the *fraction of diet from trees* reflects the fact that the plant material of a pine tree is not the major part of a possum's diet. Warburton (1978) found that radiata pine formed a significant proportion of the possum's diet in an exotic forest, ranging from nearly 8% to 48% over a year, with an average of about 25%. The fraction is set so that only this level of possum consumption occurs.

2.5. Finance Sector

The core of the financial module of this model (illustrated in Figure 8) is the routine which calculates the net present value (NPV) from growing wood in the woodlot. The model uses an NPV function provided by the software. There are two inputs, *cash outflow* and *revenues*. *Cash outflow* represents the costs that are paid during the rotation. *Revenues* selects the value of the woodlot at month 360 from the variable *wood value calculation*. The equation which performs the *wood value calculation* does so from the *wood volume* adjusted by the *merchantable timber fraction*, *average wood price*, and the *pulpwood fraction*. All these cash flows are in real terms and are pre-tax. Similarly, the discount rate is real and pre-tax (discussed in Section 2.1).

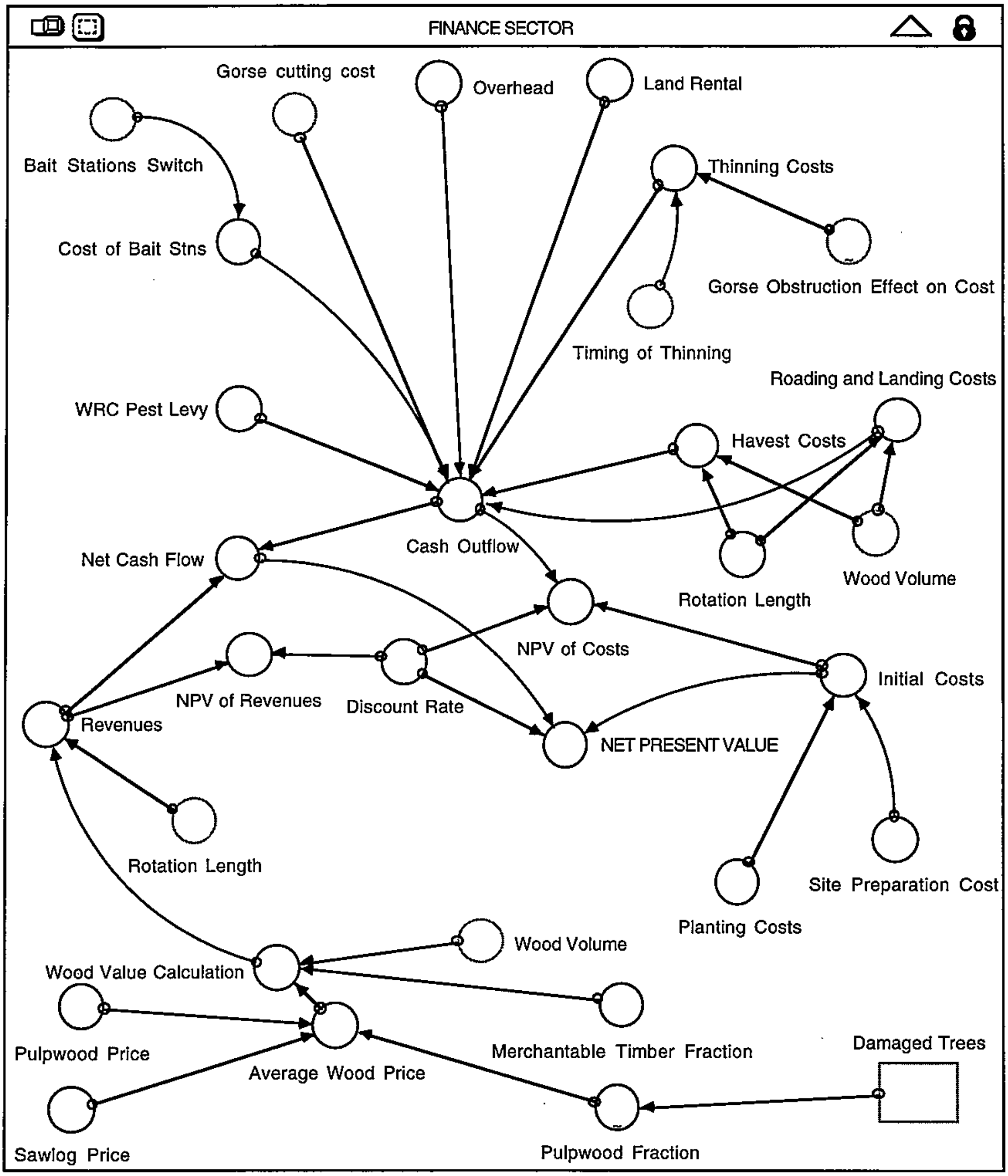

Figure 8. Stella Flow Diagram for the Finance Sector

There are three classes of cost: (a) ongoing costs - ie overhead and land rental; (b) planting, site preparation, silviculture and harvest costs; and, (c) possum and gorse management costs[8]. The main silviculture cost of the present regime, thinning, needs special mention. Thinning is

8 The amount and timing of these costs is described in the equation documentation in Appendix 1 and summarised in Appendix 2.

affected by the amount of understorey that exists within the woodlot. To reflect this a graph variable, *gorse obstruction effect on cost*, which reacts to the product of gorse density and height, applies a multiplier to the thinning costs. The graph itself is based on information in FRI (1981).

As was mentioned above the *wood value calculation* variable takes the currently calculated wood volume and adjusts it to the expected recoverable volume by the *merchantable timber fraction*. This fraction reflects the fact that there are always some losses of wood volume from breakages and inefficient log-cutting, and this is dependant on a number of factors, such as the gradient of the land, the ability of the logging contractor, etc. Next, the recoverable wood volume is multiplied by the average wood price, which is weighted by the percent share of pulpwood and sawlogs and the prices for those log grades. The weight of pulpwood in this weighted price is variable, since one of the effects of severe possum damage is to reduce the quality of the woodlot. This is simulated by increasing the proportion of pulpwood, and reducing the proportion of sawlogs, in the final wood volume. This is achieved by a graph variable called *pulpwood fraction* which responds to the number of trees left after possum damaged trees, which are malformed, are subtracted from the initial stocking.

2.6. Limitations and Validation of the Model

It should be noted that the aims of this paper are oriented towards the determination and dynamic behaviour of the most cost effective methods to control gorse and possums, in order to establish a woodlot up to about age 10 (ie the high risk period). There has been no attempt to cover the full range of issues that surround the debate on gorse and possum control. The focus in the paper is the perspective of the Makara farm woodlot owner and her financial interest in the woodlot. It is not appropriate to consider other important issues here, such as the concerns that 1080 poisoning may also kill the native bird life that may use this habitat or the spillover effects from decisions made within the woodlot on events outside the woodlot. For instance, although a pest levy is paid to the Wellington Regional Council (WRC) it is up to the land owner to request possum control activity on their land. If the land owner chooses not to have any control performed this may frustrate the plans of the WRC because the property may be acting as a reservoir of possums to surrounding properties. Time and resources have not permitted the extensive work required for an attempt to model such a complex system. However, Bennett (1994) has considered elsewhere the wider costs and benefits of possum control in New Zealand.

There are other more practical limitations of this model. For instance, the modelling of possum behaviour has been simplified. Ideally, males and females could be modelled separately, as could the age structure of the population. There are differences in behaviour in breeding, by age, and dispersion, by age and sex. However, it was felt that this part of the model does fairly represent the behaviour of a possum population in aggregate. Similarly, due to the complex nature of the relationship between possums and damage to trees, this has been simplified to a proportional relationship, although mediated through tree consumption variables.

This paper differs from the earlier work in that it attempts to consider more factors, and does so based on a more thorough assessment of the relationships. However, this has not proven a simple task with some of the relationships necessarily being proxy relationships. In some cases the primary research needed in order to define the type and nature of a connection between two variables has not been done or is in progress. For example, the relationship between *gorse height* growth and its effects on radiata pine growth is at present being examined (Richardson, *et al.*, 1993; Richardson, 1994) The result of this is that the model is illustrative rather than predictive.

As a validation exercise, to test the operation of the financial module of the model, a comparison was carried out between the model, with the impact of possums and gorse switched off, and a spreadsheet using data from the Ministry of Forestry's Wellington-Wairarapa Zone Study (Ministry of Forestry, 1994). The model was able to replicate closely the results from a monthly spreadsheet model of the investment problem.

3. MODEL BEHAVIOUR

One model run has been used to describe the normal behaviour of the model. It is called the **base case** scenario. This scenario has both possums and gorse affecting the trees in the woodlot **without any control**. The major features of this model experiment are described below and illustrated in Figure 9.

The model output graphs are annotated as follows. The graphed variables are listed across the top of the diagram. Each variable is assigned a number which relates to a similarly numbered line in the diagram space. On the vertical axis, each numbered variable is associated with a scale, which shows the minimum, middle and maximum values.

In this experiment the independent possums population at the beginning of the rotation starts at 18 per hectare. This is briefly maintained under the pressure of inward migration and then falls to about an average of about 6 per hectare by mid-rotation. This time profile reflects the time behaviour of the *carrying capacity* variable. As well as this trend behaviour the population also displays a saw-toothed shape, peaking when last year's offspring enters the juvenile population and falling as natural deaths and outward migration occur.

The height of the pine trees in the base case scenario at 30 years was 30m. The impact of gorse competition and possum damage means that the base case scenario has growth delays equivalent to about 44 months, ie just under 4 years. Wood volume was 404m^3/ha. Lastly, the net present value was \$893/ha for the base case scenario at the discount rate of 8%. The experiment began with an initial stocking of 1000 sph (stems per hectare) which was thinned from 856 to 284 sph at 141 months, ie nearly 12 years. The final stocking at harvest was 284 sph and total damaged trees per hectare was 309 trees.

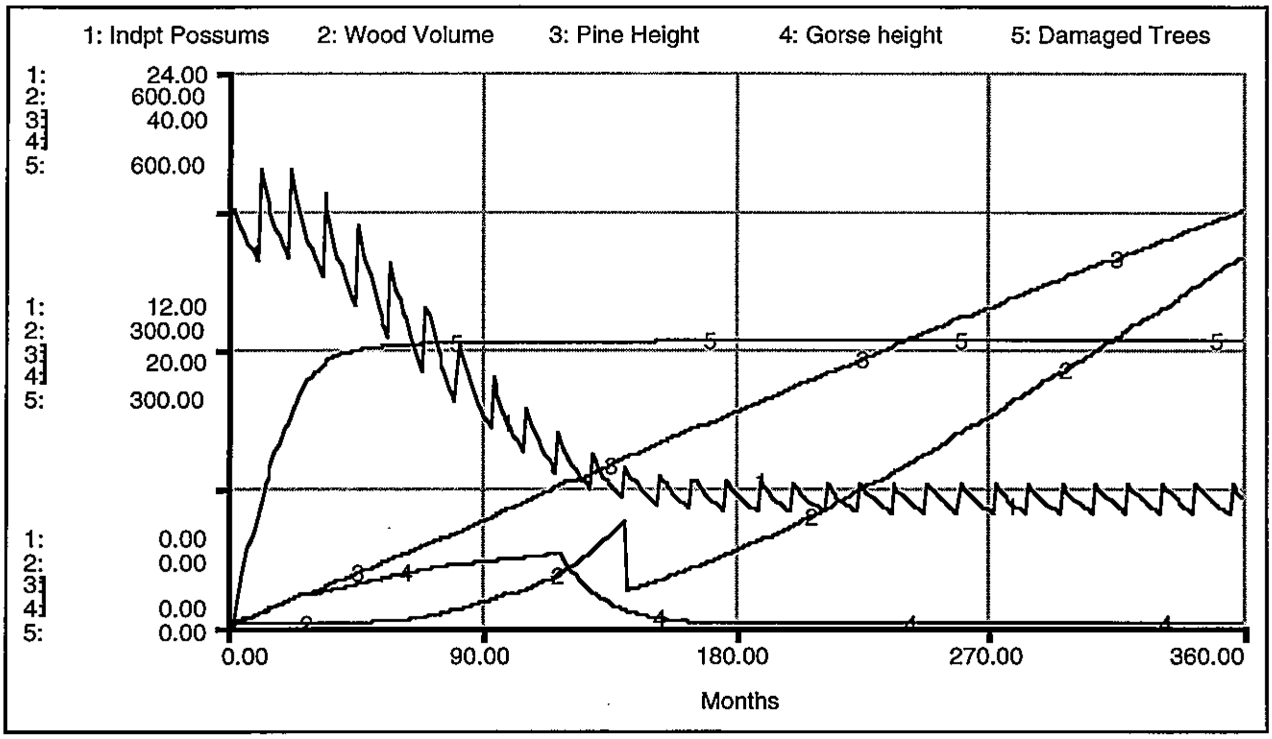

Figure 9. Base Case

4. SENSITIVITY ANALYSIS

The sensitivity analysis of the model shows the effects of changes in the migration fraction, the possum consumption factor, the gorse growth adjustment factor and the discount rate. In each of these four cases the variable is increased by an amount thought to be a significant variation, and the differences between these experiments and the base case are compared. In the case of the migration factor it is increased from 10% pa to 20% pa. The possum consumption factor is increased from 0.5 kg/month to 0.6 kg/month. The gorse growth adjustment factor is increased by 10%, from 2.6 to 2.86. Lastly, the discount rate was increased to 10%. These sensitivity experiments are summarised in Table 1.

It is relevant to ask why these four variables were chosen for a sensitivity analysis rather than another set of variables. Firstly, they are all exogenous to the model. In the case of the possum consumption factor and the gorse growth adjustment factor, they represent factors that drive their respective sectors of the model in terms of their impact on pine trees. The migration factor is an important exogenous variable affecting the possum population. Lastly, the discount rate has an important effect on the net present value calculation.

Table 1. Summary of Sensitivity Experiments

Scenario	Net Present Value @ 8% (1994 $/ha)	Average Wood Price (1994 $/m3)	Wood Volume (m3/ha)	Damaged Trees (sph)	Growth Delays (months)
Base Case	893	127.7	404	309	44
Migration Fraction	872	127.5	402	326	44
Possum Consumption	818	126.9	398	371	45
Gorse Growth Rate	-395	127.8	237	302	73
Discount Rate @ 10%	-250	127.7	404	309	44

4.1. Migration Fraction

In the base case model run the migration fraction was set at 10% per annum. For this sensitivity test it was increased to 20% per annum. This change had a small impact on the results. The net present value of the experiment was $872/ha compared to $893/ha in the base case. Further, the time of thinning and growth delays were unchanged. However, the wood volume was reduced slightly and a few more trees were damaged.

4.2. Possum Consumption Factor

The consumption by possums of radiata pine is primarily determined by the variable *possum consumption factor*, which for the model experiments is set at 0.5kg/month. In order to test the sensitivity of the model to changes in this variable, it was increased to 0.6kg/month. The results are as follows: net present value was reduced to $818/ha; wood volume was 398m^3/ha; there were 371 damaged trees per hectare; but growth delays and time of thinning were unchanged.

The extra consumption by possums and, therefore, the higher number of damaged trees led to a lower wood volume and average wood price which translated to lower revenues and the reduced net present value.

4.3. Gorse Growth Adjustment Factor

For the gorse growth process of the model to affect significantly, the growth profile of radiata pine, the base data had to be adjusted to reflect gorse growing conditions outside the Dunedin area. The adjustment used by the model experiments is a scalar of 2.6 times the base growth path. To test the model's sensitivity to changes in this variable it was increased by 10% to 2.86. The results were dramatic, as follows: net present value was -$395; wood volume was $237m^3$/ha; growth delays were extended to 73 months and thinning was delayed to month 156; and final stocking was only 200 sph.

A higher rate of gorse growth means more competition for the young pines and a greater number being over-topped, leading to less height growth and more deaths. These two facts combined mean much reduced wood volume and revenues. The cost of silvicultural operations is increased by the gorse being taller. Also, there were fewer damaged trees in this experiment due to the faster growing gorse providing some protection from possum attack.

Although these results were quite dramatic, they were not too surprising since the gorse growth rate in the base case is very similar to the tree growth rate. Therefore a small increase in gorse growth is likely to have a major impact on the volume and returns from the woodlot, especially since the base case assumes that there are no gorse control measures in place.

4.4. Discount Rate

Changing the real discount rate from 8% to 10% is an increase of 25%. The effect of this change compared to the base case was a significant worsening of the net present value calculation from $893/ha to -$250/ha. The physical measures for the woodlot were unchanged compared to the base case.

Although the net present value dropped considerably, this is to be expected when discounting cash flows over a 30 year period, as small changes to the discount rate can have a major impact on the net present value. For example, results by Cavana and Glass (1985, Table 5) show that the NPV for radiata pine on a farm woodlot in the central North Island was expected to drop from $1907/ha at a discount rate of 5% to -$588 at a discount rate of 10% (in 1983$).

5. CONTROL EXPERIMENTS

Six further model experiments were run. These are intended to show the model's response to a number of possum and gorse control regimes. Two experiments consider the impact of different gorse control regimes while not controlling possums. These experiments are "One Cut at 6 Months" and "Two Cuts at 6 and 12 Months". A further three experiments show the impact of two of the available techniques of possum control. These experiments are "1080 Poison Drops", "Bait Stations" and "1080 and Bait Stations". Finally, the last experiment considers a combined strategy called "Combined Control". The results are summarised in Tables 2 & 3 in Section 5.4.

5.1. Gorse Control Experiments

The only means of gorse control in this model is the physical cutting of gorse by a scrub-bar. The timing of the gorse cut is the main decision that is required. This needs to be done before the gorse gets too tall and is generally impossible after about four years. The variations that are considered here are a single cut or two cuts.

5.1.1. One Gorse Cut at 6 Months

In this scenario a single gorse cut is made at 6 months. The main results of the experiment are as follows: net present value was $1,097/ha at a discount rate of 8%, a gain of $204/ha over the base case; wood volume was 506m^3/ha; final stocking was 291 sph; damaged trees were up to 334; but growth delays were markedly down to only 14 months.

Gorse competition, which leads to tree growth delays, was reduced by the gorse cut so that tree growth suffered only slightly over one year of tree growth delays. This regime also reduced the mortality from over-topping. However, there were more possum damaged trees since the shielding effect of gorse was reduced. The gains in growth that occurred due to reduced gorse competition as well as lower tree mortality combined to allow a high final stocking and high wood volume. These factors produced an increase in revenues much higher than the increase in costs from this regime. The present value of the costs increased by $856/ha but the present value of the revenues increased by $1,060/ha in this regime compared to the base case.

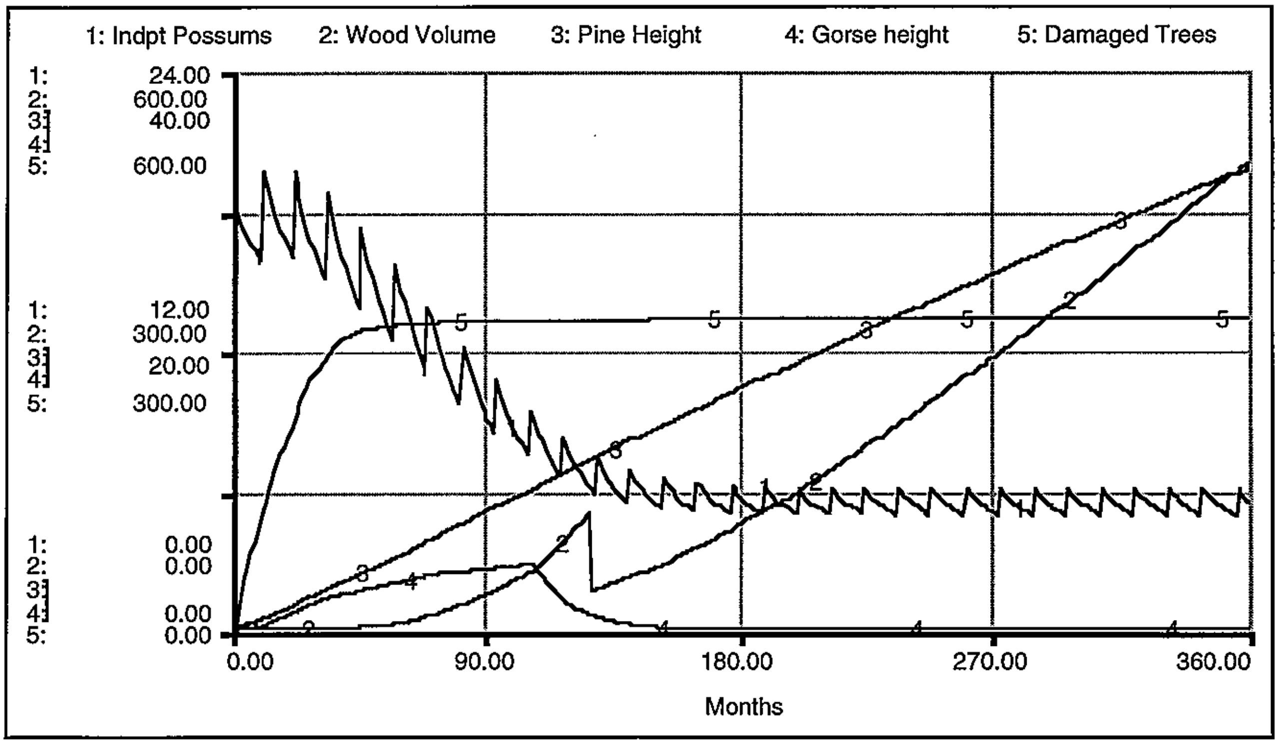

Figure 10. One Gorse Cut at 6 Months

5.1.2. Two Gorse Cuts at 6 and 12 Months

Two cuts were made on the gorse, one at 6 months, the other at 12 months. The main results per hectare of the experiment are as follows: net present value was $611 at a discount rate of 8%; wood volume was 515m^3; final stocking was 290; damaged trees increased by a further 20 trees to 354 compared to just one gorse cut; but growth delays fell by two months. It is not immediately apparent that Figures 10 and 11 are different. However, there is some separation between the pine height and gorse height line which is significant.

The net present value for this experiment was much reduced compared to both that of the previous experiment and the base case scenario. The main reason for this was that the extra gains in the wood volume from the second gorse cut were not sufficient to offset the extra cost of the operation. The present value of the costs increased by $561/ha but the present value of the revenues only increased by $75/ha in this regime compared to one gorse cut. Also the number of damaged trees increased in this experiment which has led to a lower average wood price. However, growth delays were lower than in the previous experiment.

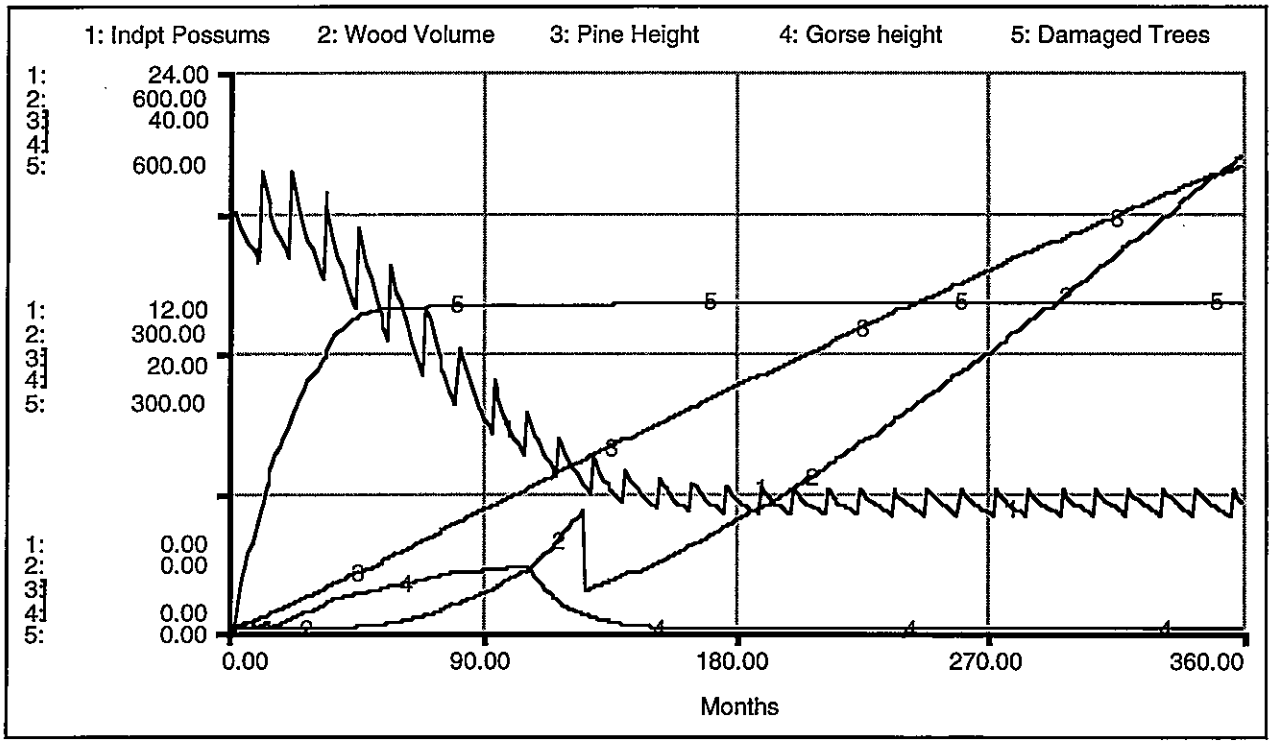

Figure 11. Two Gorse Cuts at 6 and 12 Months

5.2. Possum Control Experiments

To investigate the impact of possum control regimes, three experiments were run. The first two experiments considered two alternative means of control: 1080 poison, and bait stations. The third experiment considered a combination of the two separate experiments.

5.2.1. 1080 Poison Drops

In this experiment a 1080 poison drop is simulated. The first drop is made in month one and is then repeated every 36 months until month 181, ie about 15 years. The main results of the experiment are as follows: net present value was $1,270/ha at 8%; wood volume was 445m³/ha; final stocking was 294 sph; the number of damaged trees was reduced to just over one-third of the base case; and growth delays were reduced to 35. Figure 12 shows that after the initial reduction in the possum population there is some gain in possum numbers due to migration and births. However, the pressure from the three yearly 1080 drops reduces the possum population to low levels.

By controlling the numbers of possums in the woodlot, this regime reduced the amount of tree damage and improved the average wood price. When combined with a marginally improved wood volume and final stocking, this gave greater revenue growth. A further enhancement to this result is that there is no additional cost for this control technique as the Wellington Regional Council's Pest Levy is part of the cost structure of the base case. The effect is minimal. However, while a definite programme of control is modelled here, in reality woodlot owners are dependent on the availability of this service which can by no means be guaranteed.

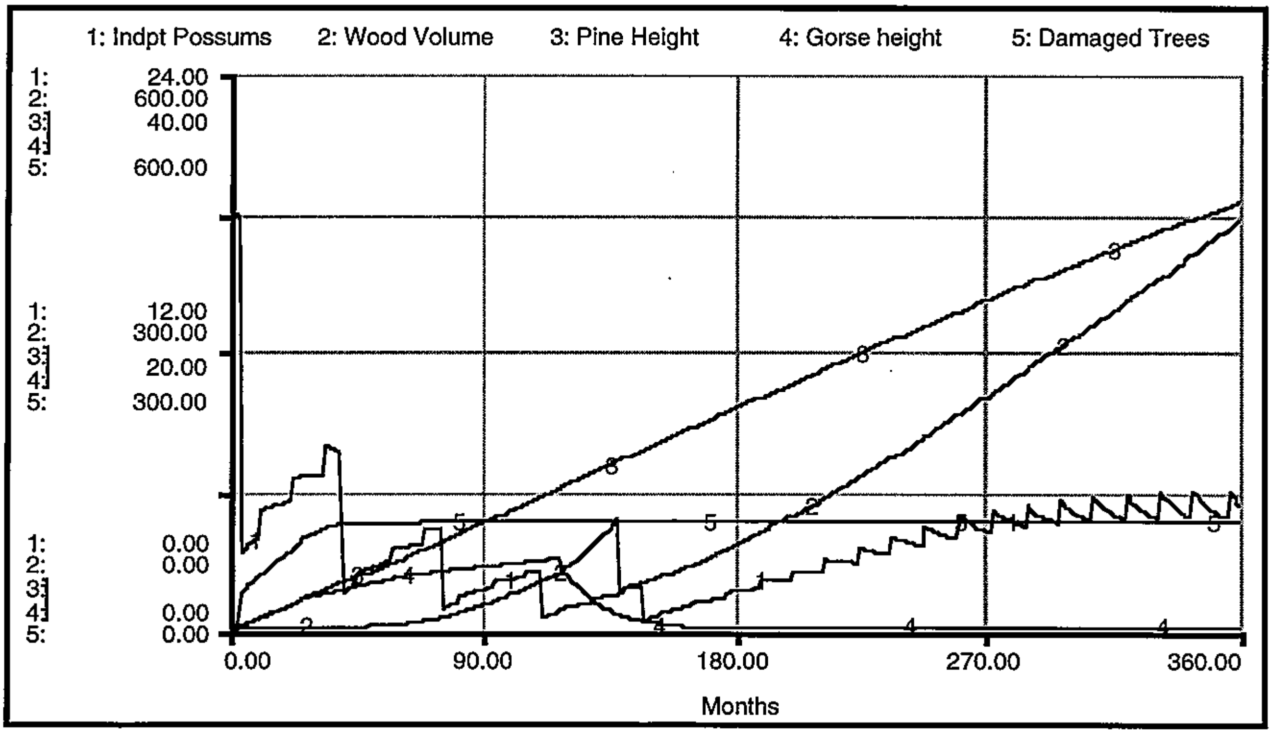

Figure 12. 1080 Poison Drops

5.2.2. Bait Stations

A bait station is a funnel-like container with a serving platform at its lower end. The station is filled with Talon baits which are anti-coagulant. Possums are drawn to the baits, which they feed on, before dying. This regime of one bait station per hectare places a constant pressure on the possum population, killing 2.5% per year.

The main results of the experiment are as follows: the net present value decreased to $526/ha at a discount rate of 8%; wood volume was 413m^3/ha; the final stocking was 286 sph; fewer trees were damaged but growth delays were only slightly less than the base case.

Since this regime did not immediately reduce the stock of possums, it was unable to check enough tree damage and subsequent growth delays to enhance the wood volume and final stocking of the woodlot. Even though the average wood price was better than the base case, it was not sufficient to cover the extra costs of the regime. In this regime the present value of the costs increased by $491/ha while the present value of the revenues increased by only $124/ha.

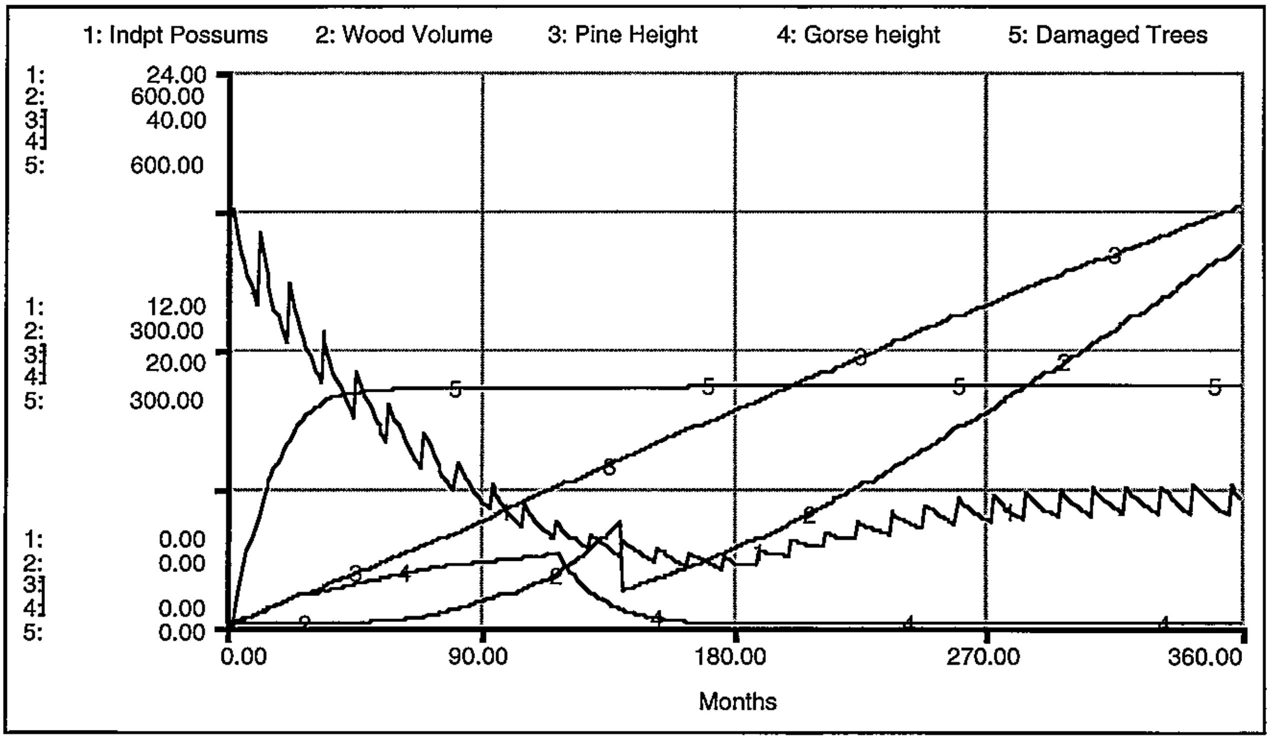

Figure 13. Bait Stations

5.2.3. 1080 and Bait Stations

This regime uses a combination of possum control mechanisms, ie 1080 poisoning and bait stations, to control the possum population. The same settings have been used as for the previous two possum control experiments. The results for the experiment are as follows: the net present value of $844/ha at 8% was slightly lower than the base case; wood volume was 449m³/ha; the final stocking was 295 sph; tree damage was much reduced - less than a third of the base case; growth delays were reduced from 44 to 34 months, ie just under 3 years.

Important here is the initial possum control effect of the 1080 poison drop as well as the suppressive effect of the bait stations. However, even with these big improvements in tree damage and the average wood price, as well as better wood volumes and final tree stockings, the costs that bait stations added resulted in little significant gain in revenues.

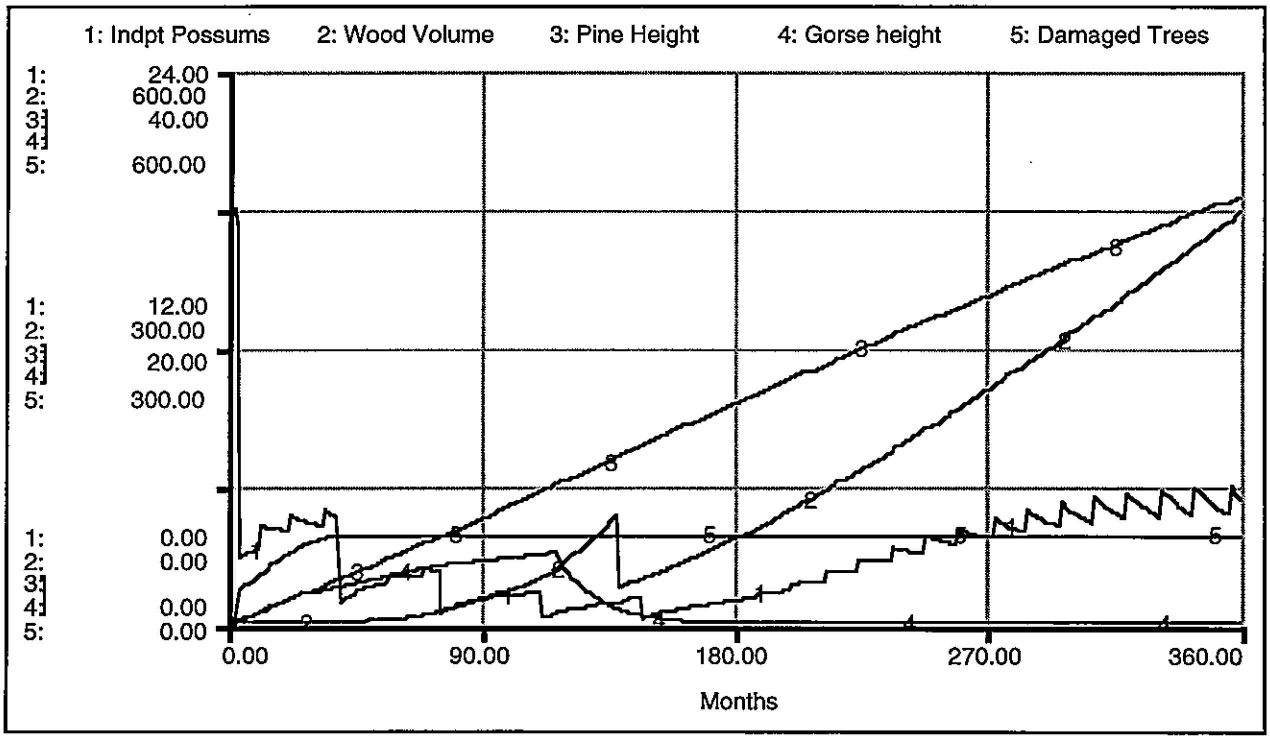

Figure 14. 1080 Poison Drops with Bait Stations

5.3. Combined Control Experiment

For this experiment one control technique is targeted at each 'problem'. Against possums a regime of 1080 poisoning drops every three years was used, beginning in the month after planting, while the releasing of the pine trees by gorse cutting was applied at 6 months after planting. The rationale for this regime was to target each 'problem' using the most cost effective technique. The main results were: the highest net present value of $1,486/ha at a discount rate of 8%; wood volume of 546m^3/ha; final stocking of 300 sph; just over a third the number of damaged trees compared to the base case; and growth delays were reduced from 44 to 7 months, ie from over three and a half years to just over a half year.

The gorse and possum control regimes complemented each other in this experiment. Gorse control markedly reduced the competition effects of gorse upon the growth of the radiata pine allowing good tree growth. Possum control by 1080 poisoning reduced the damage suffered by the pine trees which meant that the average wood price and final tree stocking were enhanced. The present value of the costs increased by $967/ha but the present value of the revenues increased by the greater amount of $1,560/ha in this regime compared to the base case.

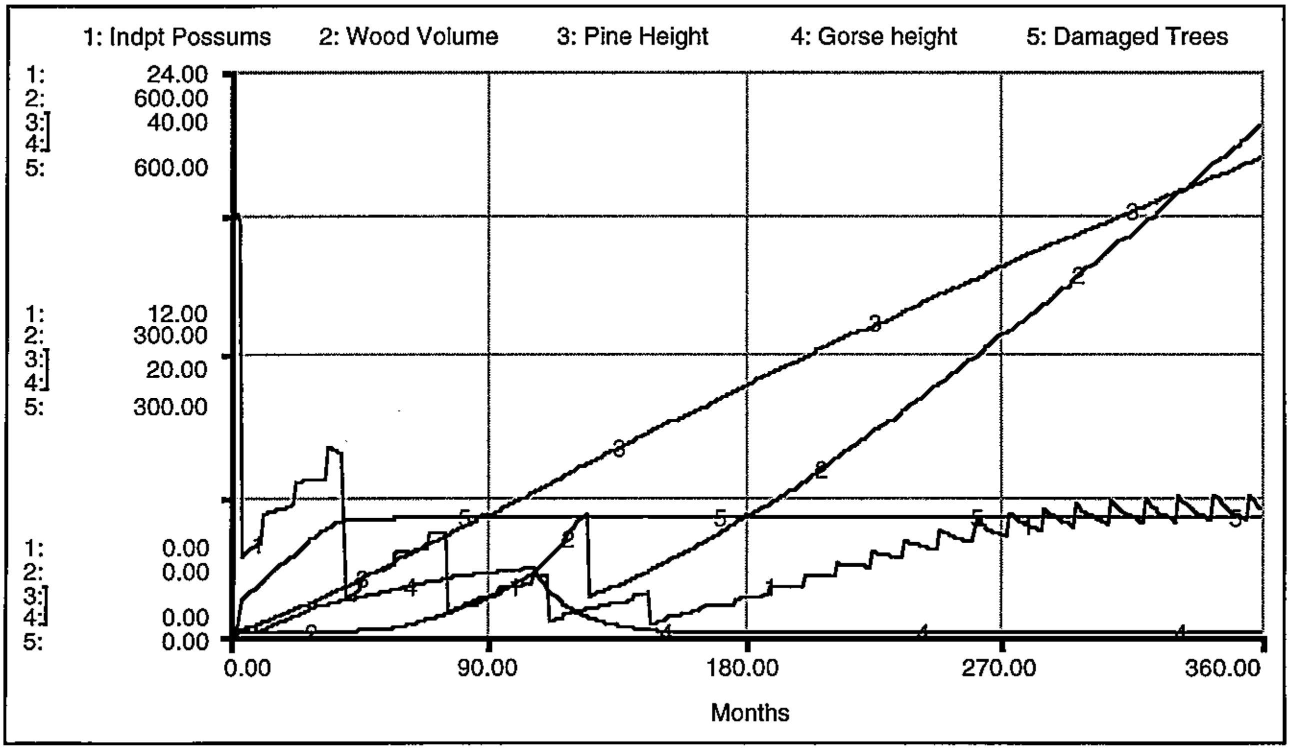

Figure 15. Combined Possum and Gorse Control

5.4. Summary of the Control Experiments

The results of the control experiments can be analysed in a number of ways. Two obvious ways of considering the results are in terms of financial indicators and physical measures. Tables 2 and 3 below presents the results in these terms. To rank the alternatives, in order to judge which regime is 'best', we have used a net present value measure calculated from pre-tax cash flows using an 8% real discount rate (displayed in Table 3).

Table 2. Summary of the Physical Measures from the Control Experiments

Figure	Scenario	Wood Volume (m3/ha)	Final Stocking (sph)	Damaged Trees (sph)	Growth Delays (months)	Time of Thinning (month)
9	Base Case	404	284	309	44	141
10	One Gorse Cut	506	291	334	14	126
11	Two Gorse Cuts	515	290	354	11	126
12	1080 Poisoning	445	294	114	35	138
13	Bait Stations	413	286	258	42	140
14	1080 and Bait Stations	449	295	95	34	138
15	Combined Control	546	300	123	7	124

Table 3. Summary of the Financial Indicators from the Control Experiments (in 1994 dollars)

Figure	Scenario	Net Present Value @ 8% ($/ha)	Rank	Present Value of Costs @ 8% ($/ha)	Present Value of Revenues @ 8% ($/ha)	Average Wood Prices ($/m3)
9	Base Case	893	4	3,327	4,220	127.7
10	One Gorse Cut	1,097	3	4,183	5,280	127.3
11	Two Gorse Cuts	611	6	4,744	5,355	127.1
12	1080 Poisoning	1,270	2	3,439	4,709	129.3
13	Bait Stations	526	7	3,818	4,344	128.3
14	1080 and Bait Stations	844	5	3,915	4,759	129.4
15	Combined Control	1,486	1	4,294	5,780	129.2

There are two main observations from these results. First, where a gorse control regime has been used the wood volumes are much higher. In all three experiments where the gorse was cut the wood volume was greater than $500m^3$/ha at age 30 years compared to the base case of $404m^3$/ha. A corollary of this finding is that growth delays are much lower compared to the base case. A supplementary observation from these regimes is that tree damage was increased. This reflected the fact that some of the shielding effect against possums that gorse provides was lost when the gorse was cut.

The second observation concerns possum control. The main effect of possum control was to reduce the number of trees damaged by the possums. With possum damaged trees reduced, the pulpwood fraction was not increased significantly and thus the average wood price remained higher. A further impact from the reduction in damaged trees was that growth delays from that source were slightly lower than the base case.

6. CONCLUSIONS

This paper has discussed a system dynamics model which has been designed to evaluate the impact of various gorse and possum control measures on the financial return of a farm woodlot in the Makara area of Wellington. A number of sensitivity tests and control experiments were presented. What is shown by these model experiments is that there is a significant gain to be made from releasing the young pine trees from the gorse, particularly if this is done early. However, it is the first cut which is important rather than subsequent ones. Costs associated with these gorse control regimes are experienced early in the rotation and not repeated. Bait stations, the worst performer, apply steady pressure on the possum population but does not achieve its impact early in the rotation when the trees are most vulnerable to possums. The costs of this control measure, though not large, are spread over the first half of the rotation. Lastly, part of the advantage that 1080 poisonings has over the other regimes is that it entails no extra cost, since its costs are already included in the base case's cost structure, through the compulsory Wellington Regional Council levy. (The size of this advantage is not very large, being of the order of 1%). However, the regime does achieve a significant impact on the possum population early in the rotation thus reducing the number of damaged trees. When the possum and gorse control measures were combined, not surprisingly, a better result occurred. It is worth cautioning that both the level of gorse competition and possum damage are at reasonably high levels, which may have produced results that are more pessimistic than may be warranted.

The low management regime discussed in this paper (ie no pruning and a single thinning to waste) could be seen as a 'default' regime for many woodlot owners. Because pruning to obtain logs may take place at any age from 3 to 10 years depending on the target diameter over stumps (usually between 13 & 19 cm) and depending on site factors, sooner or later the woodlot owner will have to spend a reasonable sum to get pruned logs at harvest. This is not always possible as cash flow for many woodlot owners is dependent on external factors such as wool and meat prices, and personal family circumstances. For example, the woodlot owner of the Makara block has decided to make the pruning decision depending on the cash flow generated from the sale of lambs and wool.

The Makara woodlot owner also found this model to be very useful for testing the sensitivity of factors such as possum numbers and gorse growth rate; so she could get a feel for whether or not she should change the gorse and possum control measures in order to get a reasonable tree crop. Log prices for the different grades were also adjusted and the model re-run suggesting sometimes entirely different control regimes for gorse and possums.

Once the trees are past the establishment phase (for example 4 years), gorse and possums are not such a problem and can largely be ignored, except perhaps for some low level possum control. Thus the model is not so concerned with the type of management (silvicultural) regime used regarding pruning and thinning of the forest. Once the trees are 4 years old and established, a wide variety of management regimes (eg pulp, sawlogs or pruned logs) can be chosen. Consequently, the model presented here could be further developed to allow for different silvicultural regimes.

Finally, what this model has clearly demonstrated is the complex nature of the dynamic behaviour of a system involving biological and environmental factors (ie possums, gorse and trees) and human intervention (in terms of silviculture, and possum and gorse control). Control measures have been evaluated with the aid of a system dynamics model and a range of financial indicators and physical measures have been provided to assist with decision making. This modelling approach allows crucial inputs into the discounted cash flow analysis, whose values depend on the feedback effects of the interactions of possums, gorse and pine trees, to be included and to affect the results. Further, the method, when combined with the graphics based modelling tools now available, provides a powerful and intuitive framework within which to achieve modelling objectives. We hope that the approach outlined in this paper will be of value to farm woodlot managers dealing these types of problems.

ACKNOWLEDGMENTS

There are a number of people who have provided very generous assistance with this project. Many of them have helped by being sounding boards on whether our vision of how a particular part of the model boundary worked was on the right track. Others helped by allowing access to data, information or direction to the same. However, these people bear no responsibility for the work contained herein, that being ours alone. Their names are as follows: Fiona Allen, Michael Young and Mack Morum for their earlier work on the original models; Peter Gorman and Hamish Levack from the Ministry of Forestry; Bob Brockie of Victoria University of Wellington; Murray Efford of Landcare Research; Brian Richardson and Graham West from the Forest Research Institute; and Norman Hawcroft for his extremely helpful review comments on an earlier version of this paper.

REFERENCES

Allen, F., and R. Taylor (1994), *Possum Control on a Farm Woodlot: Report on Possum Control Alternatives for Optimising the Return from a Farm Woodlot*, Unpublished report for MMBA 572, Graduate School of Business and Government Management, Victoria University of Wellington.

Baker, P. (1995), Personal communication, New Zealand Rural Fire Service, Napier.

Bell, B.D. (1981), Breeding and Condition of Possums Trichosurus Vulpecula in the Orongorongo Valley, near Wellington, New Zealand 1966-1975, in Bell, B.D., (Ed.), *Proceedings of the First Symposium on Marsupials in New Zealand*, Zoology Publications of Victoria University of Wellington, No.74.

Bennett, J. (1994), *Cost Benefit Analysis of Possum Control in New Zealand*, Graduate School of Business and Government Management, Victoria University of Wellington (The GSBGM Project Report Series, No. 1, October 1994).

Bennett, J., M. Young and M. Morum (1994), *Strategic Model: Gorse Control in a 10 ha farm forest*, Unpublished report for MMBA 572, Graduate School of Business and Government Management, Victoria University of Wellington.

Brockie, R.E. (1995), Personal communication, Victoria University of Wellington, Wellington.

Brockie, R.E., B.D. Bell and A.J. White (1981), Age Structure and Mortality of Possum Trichosurus Vulpecula Populations from New Zealand in Bell, B.D., (Ed.), *Proceedings of the First Symposium on Marsupials in New Zealand*, Zoology Publications of Victoria University of Wellington, No.74.

Burkhart, H.E. and R.B. Tennent (1977), Site Equation for Radiata Pine in New Zealand, *New Zealand Journal of Forestry Science*, Vol 7(3).

Carter Holt Harvey Ltd (1994), *Carter Holt Harvey Annual Report 1994*, Carter Holt Harvey Limited, Private Bag, Auckland

Cavana, R.Y. and R.G. Coyle (1984), A Policy Analysis Model for New Zealand's Plantation Forestry System, *New Zealand Journal of Forestry*, Vol 29(1), pp. 24-50.

Cavana, R.Y. and B.P. Glass (1985), Economic Analysis of Selected Special-Purpose Species Regimes, *New Zealand Journal of Forestry Science*, Vol 15(2), pp. 180-94.

Checkland, P. (1981), *Systems Thinking, Systems Practice*, Wiley, Chichester, UK.

Clout, M.N. (1977), *Ecology of the Possum in Pine Plantations*, Unpublished doctoral dissertation, University of Auckland.

Clout, M.N., and M.G. Efford (1984), Sex Differences in the Dispersal and Settlement of Brushtail Possum (Trichosurus Vulpecula), *Journal of Animal Ecology*, Vol 53.

Coyle, R.G. (1977), *Management System Dynamics*, Wiley, New York.

Cowan, P.E. (1990), Brushtail Possum, in King, C.M., (Ed.), *The Handbook of New Zealand Mammals*, Oxford University Press.

Efford, M. (1995), Personal communication, Landcare Research Ltd, Dunedin.

Fletcher Challenge Ltd (1994), *Fletcher Challenge Forest Division Interim Report 1993/94*, Fletcher Challenge Limited, Private Bag, Auckland.

F.R.I. (1981), Long Term Gorse and Broom Control, *What's New in Forest Research*, Forest Research Institute, No.100.

Forrester, J.W. (1961), *Industrial Dynamics*, MIT Press, Cambridge, Mass.

Gibbs, J.A. (1973), The Effects of Density on Animal Populations, in Orwin, J.,(Ed.), *Assessment and Management of Introduced Animals in New Zealand Forests*, Forest Research Institute Symposium, No.14.

Gorman, P. (1995), Personal communication, Ministry of Forestry, Wellington.

Keber, A.W. (1988), *An Enquiry into the Economic Significance of Possum Damage in an Exotic Forest near Taupo*, Unpublished doctoral dissertation, 2 vols., University of Auckland.

Lee, W.G., R.B. Allen and P.N. Johnson (1986), Succession and Dynamics of Gorse (Ulex europaeus L.) Communities in the Dunedin Ecological District, South Island, New Zealand, *New Zealand Journal of Botany*, Vol.24(2).

Levack, H.H. (Ed.) (1986), *1986 Forestry Handbook*, New Zealand Institute of Foresters (inc.).

Madgwick, H.A.I., D.S. Jackson and P.J. Knight (1977), Above-ground Dry Matter, Energy, and Nutrient Content of Trees in an Age Series of Pinus Radiata Plantations, *New Zealand Journal of Forestry Science*, Vol.7(3).

Ministry of Forestry (1994), *Wellington-Wairarapa Zone Study*, Ministry of Forestry, Wellington.

Peterson, S., and B. Richmond (1994), *STELLA II Technical Documentation*, High Performance Systems Inc., Hanover, NH 03755.

Richardson, B. (1994), Personal communication, Forest Research Institute, Rotorua.

Richardson, B. and G. West (1994), Radiata Pine Growth Trends Following Weed Control, *New Zealand Journal of Forestry* (Forthcoming).

Richardson, B., A. Vanner, N. Davenhill, J. Balneaves, K. Miller, and J. Ray (1993), Interspecific Competition Between Pinus Radiata and some Weed Species - First-Year Results, *New Zealand Journal of Forestry Science*, Vol 23(2).

Seitzer, S., W. Judd, and K. Warne (1992), Possum: An Ecological Nightmare, *New Zealand Geographic*, No.13, Jan-Mar.

Warburton, B. (1978), Foods of the Australian Brush-tailed Possum (Trichosurus Vulpecula) in an Exotic Forest, *New Zealand Journal of Ecology*, Vol.1.

Whiteside, I.D. (1990), STANDPAC Modelling System for Radiata Pine, in: James, R.N. and G.L.Talton, (Eds), *New Approaches to Spacing and Thinning in Plantation Forestry: proceedings of a IUFRO conference*, held at the Forest Research Institute, Rotorua, Ministry of Forestry, FRI Bulletin 151.

Wolstenholm, E.F., and R.G. Coyle (1983), The Development of System Dynamics as a Methodology for System Descriptions and Qualitative Analysis, *Journal of the Operations Research Society*, Vol 34, No.7: 569-581.

APPENDIX 1

DOCUMENTED LISTING OF THE FARM WOODLOT MODEL

FINANCE SECTOR

Average_Wood_Price = (1-Pulpwood_Fraction)*Sawlog_Price+Pulpwood_Fraction*Pulpwood_Price

DOCUMENT: A weighted average wood price ($ per cubic metre) between sawlogs and pulpwood. Weighted by the variable 'pulpwood fraction'

Cash_Outflow = Overhead + Land_Rental + Gorse_cutting_cost + Cost_of_Bait_Stns + WRC_Pest_Levy + Thinning_Costs + Roading_and_Landing_Costs + Havest_Costs

DOCUMENT: This variable collects the cash expenses of running the woodlot.

Cost_of_Bait_Stns = If (Bait_Stations_Switch=1 AND TIME<181) then pulse (40,1,1000) + pulse (20,1,5) else 0

DOCUMENT: When the bait station control regime is in use and the time into the rotation is less than 15 years, this variable charges expenses with an initial cost of $40 and a recurring cost every 5 months of $20, beginning in the first month.

Havest_Costs = PULSE(26.2*Wood_Volume,Rotation_Length,100) {$/ha}

DOCUMENT: The Harvest Costs include logging and loading, management, and transport 20km, respectively. Costs are derived from MoF, Wellington-Wairarapa Zone Study, MoF-Wgtn, 1994.

Initial_Costs = Planting_Costs+Site_Preparation_Cost

Discount_Rate = 8 {% pa}

DOCUMENT: The real pre-tax discount rate for NPV calculations.

Land_Rental = 80/12 {$/ha per month}

DOCUMENT: The land rental is a value to reflect the opportunity costs applying the land to forestry rather than other uses, eg. grazing. The amount is based on current grazing rentals in the Makara area (Bennett, pers. comm.)

Merchantable_Timber_Fraction = 0.90

DOCUMENT: This fraction refer to the fact that there are breakage and malformation of logs such that the recoverable volume is less than that of the standing trees

Net_Cash_Flow = Revenues-Cash_Outflow

NET_PRESENT_VALUE = NPV(Net_Cash_Flow,(Interest/1200),-Initial_Costs) {$/ha}

NPV_of_Costs = NPV(Cash_Outflow,(Interest/1200),Initial_Costs) {$/ha}

NPV_of_Revenues = NPV(Revenues,(Interest/1200),0) {$/ha}

Overhead = 50/12 {$/ha per month}

DOCUMENT: Overhead of $50 per heactare per annum - this covers manager's time for checking plantation and contingency work. This is paid out even over the length of the rotation.

Planting_Costs = 0.53*1000 {$/ha}

DOCUMENT: The cost per seedling of 53 cents is drawn from the mid point of the cost of seedlings contained in Ministry of Forestry, Wellington-Wairarapa Zone Study, Ministry of Forestry, Wellington, 1994. This gives a cost per hectare.

Pulpwood_Price = 57.5 {$ per cubic metre}

DOCUMENT: This price is the mid-point of the at mill door or wharf price for pulp logs given in Ministry of Forestry, Wellington-Wairarapa Zone Study, Ministry of Forestry, Wellington, 1994.

Revenues = PULSE(Wood_Value_Calculation,Rotation_Length,100) {$/ha}

DOCUMENT: Revenues occur when the woodlot is havested at a time determined by the 'rotation length' variable. The amount of those revenues is given by the variable 'wood value calulation'

Roading_and_Landing_Costs = PULSE(3*Wood_Volume,(Rotation_Length-12),100) {$/ha}

DOCUMENT: Roading and landings costs are incurred in the year before harvest. The cost is $3 per cubic metre per hectare.

Rotation_Length = 360 {months}

Sawlog_Price = 146 {$ per cubic metre}

DOCUMENT: This price is the mid-point of the weighted average high and low sawlog prices given in MoF, Wellington-Wairarapa Zone Study, MoF-Wgtn, 1994. The weights used are the percent share that each grade of sawlog contributes to the total volume of sawlogs. The implicit assumption is that if the total proportion of sawlogs changes then the composition of this by grade remains unchanged.

Site_Preparation_Cost = 100 {$/ha}

DOCUMENT: Site preparation costs: one block on the Makara property was prepared by manual clearing with a 'scrubber bar' - cost=$60; The second block first received an aerial spray with grazon, was burnt and then resprayed - cost=$140. The value of $100 is a compromise. Another source suggests $95/ha (MoF, 1994)

Thinning_Costs = PULSE((Gorse_Obstruction_Effect_on_Cost*325),Timing_of_Thinning,1000) {$/ha}

DOCUMENT: The cost of $325 is taken from MoF, Wellington-Wairarapa Zone Study, MoF-Wgtn, 1994, (low management regime). This cost is adjusted by any effect from gorse obstruction. When it occurs is defined by the 'timing of thinning' variable.

Wood_Value_Calculation = Wood_Volume*Merchantable_Timber_Fraction*Average_Wood_Price {$/ha}

DOCUMENT: This variable calculates continuously a value for the trees in the woodlot. It is simply a recoverable wood volume (in cubic metres) multiplied by a weighted average wood price (in $ per cubic metre). Strictly, this variable is meaningless until after age ten.

WRC_Pest_Levy = pulse(0.6653,6,12) {$/ha}

DOCUMENT: The Welington Regional Council controls pest management in the Makara area. Each year a 'pest' levy is paid, whether any pest control work is done or not. It is a flat rate of $0.6653/ha (in 1993/94) on rateable properties over 10 ha (determined with reference to Valuation NZ).

Pulpwood_Fraction = GRAPH((1000-0.38*Damaged_Trees))

(500, 0.5), (550, 0.44), (600, 0.38), (650, 0.34), (700, 0.3), (750, 0.26), (800, 0.24), (850, 0.22), (900, 0.2), (950, 0.19), (1000, 0.18)

DOCUMENT: In woodlots where there is little damage or loss from possum and a low intensity management regime is being followed about 18% of the wood volume will be pulp wood. However, where there has been significant damage, either from direct possum damage or indirectly from disease, the wood quality can be expected to fall (Keber,1988). This is reflected in an increasing proportion of pulp wood in the harvest. The input function subtracts an adjusted number of damaged trees from the initial stocking. The adjustment reflects the proportion of malformed trees that result from possum damage (see main report).

GORSE SECTOR

Gorse_Density(t) = Gorse_Density(t - dt) + (Gorse_coverage_rate) * dt

INIT Gorse_Density = 0

DOCUMENT: A reservoir of gorse coverage. This variable indicates the current amount of gorse density as per the interpretation given to the variable 'Maximum Gorse Density'.

INFLOWS:

Gorse_coverage_rate = IF Gorse_height < 0.1 THEN ((-1*Gorse_Density)/DT) ELSE (IF Gorse_Density > Maximum_Gorse_Density THEN 0 ELSE 0.139)

DOCUMENT: This variable says two things. First, if gorse is cut to a height less than 10cm then reset the gorse density to zero. Second, if the current density is greater than the maximum for the site then stop adding to the gorse density, otherwise add 0.139 each month. The figure 0.139 is calibrated to give full gorse density in three years.

Gorse_height(t) = Gorse_height(t - dt) + (Additions_to_Gorse_Height - Cutting_of_Gorse) * dt

INIT Gorse_height = 0

DOCUMENT: Reservoir for gorse growth. Until the time when the pine trees overtop and shade out the gorse this variable represents the height to which the gorse has grown. After that time it should be reinterpreted as an index of the effective height, reflecting its ability to be obstructive.

INFLOWS:

Additions_to_Gorse_Height = if(Pine_Height>10) then 0 else Gorse_growth_adjustment_factor*Gorse_Growth_Rate

DOCUMENT: This inflow states that gorse will continue to grow until the height of the radiata pine is greater than about 10 metres at which time the canopy of the woodlot should have closed.

OUTFLOWS:

Cutting_of_Gorse = IF (Pine_Height>10) THEN (0.07*Gorse_height) ELSE (IF TIME<49 THEN (pulse(Gorse_height,Time_of_First_Cut,500)+pulse(Gorse_height,Time_of_Second_Cut,500)) ELSE 0)

DOCUMENT: When the radiata pine canopy closure begins the gorse is deprived of light and it begins to stop growing. After about two years this drying out has proceeded to a stage such that the woodlot is reasonably accessible at a reasonable cost. (Peter Gorman, 1995) This is simulated by the gorse height being progressively reduced by 7 percent per month. When this overtopping process is not occurring then this variable is used to simulate the gorse control regime of cutting the gorse.

Gorse_cutting_cost = If (Cutting_of_Gorse >0 AND time<49) then Stems_per_Ha*.60 else 0

Gorse_growth_adjustment_factor = 2.6

DOCUMENT: An adjustment factor to ratchet the growth rate of gorse up or down relative to the base gorse growth data.

Maximum_Gorse_Density = 5

DOCUMENT: This variable sets the maximum density for gorse that occurs on our site. The variable is an index with the following loose interpretation; a value of 3 implies about 60% coverage while a 5 implies full coverage.

Time_of_First_Cut = 1000 {month}

Time_of_Second_Cut = 1000 {month}

Gorse_Growth_Rate = GRAPH(Gorse_height)

(0.00, 0.033), (0.2, 0.033), (0.4, 0.033), (0.6, 0.033), (0.8, 0.033), (1.00, 0.033), (1.20, 0.033), (1.40, 0.033), (1.60, 0.033), (1.80, 0.033), (2.00, 0.033), (2.20, 0.0166), (2.40, 0.0166), (2.60, 0.0166), (2.80, 0.0166), (3.00, 0.0166), (3.20, 0.0166), (3.40, 0.0166), (3.60, 0.0166), (3.80, 0.0166), (4.00, 0.0166), (4.20, 0.008), (4.40, 0.008), (4.60, 0.008), (4.80, 0.008), (5.00, 0.008), (5.20, 0.008), (5.40, 0.008), (5.60, 0.008), (5.80, 0.008), (6.00, 0.008), (6.20, -0.008), (6.40, -0.008), (6.60, -0.008), (6.80, -0.008), (7.00, -0.008)

DOCUMENT: Graph of gorse growth rate vs gorse height. In this model it is based on the work of Lee, Allen and Johnson (1986). The data was collected in Dunedin and thus may be slower growing due to the low temperatures

Gorse_Obstruction_Effect_on_Cost = GRAPH(Gorse_Density_Effect*Gorse_height)

(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.11), (5.00, 1.22), (6.00, 1.28), (7.00, 1.37), (8.00, 1.60), (9.00, 1.80), (10.0, 2.00)

DOCUMENT: This is a synthetic index which intends to capture the relationship between the height of the gorse and its density and cost. FRI Bulletin, No.100, reports that in the Ashley forest, gorse cost cost increases for each pruning lift of 22%, 28% and 37% for thinning. Further, some cost in the South Is. were up to 60%. The curve was formed by calculating the index for different heights and densities and then considering the level of difficulty posed by the different height-density combinations (Gorman, 1995).

Gorse_Obstruction_Effect_on_Possums = GRAPH(Gorse_Density_Effect*Gorse_height)

(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 0.75), (4.00, 0.5), (5.00, 0.27), (6.00, 0.18), (7.00, 0.1), (8.00, 0.1), (9.00, 0.05), (10.0, 0.05)

DOCUMENT: This relationship aims to reflect the fact that in dense and tall gorse stands, possums are obstructed from access to the pine trees (Clout, 1977)

Gorse_tree_death_factor = GRAPH(Gorse_height/Pine_Height)

(1.00, 0.00), (1.06, 1.50), (1.11, 2.00), (1.17, 4.00), (1.22, 5.50), (1.28, 8.00), (1.33, 15.0), (1.39, 34.0), (1.44, 58.5), (1.50, 100)

DOCUMENT: This is the tree death relationship from Bennett, et al (1994). The greater the amount of overtopping of the pine trees by the gorse the greater the consequent number of tree deaths.

POSSUM KILLS SUB-SECTOR

Adult_Killings = Kills_by_1080_on_Adults+Kills_by_Bait_Stns_on_Adults {adult possums per ha}

Bait_Stations_Switch = 0

DOCUMENT: This variable switches the use of bait stations on (1) or off (0).

Effectiveness_of_1080 = 0.8

DOCUMENT: Proportion of independant possums killed by a 1080 poison drop.

Interval_Between_1080_Drops = 36 {months}

Juvenile_Killings = Kills_by_1080_on_Juveniles+Kills_by_Bait_Stns_on_Juveniles {juvenile possums per ha}

Kills_by_1080_on_Adults = IF TIME<181 THEN (pulse (Adult_Possums * Effectiveness_of_1080, Time_of_1st_1080_Drop, Interval_Between_1080_Drops) * Switch_for_1080) ELSE 0 {adult possums per ha}

DOCUMENT: This variable calculates the number of adult deaths from a 1080 poison drop and this regime is only used for the first fifteen years of the rotation.

Kills_by_1080_on_Juveniles = IF TIME<181 THEN (pulse (Juveniles * Effectiveness_of_1080, Time_of_1st_1080_Drop, Interval_Between_1080_Drops) * Switch_for_1080) ELSE 0 {juvenile possums per ha}

DOCUMENT: This variable calculates the number of juvenile possum deaths from a 1080 poisoning drop.

Kills_by_Bait_Stns_on_Adults = IF TIME<181 THEN (Adult_Possums * Kill_Rate_of_Bait_Stations * Bait_Stations_Switch) ELSE 0 {adult possums per ha}

DOCUMENT: Adult possum deaths from the use of bait stations.

Kills_by_Bait_Stns_on_Juveniles = IF TIME<181 THEN (Juveniles * Kill_Rate_of_Bait_Stations * Bait_Stations_Switch) ELSE 0 {juvenile possums per ha}

DOCUMENT: Juvenile possum deaths from the use of bait stations.

Kill_Rate_of_Bait_Stations = 0.019 {proportion of possums per ha per month}

Switch_for_1080 = 0

DOCUMENT: This variable switches 1080 poison drops on (1) or off (0).

Time_of_1st_1080_Drop = 1 {month}

POSSUM POPULATION SUB-SECTOR

Adult_Possums(t) = Adult_Possums(t - dt) + (Maturity_Rate - Adult_Deaths) * dt

INIT Adult_Possums = 13

DOCUMENT: A usual range of population density is 0.1/ha to 25/ha of independant possum. The estimated initial carrying capacity of the woodlot is about 18 independant possums. This high value reflects that the habitat is initially a native bush margin which usualy has high stockings (Cowan, 1990).

INFLOWS:

Maturity_Rate = Juveniles/Time_to_Maturity

DOCUMENT: The rate at which juveniles become adult possums.

OUTFLOWS:

Adult_Deaths = (Adult_Possums*Natural_Death_Fraction)+Adult_Killings

DOCUMENT: Deaths describes population mortality in terms of losses due to natural causes and those killings resulting from the action of human control measures. For example, 1080 poisoning and bait stations. The variable is in possums per hectare per month.

Juveniles(t) = Juveniles(t - dt) + (Pouch_Leaving_Rate + Inward_Migration - Outward_Migration - Maturity_Rate - Juvenile_Deaths) * dt

INIT Juveniles = 5

DOCUMENT: Female possum are not generally able to reproduce until they are at least one year olds, if not two year olds, so in the model all young enter the juveniles stock to delay their entry into the adult possum population until after further sixteen months (Cowan, 1990).

INFLOWS:

Pouch_Leaving_Rate = DELAY(Births,8,0) {This delay represents the average time, in months, that is spent in the pouch}

Inward_Migration = (Migration_Mechanism_Weight*(Carrying_Capacity*(Migration_Fraction/12)))+((1-Migration_Mechanism_Weight)*((Carrying_Capacity-Indpt_Possums)/Avg_Delay_in_Possum_Arrivals))

DOCUMENT: There are two proposed migration mechanisms. First, migration is independent of the habitat or current stocking of the woodlot and therefore is at a fixed constant rate. Second, migration is dependant on the current stocking and habitat, proxied by the difference between carrying capacity and the current stocking. These mechanisms can be used separately or mixed.

If 'Migration Mechanism weight is equal to 1 the first mechanism is used, whereas if it is 0 then the second applies. For the model experiments only the first mechanism was used.

OUTFLOWS:

Outward_Migration = (Juveniles*Dispersal_Fraction)/Time_to_Maturity

DOCUMENT: While young possums are juveniles, a proportion of them disperse from their maternal range to what will become their own home range. This behaviour is much more prevalent among males than females, however, the model does not distinguish this behaviour.

Maturity_Rate = Juveniles/Time_to_Maturity

DOCUMENT: The rate at which juveniles become adult possums.

Juvenile_Deaths = Juveniles*Natural_Death_Fraction+Juvenile_Killings

DOCUMENT: The equivalent of adult deaths, for juveniles.

Pouch_Young(t) = Pouch_Young(t - dt) + (Births - Pouch_Leaving_Rate - Pouch_Deaths_from_Adult_Killings) * dt

INIT Pouch_Young = 0

DOCUMENT: This stock holds those possums which are not as yet independent. Births occur in about late April to early June and then the pouch young leave their mother after eight months.

INFLOWS:

Births = pulse(4,0,1000)+pulse((Adult_Possums*Birth_Fraction),11,12)

DOCUMENT: Births occur in the period April to June, with the pouch young entering the juvenile population after eight months. In terms of the model this birth pulse has been centred on May. Since the model begins running in June (trees planted in June-July) this implies that the first pulse occurs after 11 periods, repeating 12 monthly thereafter.

The argument "pulse(4,0,1000)" initialises the pouch young stock at 4 from the beginning of the model run. This is to reflect those females who have just given birth in the previous month.

OUTFLOWS:

Pouch_Leaving_Rate = DELAY(Births,8,0) {This delay represents the average time that is spent in the pouch}

Pouch_Deaths_from_Adult_Killings = Birth_Fraction*(1-Adult_Kill_survival_fraction)*Adult_Killings

DOCUMENT: Apart from the natural mortality associated with the birth of young possum - which is included in the birth fraction estimate - pouch young deaths can also result from the death of a female, who has young, from 1080 poisoning or bait stations. To reflect this this outflow adjusts adult killings by the birth fraction to give an estimate of the number of females with young. This figure is further adjusted by a fraction representing proportion of young who do not survive their mother being killed.

Adult_Kill_survival_fraction = 0.1

DOCUMENT: The proportion of pouch young who survive when their mother is killed by 1080 or bait stations. This can be thought of as pouch young who are nearly ready to leave the pouch at the time of the parents death.

Avg_Delay_in_Possum_Arrivals = 24 {The average length of time for possum to recolonise after extinction}

DOCUMENT: Clout (1977) culled one of his radiata pine study blocks to extinction. Possum numbers returned to 50% of capacity after one year - >24. Work by Green & Coleman in native bush at Mt. Brian O'Lynn found a return to 50% after three years - <72.

Birth_Fraction = 0.3

DOCUMENT: "80-100% of adult female (3-10 years old) produce young each year." (Cowan, 1990) while a lower rate holds for younger females. Survival of pouch young ranges from 0% to 90%> and depends on the age of the female. In a review of the literature, Clout (1977) noted a birth rate range from 0.7 to 1.8 births per female. Also, Brockie noted that a typical recruitment range was between 0.15 to 0.35 of the population (Brockie, 1995). Given the high birth rates mentioned by Clout (1977) it was decided to choose a figure which was high within the range given by Brockie.

Dispersal_Fraction = 0.5

DOCUMENT: The proportion of juveniles who disperse from their home range.

Indpt_Possums = Adult_Possums+Juveniles {Total of independent possums}

Migration_Fraction = 0.10 {fraction per year}

Migration_Mechanism_Weight = 1 {sets the split between the two alternative migration mechanisms}

Natural_Death_Fraction = 0.012/(Density_Adjuster)

DOCUMENT: Death rates estimated from literature search at 25% per annum at carrying capacity. A more 'normal' mortality rate could be 15%, (Brockie, Bell & White, 1981.) Figure used is the per month rate. A density adjuster has been included to reflect higher densities leading to lower animal condition and thus higher death rates. It is Calibrated to give 25% at carrying capacity, and 15% at about 60% of carrying capacity.

Time_to_Maturity = 16 {This is the average time that is spent as a juvenile}

Total_Possums = Indpt_Possums+Pouch_Young

Carrying_Capacity = GRAPH(TIME)

(0.00, 18.0), (36.0, 13.0), (72.0, 8.00), (108, 5.00), (144, 5.00), (180, 5.00), (216, 5.00), (252, 5.00), (288, 5.00), (324, 5.00), (360, 5.00)

DOCUMENT: Carrying Capacity equals the maximum number of possums per hectare the woodlot will support. Carrying capacity reflects a number of factors, such as, the numbers in the surrounding country (related to whether there is native bush nearby), availability of den sites, food availabilty, etc. An approximate number, supplied by the Wellington Regional Council for the Makara Valley, was 18. However, Clout (1977) and Keber (1988) showed a stocking of 3/ha in mature pine forest. Numbers of the order of 16 - 25/ha apply where there are forest/scrub-pasture margins, which is the case in the woodlot. So to reflect these two extremes a graph has been used which begins at 18 but declines to 5 by 9 years.

Density_Adjuster = GRAPH(Indpt_Possums/Carrying_Capacity)

(0.00, 3.00), (0.1, 3.00), (0.2, 2.50), (0.3, 2.00), (0.4, 1.70), (0.5, 1.50), (0.6, 1.20), (0.7, 1.00), (0.8, 1.00), (0.9, 0.8), (1.00, 0.7), (1.10, 0.6), (1.20, 0.5), (1.30, 0.4), (1.40, 0.4), (1.50, 0.4)

DOCUMENT: This density adjuster is to reflect the way that nearness to the carrying capacity of an area (which itself reflects the availability of food, den sites etc.) reduces the condition of the animals within leading to lower birth rates and higher death rates (Gibbs, 1973).

POSSUM TREE CONSUMPTION SUB-SECTOR

Food_Consumption = Indpt_Possums * Possum_Consumption_Factor * Fraction_of_Diet_from_Trees * Gorse_Obstruction_Effect_on_Possums

DOCUMENT: The total amount of tree dry matter consumed by possums per month is the product of their numbers and their average monthly consumption. Also, their consumption of trees is affected by the fraction that trees make up of their diet and is further modified by an obstruction effect from growing gorse.

Fraction_of_Diet_from_Trees = 0.25

DOCUMENT: The work by Warburton (1978) indicates that the proportion that radiata pine formed of a possums diet was an average 25% over a year.

Possum_Consumption_Factor = 0.5

DOCUMENT: Harvie (1973) suggests that possums have a mean daily intake of 350 grams of food (wet weight). This figure gives a monthly consumption of 10.5 kg. Assuming a dry-weight of 5% of wet-weight results in about 525 grams per month of wet weight, ie. 10.5*0.05.

TREE SECTOR

Accumulated_Growth_Delays(t) = Accumulated_Growth_Delays(t - dt) + (Growth_Delays) * dt

INIT Accumulated_Growth_Delays = 0

DOCUMENT: This stock accumulates the flow of growth delays arising from the activity of gorse and possums.

INFLOWS:

Growth_Delays = Gorse_Density_Effect * Effect_of_gorse_height_on_Trees + Effect_on_Tree_Growth_of_Possum_Damage

DOCUMENT: Growth delays on Radiata are simulated by 'Effect of Gorse height on Trees' which is further modified by the 'Gorse Density Effect'. The greater is the gorse cover, the greater the 'Effect of gorse height on trees'. Also, growth delays created by possum damage are added.

Damaged_Trees(t) = Damaged_Trees(t - dt) + (Trees_Damaged_by_Possums) * dt

INIT Damaged_Trees = 0

DOCUMENT: This variable accumulates the number of pine trees that suffer damage from possums.

INFLOWS:

Trees_Damaged_by_Possums = IF TIME<180 THEN ((Food_Consumption/Food_Available)-Trees_Killed_by_Possums) ELSE 0

DOCUMENT: This flow variable calculates the number of damaged trees in the woodlot. The calculation takes the amount of consumption possible during a month by the resident possum population and divides that by the amount of food available on a single tree, giving the number of trees damaged. Subtracted from this is the number of trees that die from the damage.

Dead_Trees_from_Possums(t) = Dead_Trees_from_Possums(t - dt) + (Trees_Killed_by_Possums) * dt

INIT Dead_Trees_from_Possums = 0

DOCUMENT: A reservoir for dead trees due to possum damage.

INFLOWS:

Trees_Killed_by_Possums = IF TIME<180 THEN ((Food_Consumption/Food_Available)/7) ELSE 0

DOCUMENT: The number of possum killed trees is determined by dividing the amount that the possum population can eat in a month by the amount of edible matter on a pine tree to get the number damaged. This is then divided by seven to obtained the number killed. A review of possum damage experience suggests that the mean number of damaged trees being 35% and the number dying being one-seventh of that, ie. 5% (Clout, 1977).

Stems_per_Ha(t) = Stems_per_Ha(t - dt) + (- Thinning - Trees_Killed_by_Possums - Tree_Mortality_from_Gorse) * dt

INIT Stems_per_Ha = 1000

DOCUMENT: The number of stems of viable radiata pine remaining per hectare.

OUTFLOWS:

Thinning = STEP(((Stems_per_Ha-Thinning_Stocking)/DT),Timing_of_Thinning)

DOCUMENT: The silvicultural technique of removing a certain proportion of the current stocking in order to promote stem growth. The variable removes a number of stems determined by 'thinning stocking' at a time set by 'timing of thinning'.

Trees_Killed_by_Possums = IF TIME<180 THEN ((Food_Consumption/Food_Available)/7) ELSE 0

DOCUMENT: The number of possum killed trees is determined by dividing the amount that the possum population can eat in a month by the amount of edible matter on a pine tree to get the number damaged. This is then divided by seven to obtained the number killed. A review of possum damage experience suggests that the mean number of damaged trees being 35% and the number dying being one-seventh of that, ie. 5% (Clout, 1977).

Tree_Mortality_from_Gorse = DELAY((Gorse_tree_death_factor/100)*Stems_per_Ha,12)

DOCUMENT: This mechanism removes a percentage of the current stems per hectare depending on the gorse tree death factor.

Trees_Killed_by_Gorse(t) = Trees_Killed_by_Gorse(t - dt) + (Tree_Mortality_from_Gorse) * dt

INIT Trees_Killed_by_Gorse = 0

DOCUMENT: A reservoir of dead trees due to gorse over-topping.

INFLOWS:

Tree_Mortality_from_Gorse = DELAY((Gorse_tree_death_factor/100)*Stems_per_Ha,12)

DOCUMENT: This mechanism removes a percentage of the current stems per hectare depending on the gorse tree death factor.

Basal_Area = (PI*(Diameter_at_Breast_Height*100)^2)/40000

DOCUMENT: Standard Basal Area equation (see Levack (1986)).

Effective_Site_Index = 24-DELAY(Accumulated_Growth_Delays,12)

DOCUMENT: The site index chosen here is 24 at year 20. The value was chosen due to the topography and exposure effects of the site whose site index is thought to range between 18 and 28 (Baker, 1995). The effects of gorse and possums upon tree growth is simulated here by a reduction in the site index (see West and Richardson, 1993). Further, the effect appears to be delayed by about 1 year (Richardson, et al, 1993, Richardson, 1994).

Pine_Height = (Effective_Site_Index/(1-EXP(-0.0009185*Effective_Site_Index*20))^1.1965)*((1-EXP(-0.0009185*Effective_Site_Index*(TIME/12)))^1.1965)+0.15

DOCUMENT: Burkhart, HE., RB., Tennent, Site Index Equations for Radiata Pine in New Zealand, NZJFor.Sci, 7(3), 1977. The coefficients used represent those for the Wellington Conservancy, eg. the Esk, Gwavas and Ngaumu Forests. An adjustment factor to give a non zero starting value for height and reflect the fact that a tree has some height when planted, is included. The adjustment is 0.15.

Thinning_Stocking = IF TIME = Timing_of_Thinning THEN Final_Stocking_Decision ELSE 300

Timing_of_Thinning = IF (Pine_Height>12.0 AND Pine_Height<12.09) THEN (TIME) ELSE 1000

Wood_Volume = 0.84*(Stems_per_Ha*Basal_Area)+0.297*Pine_Height*(Stems_per_Ha*Basal_Area)

DOCUMENT: This is a standard Stand Volume/Basal Area ratio equation. That is, V/B = a + bH, where V = volume, B is basal area and H is mean top height. The equation is function no. 7, part of the library of ratio equations held by the FRI in Rotorua. This equation is for the Hawkes Bay/ Ngaumu forest areas. The coefficients are: a = 0.84 (se = 0.0168); and b = 0.297 (se = 0.0008); the R2 is 0.98.

Diameter_at_Breast_Height = GRAPH(Pine_Height)

(0.00, 0.01), (2.50, 0.027), (5.00, 0.055), (7.50, 0.107), (10.0, 0.147), (12.5, 0.205), (15.0, 0.25), (17.5, 0.292), (20.0, 0.327), (22.5, 0.358), (25.0, 0.385), (27.5, 0.408), (30.0, 0.43), (32.5, 0.45), (35.0, 0.469), (37.5, 0.486), (40.0, 0.495), (42.5, 0.504), (45.0, 0.51), (47.5, 0.513), (50.0, 0.516)

DOCUMENT: This Height/DBH curve is derived from a run of STANDPAC supplied by Peter Gorman of the Southern North Island Office of the Ministry of Forestry. It was based on a GF17 growing in the Wellington region.

Effect_of_gorse_height_on_Trees = GRAPH(Gorse_height/Pine_Height)

(0.00, 0.00), (0.1, 0.00), (0.2, 0.00), (0.3, 0.00), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.021), (0.9, 0.042), (1.00, 0.063), (1.10, 0.083), (1.20, 0.104), (1.30, 0.125), (1.40, 0.146), (1.50, 0.166)

DOCUMENT: This is a hypothetical relationship which says that when a tree has height competition of about 75% of its height, delays in the growth of the tree begin (Richardson, 1994) Here this is implemented by feeding in monthly reductions to the effective site index of the woodlot. The graph is drawn so that each 10 percent step in the ratio of gorse height to tree height is associated with a reduction of the effective site index which if experienced over the period of 12 months leads to an X metre reduction. At 80 percent the reduction is about 0.25 m while at 150 percent it is about 2 m

Effect_on_Tree_Growth_of_Possum_Damage = GRAPH(IF TIME<180 THEN Damaged_Trees ELSE 0)

(0.00, 0.00), (100, 0.002), (200, 0.004), (300, 0.006), (400, 0.006), (500, 0.006), (600, 0.007), (700, 0.007), (800, 0.007), (900, 0.007), (1000, 0.008)

DOCUMENT: This variable takes a continous assesssment of the surviving trees until month 180 and derives a value which is the growth delay imposed on radiata pine by possum browsing, bark stripping etc. Keber (1987) in a 'browsing' simulation found that 10% browse had no significant effect on height growth but that 25% or more did. Further, the type of damage mattered as well. Trees with broken leaders suffered the loss of the equivalent of a growing season's worth of height growth.

The relationship posited here is a proxy one, assuming that the number of damaged trees is a reasonable indicator of the severity of the damge inflicted by possums and that it is proportional to the number of possums. At low damage of about 10% the reduction in growth over the rotation is equivalent to about a third of a metre whereas more severe damage at around 35% is equal to over a metre.

Final_Stocking_Decision = GRAPH((Stems_per_Ha-(0.38*Damaged_Trees)))

(400, 200), (500, 230), (600, 260), (700, 280), (800, 290), (900, 300)

DOCUMENT: The final stocking decision gives the proportion of the remaining undamaged trees which are to be considered for final stocking. It is standard practice to plant two to three trees in order to get one tree of good size and form - that is, retain about 30%. Further, about 5-10% of trees are expected to suffer mortality from factors other than possum damage, such as poor planting, releasing, etc (Gorman, 1995) The rule here is to consider the number of useable trees - given by the surviving trees at thinning less the proportion of possum damaged trees which are malformed - and choose a final stocking according to the graph function. The more dead or malformed trees the lower the final stocking.

Food_Available = GRAPH(TIME)

(0.00, 0.1), (12.0, 0.2), (24.0, 0.3), (36.0, 0.4), (48.0, 0.6), (60.0, 0.8), (72.0, 1.00), (84.0, 4.90), (96.0, 4.53), (108, 6.25), (120, 10.8), (132, 11.0), (144, 11.2), (156, 11.6), (168, 11.9), (180, 12.2), (192, 12.4), (204, 12.7), (216, 13.7), (228, 14.5), (240, 15.3), (252, 16.1), (264, 17.0), (276, 18.0), (288, 18.5), (300, 19.0), (312, 19.4), (324, 19.7), (336, 20.0)

DOCUMENT: This graph of 'kilograms of dry-matter per stem' is loosely based on the work by Madgwick, et al, 7(3) NZJFor.Sci. (1977). However, in order to produce a time profile that is closer to our expectation of when damage occurs and its severity, the figures to 72 months have been altered to give the required profile. The expected profile is that pine trees are particularly vulnerable for their first six years and with little damage done after 15 years. Further, the figures are calibrated to produce damage of about 30% in the base case.

Gorse_Density_Effect = GRAPH(Gorse_Density)

(0.00, 0.00), (1.00, 0.4), (2.00, 0.8), (3.00, 1.20), (4.00, 1.60), (5.00, 2.00)

DOCUMENT: This reflects the way that the density of gorse cover affects the impact of gorse competition on tree growth. Below 60% coverage reduces the effect of the competition while 60% and above intensifies the effect.

APPENDIX 2

SUMMARY OF INPUT COSTS AND REVENUES

Table A. Costs and Revenues of Management Regime for the Base Case ($1994)

Operation	Timing of Operation (month)	Revenues ($/ha)	Costs ($/ha)
Site Preparation	0		100
Planting	0		530
Overhead	each year		50
Land Rental	each year		80
Thinning[a]	141		325
Roading and Landings[b]	348		1,212
Harvest[b]	360	46,432	10,585

(a) This cost can be increased by the model if there is gorse obstruction at the time of thinning.
(b) These costs and revenues are on the basis of a wood volume of 404m3.

Table B. Costs of Possum and Gorse Control ($1994)

Operation	Timing of Costs	Costs ($/ha)
Gorse Cutting[a]	when required	600
1080 Poison Drop	each year	47
Bait Stations	set up	40
	every 5 months	20

(a) This cost assumes 1000 stems per hectare.

THE GSBGM WORKING PAPER SERIES

The main purpose of this series is to reach a wide audience quickly for feedback on recently completed or in progress research. All papers are reviewed before publication.

A full catalogue with abstracts and details of other publications is available, for enquires and to be included in our distribution list, write to:

Monica Cartner
Research Programmes Co-ordinator,
GSBGM, Victoria University of Wellington,
PO Box 600, Wellington, New Zealand
Tel: (04) 495 5085; Fax: (04) 712 200

Code in bold denotes order number, eg: WP 1/91

--- Group denotes the author's academic discipline Group (note this does not necessarily define the subject matter, as staff's interests may not be confined to the subjects they teach).

1990 - 1993 titles available on request.

WP 1/95 **Management Group**
Gilbertson, D.K., Wright, H., Yska, G, Gilbertson, D.W. and 1994 Students of MGMT 306 'Kiwi entrepreneurs: A study.'

WP 2/95 **Management Group**
Cavana, R. 'Policy issues related to coastal and international shipping in New Zealand'

Shipping policy issues. *Transportant: The Journal of the Chartered Institute of Transport in New Zealand* 1995, Vol 25, No 2, 17-19.

WP 3/95 **Information Systems Group**
Bonner, Marcus 'On seeing information systems as bridges'

WP 4/95 **Management Group**
Cavana, Bob, Rob Crozier, Barrie Davis and Perumal Pillai 'A survey of academic staff attitudes towards the system of academic titles used in New Zealand universities'

WP 5/95 **Econometrics Group**
Krawczyk, J.B. and G. Zaccour 'Pollution management through levies and subsidies'

WP 6/95 **Marketing Group**
Ashill, Nicholas and Malcolm Wright 'Marketing information systems - A review and reconceptulisation'

WP 7/95 **Information Systems Group**
Casey, Mary-Ellen 'An exploratory study into the use of information technology as an important enabler of organisational differentiation in the financial sector'

WP 8/95 **Economics Group**
Boles de Boer, David and Lewis Evans 'The economic efficiency of telecommunications in a deregulated market: the case of New Zealand'

WP 9/95 **Management Group**
Mabin, Victoria J. 'Using spreadsheet optimisation facilities as a decision aid within the theory of constraints framework'

WP 10/95 **Economics Group**
M. Khaled, M.D. Adams and M. Pickford 'Estimates of scale and scope economies in the New Zealand life insurance industry.'

WP 11/95 **Economics Group**
John A. Carlson and Robert A. Buckle 'Price duration with two-sided pricing rules'

WP 12/95 **Economics Group**
Ganesh Nana 'Developing a multi-sectoral CGE model of the New Zeland economy.'

WP 13/95 **Money and Finance Group and Economics Group**
Stephen Burnell, Lewis Evans and Shuntian Yao 'Network games: The optimal network contract and the efficiency of bypass in oligopolistic network industries under light regulation'

WP 14/95 **Economic History Group**
Gordon Boyce 'The Nickel Syndicate, 1901 - 1939'

WP 15/95 **Money and Finance Group**
Jan Whitwell 'Monetary disinflation with inflation inertia: Central bank autonomy in an open economy'

WP 16/95 **Economics Group**
Emery, H. Daniel V. Gordon and Doug McClintock 'On the efficacy of construction site safety inspections.'

WP 17/95 **Economics Group**
Ganesh Nana 'An inter-temporal CGE model with fiscal and sector balances'

WP 18/95 **Economics Group**
Jie Zhang 'Government debt, human capital, and endogenous growth'

WP 19/95 **Accountancy Group**
Zahirul Hoque and Manzurul Alam 'Quality management and accounting in a New Zealand service organisation: Towards an institutional perspective on management accounting'

WP 20/95 **Economics Group**
Paul Calcott 'Can we test for supplier-induced demand by comparing informed with uninformed consumers?'

WP 1/96 **Management Group**
M.W. Lee, J. Bennett, R.J. Taylor and R.Y. Cavana 'A dynamic simulation model for possum and gorse control on a farm woodlot.'