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Report Cover Page

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A tool to support the decision to switch between eradication and containment of an invasion
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Summary

The primary objective of this project is to develop a tool that will improve decisions about appropriate pest management activities over time (eradicate, contain or do nothing) and use case studies to determine rules-of-thumb for management in a range of invasion scenarios. The tool was implemented as an Excel spreadsheet and is based on a model that considers the simplest possible representation of a managed invasion, accounting for the spread rate of the invasion, damages caused by the invader and control costs. We present and solve this generic model to obtain an understanding of the eradication / containment decision. We then apply the model to two case studies and present results from both case studies in addition to some generic modelling to help gain insight into the decision problem.

Two case studies were selected through a workshop attended by a range of Commonwealth, State and academic participants. The two case studies chosen were Siam weed in Queensland and European House Borer (EHB) in Western Australia:

- Siam Weed is one of the world's worst weeds. It is a fast growing perennial shrub that thrives in disturbed habitats and can completely dominate the landscape it invades. It was first detected in Australia in 1994, and became the target of a national cost-shared eradication programme in 1995. Siam weed has the potential to infest large areas of coastal land in northern Australia, invading productive agricultural land and ecosystems known for their high environmental values.
- EHB is a serious insect pest of untreated dry softwood. In areas near Perth it has been found in pine plantations, where it infests dead pinewood, and in untreated manufactured articles derived from pine timber, including structural timber in several homes. Most of the damage is experienced by households and businesses that use pine wood, and control involves "packages" of actions that include building restrictions, and early harvest of infested plantations.

Finally, we provide recommendations for future development and use of the tool and associated model, including practical suggestions for data recording and extraction in future pest/disease management programmes.

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A tool to support the decision to switch between eradication and containment of an invasion

ACERA Project No. 1004 C

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University of New England

Final Report

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Disclaimer

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1. Executive Summary

The primary objective of this project is to develop a tool that will improve decisions about appropriate pest management activities over time (eradicate, contain or do nothing) and use case-studies to determine rules-of-thumb for management in a range of invasion scenarios. The original tool was implemented as an Excel spreadsheet and takes account of the spread rate of the invasion, damages caused by the invader and control costs.

A workshop to discuss case studies was held in April 2011 and involved participants from commonwealth, state and academic institutions who were familiar with a significant number of Australian invasion cases. The workshop resulted in the selection of two case studies: i) Siam weed in Queensland and ii) European House Borer (EHB) in Western Australia. Both infestations have been the subject of benefit-cost analyses and hence some of the information required for the model was already available. Updated information on extent of the invasions, spread rate, control costs and damages was required to complete the case studies. Not all the information needed was able to be obtained within the time required to complete the project because of constraints in staff-time and/or lack of in-house GIS expertise required to extract data from existing maps in state agencies. We conducted our case studies using the best data available, complemented by information from the original benefit cost analyses and advice from program staff.

Initial analysis using a generic model that consists of the simplest possible representation of a managed invasion indicated the maximum area that should be targeted for eradication based on costs of control and damages caused the spreading invasion. Introducing uncertainty caused the optimal solution to prescribe caution by targeting larger areas for eradication than in the deterministic case. Introducing nonlinear costs and damages was found to produce two distinct decision points: where it becomes optimal to give up on eradication (*switching point*) and where it becomes optimal to apply just enough control to maintain the invasion at a steady state (*containment point*). The positions of these two points were affected by the relative values of damage and cost parameters.

The generic model is used to help readers understand how to interpret the solutions of state-based decision models. The advantage of this approach is that the optimal action is expressed as a decision rule, rather than a single decision value for a particular situation. This provides tactical management capacity that is robust to uncertainty; the optimal control rule can be applied at any point in time, based on the observed state of the invasion at that time, even after random effects have caused the results of our previous actions to be off target.

The generic model was able to be applied to Siam Weed with little modification. Siam Weed is a fast growing perennial shrub that thrives in disturbed habitats such as pastures, roadsides and riverbanks and can completely dominate the landscape it invades. It was first detected in Australia in 1994, around the Tully River catchment south of Cairns and became the target of a national cost-shared eradication programme in 1995. Siam weed has the potential to infest large areas of coastal land in New South Wales, the Northern Territory, Western Australia and Queensland, invading productive agricultural land and ecosystems known for their high environmental values.

Results of the Siam Weed case study indicated that, given our best estimates of costs and damages, it would be optimal to eradicate the invasion even if it covers several million hectares, at a cost of several billion dollars in present-value terms. Obviously, this management approach is not feasible because of limited budgets. This results points to the limitation of a simple decision model with no budget constraint. The decision is made purely based on the marginal costs and marginal damages of the invasion, ignoring that unlimited resources are not available to manage the invasion. While the model provides interesting insights, it will be of more value as a decision tool when a budget constraint is included in the derivation of the optimization model. The model prescribes that the current extent of the invasion (about 15,000 hectares) should be the target of eradication and the estimated cost is $18 million in present-value terms. However, this is a deterministic estimate and does not account for the probability of failure.

The European House Borer (EHB) study required a different model to be designed to account for important features in this type of invasion, where the main habitat is pine forest but the damage applies to households. EHB is a serious insect pest of untreated dry softwood. The adult beetle lays its eggs in the deadwood and its larvae feed on the timber causing serious structural damage. EHB was first detected in a private residence in Western Australia in January 2004 and, when subsequent surveillance uncovered additional infested properties, the incursion became the focus of an eradication programme.

Based on the features of this invasion a new model was designed (described in Appendix B). The model consists of three state variables: forest infested, houses at risk and houses infested; and control of the invasion involves “packages” of actions, including building restrictions, early harvest of infested plantations and enhanced forest ‘hygiene’. The model was implemented in Excel and made available to the EHB team to facilitate the estimation of parameters for future decision analysis. Using a combination of best estimates available and plausible values for unknown parameters, we obtained results that are roughly compatible with a previous benefit-cost analysis. Our results indicate that any form of control is preferable to no control at all, based on the damages to Western Australia relative to the cost of control. Additional work is required to determine the best way to manage the invasion given the limited resources available to clear infested forests and repair infested houses. The EHB case study concludes with a brief description of work in progress consisting of exploratory spatial analysis to determine the contribution that new spatio-temporal analytical techniques may offer when limited data are available.

This report concludes by providing recommendations arising from the study. A summary of recommendations is presented below.

Key Findings:

- Using an optimization framework, based on benefits and costs, results in eradication for very large invasion areas. This is the case even when damages are moderate, because benefits include avoided future control costs.
- Introducing nonlinear costs and damages was found to produce two distinct decision points: where it becomes optimal to give up on eradication (*switching point*) and where it becomes optimal to apply just enough control to maintain the invasion at a steady state (*containment point*).
- The introduction of uncertainty in the model results in larger areas being targeted for eradication than occurred in the deterministic case, reflecting cautious behaviour when future outcomes are uncertain.
- The deterministic model for Siam weed prescribes that the current extent of the invasion (about 15,000 hectares) should be the target of eradication and the estimated cost is $18 million in present-value terms, but this result does not account for the probability of failure.
- Our findings from the European House Borer application indicate that any form of control of the current outbreak is preferable to no control at all, based on the damages to Western Australia relative to the cost of control.

Recommendations:

1. We recommend that the decision tool developed here be used by managers before considering a full benefit-cost analysis of an invasion to identify the kinds of costs and damages involved and the sorts of budgets that may be required for eradication.
2. The basic decision model needs to be extended to include the budget as a constraint in the optimization model, to make it more applicable to the real world where biosecurity resources can be severely limited.

3. The constrained model should be applied to Siam weed in close collaboration with the programme team to help develop tactical management capacity. This would benefit the Siam Weed programme but is also likely to have spinoffs that improve the management of invasions in general.
4. The EHB team, with the assistance of the simulation model developed in this project, should consider and agree on sets of parameter values to be used in further analysis. This should be followed by scenario analysis of alternative policies in stochastic mode, so that realistic expectations are derived that account for the probability of failure.
5. The state-based optimization model for EHB could be developed to provide the EHB team with a tactical management tool that is robust to random shocks.
6. The difficulty of extracting data from existing databases needs to be addressed by developing protocols for data sharing that account for security concerns while at the same time allowing teams with the specialised skills to access the data.
7. The information required for decision models is often not available because it was not recorded at the time, even when this would have been easy to do. It would be worth developing lists of data that should be recorded for any managed invasion and protocols for storing and sharing them.

2. Introduction

Biosecurity managers require tools to assist with planning, implementation and evaluation of invasive-species management activities. Ideally these tools should be based on sound scientific and economic principles, they should be robust to uncertainty and, for decision-makers to have confidence in them, they should be validated and peer-reviewed.

One of the decision tools most often requested by biosecurity managers is one to help decide whether to attempt eradication, contain, or do nothing in response to a biological invasion. In this project we develop and test a simple decision tool that can help to determine whether a particular invasion should be eradicated, contained, or allowed to spread while more information is gathered. The tool is based on minimal information and was tested with case-studies of relevance to biosecurity agencies in Australia. Such a tool, despite its relative simplicity, may also be used to investigate alternative invasion scenarios and develop rules-of-thumb for management, provided it proves to be robust across a range of situations.

The overall objective of this project is to improve decisions about appropriate pest management activities over time (eradicate, contain or do nothing) and use case-studies to determine rules-of-thumb for management in a range of invasion scenarios.

This document presents the final report, consisting of a discussion of the models and their application to two case studies: (1) Siam Weed (*Chromolaena odorata*) in northern Queensland, managed by Biosecurity Queensland; and (2) European House Borer (EHB) (*Hylotrupes bajulus*) in Western Australia, managed by the Department of Food and Agriculture of Western Australia:

1. Siam Weed is considered one of the world’s worst weeds. It is a fast growing perennial shrub that thrives in disturbed habitats such as pastures, roadsides and riverbanks and can completely dominate the landscape it invades. It was first detected in Australia in 1994, around the Tully River catchment south of Cairns and became the target of a national cost-shared eradication programme in 1995. Siam weed has the potential to infest large areas of coastal land in New South Wales, the Northern Territory, Western Australia and Queensland, invading productive agricultural land and ecosystems known for their high environmental values.

2. EHB is a serious insect pest of untreated dry softwood. It was detected in a private residence in Western Australia in January 2004 and, when subsequent surveillance uncovered additional infested properties, the incursion became the focus of an eradication programme. In Western Australia EHB has also been found in pine plantations, where it infests dead pinewood, and in untreated manufactured articles derived from pine timber, including structural timber in several homes. The adult

beetle lays its eggs in the deadwood and its larvae feed on the timber causing serious structural damage.

Both infestations have been the subject of benefit costs analyses and hence some of the information required is already available. However, updated information on extent of the invasions, spread rate, control costs and damages was required to complete the case studies. Not all the information needed was able to be obtained within the time required to complete the project because of constraints on staff-time and/or lack of GIS expertise in both control programs. Therefore the analysis was conducted using the best data available, complemented by information from the original benefit cost analyses and advice from program staff.

While application of the generic model to Siam weed was relatively simple, requiring only minor modifications of the model, mathematical representation of the EHB invasion was more complicated, requiring a different model to be designed to account for important features in this type of invasion. While pine forest is the main habitat of EHB, most of the damage is experienced by households and businesses that use pine wood, particularly businesses involved in inter-state trade where the use of untreated pine pallets is typical. In addition, control of EHB involves “packages” of actions that cannot be easily related to reductions in area invaded as continuous variables.

In this report we present a generic model, background information on the Siam weed and EHB invasions, application of the generic model to Siam weed, and a description of the model developed for EHB. We also present results from simulations and identify future work with potential for high payoffs. We conclude with a series of recommendations for application of our findings.

3. The basic model

The decision about whether to eradicate or contain must be based on solid scientific and economic foundations and must be robust to uncertainty. In developing a decision tool that meets these objectives we started with the simplest possible model -- based on a clear description of the state of the invasion at any given time and considering the future consequences of current decisions, including the decision to do nothing.

The simplest possible model of a managed invasion has three components:

- A growth (spread) curve
- A damage curve
- A cost curve

The mathematical model is described in Appendix A. This section presents a description of the numerical version of the model, which was implemented as an Excel file. The model requires five parameters:

- Specific growth rate (*r*)
- Area at risk (*K* in ha)
- Damage (β_D in \$/ha)
- Control Cost (β_C in \$/ha)
- Discount rate (δ in %)

Using this information the model calculates the maximum area that should be targeted for eradication and the area at which containment should occur when applicable. The calculation is based on an optimization model that minimises the combined cost of controlling the invasion plus the damages caused by the invasion. The area at which eradication is no longer the optimal course of action is referred to as the *Switching Point*.

The model was distributed to a group of potential end users and went through two iterations of improvements based on user feedback. The current version of the model (version 3.0) is described here. The model is contained in the Excel file Switching_Point_Mod_v3.0.xls and is accompanied by a manual. This section presents only an overview of data requirements and results. For more details refer to the user manual.

In summary, the decision whether to eradicate or not is based on minimising the total cost of the invasion over time. This includes the cost of control as well as the damage caused by allowing the invasion to spread. Both the control cost and the damage cost are measured on a per hectare basis. This means that each additional hectare invaded increases all costs and damages proportionally, which is the same as assuming that the landscape is relatively homogenous.

Damages and control costs are not always easy to estimate. Many different factors and activities may need to be measured and several sectors of the economy may need to be considered, depending on the type of invasive and the environments that are invaded. The model was designed to assist users obtain plausible per-hectare values by completing a set of tables (Figure 1).

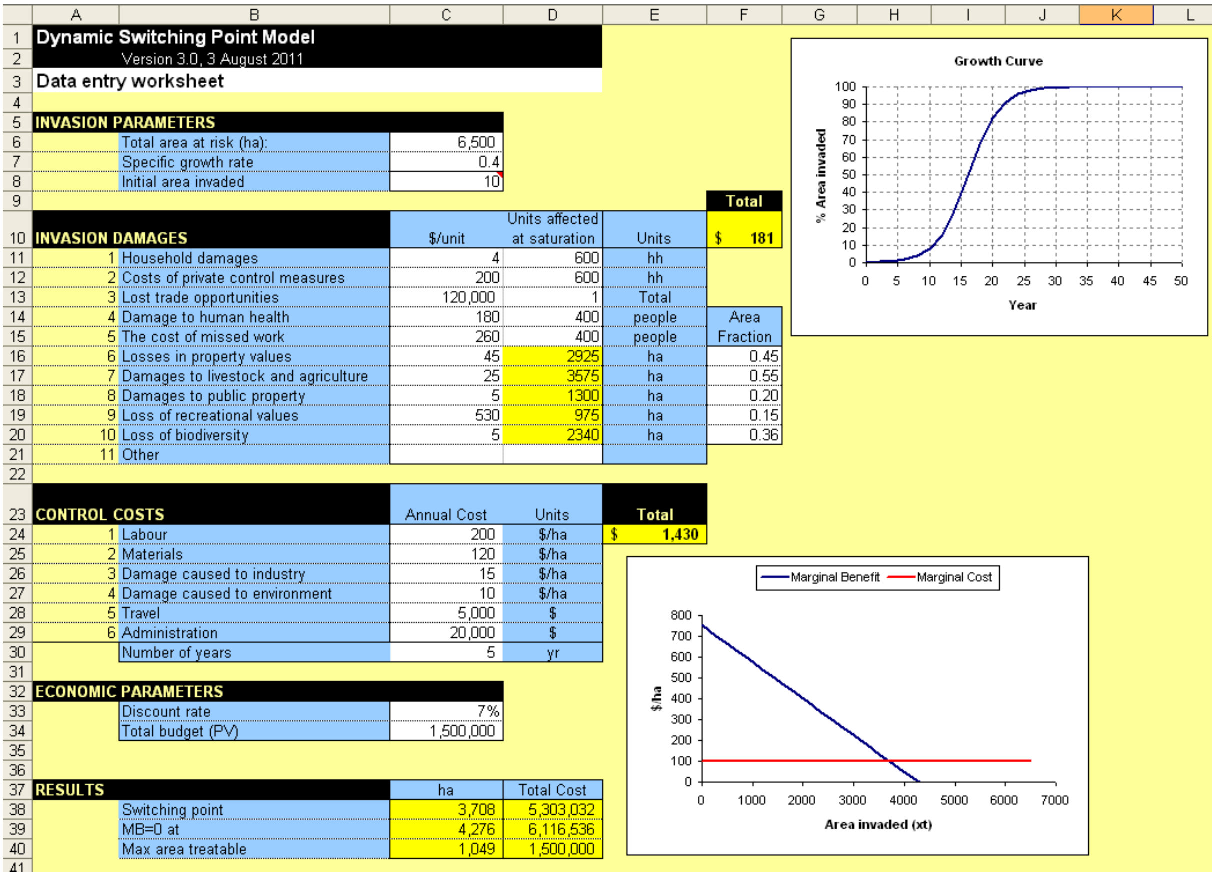

Figure 1. The Model Worksheet in the Switching Point Model

The user must enter 4 types of inputs:

- **Invasion Parameters**: are associated with the growth curve represented by a logistic equation (see the plot on the top right of Figure 1).
- **Invasion Damages**: contains a breakdown of the various components of the damage curve. The parameters contained in this table are used to calculate a single value for damages per hectare. The cell labelled *Total* on the top right of this table represents the Damage Parameter (β_D).

- **Control Costs**: contains a breakdown of the various components of the cost curve. The parameters contained in this table are used to calculate a single value for the cost of control per hectare. The cell labelled *Total* on the top right of this table represents the Cost Parameter (β_C). Costs are calculated in present value terms based on the number of years required to eliminate the infestation, such as repeat visits required to eliminate the seedbank.

- **Economic Parameters**: this table comprises the discount rate and the budget. The budget does not affect the actual calculation of the switching point, but it is used to calculate the maximum area that could be eradicated when the budget constraint is binding.

The results are presented in terms of areas and costs (Figure 1). Three points are identified:

- The switching point: where marginal benefit (MB) equals marginal cost (MC). This is where eradication ceases to be the optimal option. It is illustrated graphically in the bottom chart in Figure 1.

- The point at which the marginal benefit of control is zero (MB=0). This is where the marginal benefit curve crosses the horizontal axis.

- The maximum area that can be treated with the given budget constraint.

These components are explained in more detail below.

3.1. Damages

The damages per hectare (β_D in Appendix A) are calculated from the itemised entries in the "Invasion Damage" table. This value is $181/ha for the example in Figure 1 (cell F10). The list of possible damages is presented in Table 1 followed by brief explanations of each. For each category, the user needs to assess the damage at saturation -- the number of units (households, hectares etc) that will be affected if the whole area at risk becomes invaded.

Table 1. Types of damages that may need to be considered

ID	Description	Units of measurement
D1	Household damages	number of households
D2	Costs of private control measures	number of households
D3	Lost trade opportunities	Total amount
D4	Damage to human health	number of people
D5	The cost of missed work	number of people
D6	Losses in property values	ha
D7	Damages to livestock and agriculture	ha
D8	Damages to public property	ha
D9	Loss of recreational values	ha
D10	Loss of biodiversity	ha
D11	Other	

As an example assume there are 2,400 households in the area at risk and ¼ of them are expected to be affected. Then the entry under *Units affected at saturation* is 0.25 × 2,400 = 600 households. The dollar value for this damage would be the average cost incurred per household.

Lost trade opportunities (D3) are presented as a total amount in the table, but they could be expressed in different units depending on the nature of this loss. For example, if the number of tourists visiting the area drops as a result of the invasion, the units at saturation would be the annual reduction in the number of tourists and the value would be the average amount spent per tourist. If there are several industries or sectors affected this parameter would measure the total loss across all industries or sectors.

Damage to human health (D4) and the cost of missed work (D5) are in terms of number of people affected. As an example, assume the population in the area at risk is 10,000 people and 4% of them are expected to be affected at saturation, then the entry in this column is 10,000 × 0.04 = 400 people. The cost per unit could be calculated based on average medical expenses per person for D4 and average numbers of hours missed multiplied by the average wage rate for D5.

The next five damage types (D6 to D10) are on a per-hectare basis and their values would depend on the proportion of the area at risk that represents each damage type. Other costs not considered on this list can be included in the final row of the damages table (D11).

3.2. Control Costs

The costs per ha (β_C in Appendix A) are calculated from the itemised entries in the "Control Costs" table (Table 2). This value is $1,430/ha for the example in Figure 1 (cell E24). As above, different parameters have different units of measurement. Costs are expressed on an annual basis and the number of years required to eliminate the invasion are used to calculate the present value of eradication costs. For example, if clearing weeds from one hectare of land requires 10 years of repeat visits until the seedbank is exhausted, then this number of years must be entered so the present value of all costs can be calculated.

Table 2. Itemised control costs

ID	Description	Units
C1	Labour	$/ha
C2	Materials	$/ha
C3	Damage caused to industry	$/ha
C4	Damage caused to environment	$/ha
C5	Travel	$
C6	Administration	$
C7	Number of years	years

The formula used to calculate the present value of costs is based on the number of years the invasion will need to be revisited to achieve eradication. The present value of a stream of future payments (*FV*) expected to occur for *T* years is:

$$PV(T) = FV \frac{1-(1+\delta)^{-T}}{\delta} \qquad (1)$$

where δ is the discount rate. The value of δ is normally set between 5% and 7% based on the return of (relatively risk-free) treasury bonds, but it can be set lower for cases that have social benefits or higher for commercial purposes. Equation (1) is derived from applying the standard discounting formula for a single future payment to a stream of equal payments (the derivation is presented in Appendix B). This calculation is done in the background within the Excel model and users are not required to understand it. They are only required to enter expected annual costs and the expected duration of the eradication effort.

Labour costs (C1) are relatively straightforward to calculate based on the number of hours required to clear one hectare (including search and treatment activities) multiplied by the wage rate. Materials costs (C2) normally represent chemicals used for treatment, but could also include depreciation of any machinery and equipment used.

The costs of damages to industry (C3) or the environment (C4) are those caused by the control method itself, as opposed to those caused by the invading organism considered in the previous section. For example, damages to industry are caused when control involves killing livestock, and damages to the environment occur when chemicals used to control the invader also kill native organisms.

The costs of travel (C5) and administration (C6) are calculated on a per-year rather than per-hectare basis. Cost of travel to infested sites is the sum of air and road travel plus any per-diems paid to staff. The costs of administration would include office expenses, including annual salaries of managers but excluding the salaries associated with labour already counted in D1.

The approach used to calculate the present value of eradication costs (equation 1) assumes that annual costs remain constant throughout the eradication effort. In reality, some costs will decrease as eradication is approached, for example less chemicals may be needed as the main infestation is eliminated and only small seedlings need to be killed in repeat visits. However, search costs are normally the major component of control costs and they will not decrease if the whole area managed is searched every year. In any event, it would be a simple matter to modify this part of the model and allow decreasing control costs to occur through time. It would involve replacing equation (1) with a table listing the expected costs through time. These individual entries would then be discounted based on the year when they occur and the discounted values would be summed to obtain the present value. Implementing this would require additional user input and defeat our purpose of producing the simplest possible model, but it could be incorporated in future versions.

3.3. Results

Results for the example given in Figure 1 (the Base case) indicate that the switching point is at 3,700 ha, but to treat this area a budget of $5.3 million (in present value terms) would be required (Table 3). The position and cost of the switching point change as the parameter values change. In some cases the per-unit damages and costs also change because individual costs and damages vary in their units of measurement (see Tables 1 and 2), so a doubling of all costs or damages does not result in a doubling in the value per hectare.

Table 3. Summary of results from sensitivity analysis using the model illustrated in Figure 1 and described in Appendix 1

Scenario	Damage $/ha	Cost $/ha	Maximum area treatable (ha)	Switching Point	
				Area	Total Cost ($M)
Base	181	1,430	1,398	3,708	5.30
Total area at risk × 2	148	1,422	1,406	7,059	10.04
Specific growth rate × 2	181	1,430	1,398	3,479	4.98
Discount rate × 2	181	1,198	1,670	3,338	4.00
Number of years × 2	181	2,450	816	3,280	8.04
Damages × 2	361	1,430	1,398	4,734	6.77
Costs × 2	181	2,861	699	3,194	9.14

Comparison of the Base case with the various scenarios shows that the position of the switching point is affected mostly by the total area at risk and the damages (Figure 2A). In both cases there is a direct relationship, resulting respectively in a 90% and a 28% increase in the maximum area that should be eradicated (Figure 2B). All the other parameters are negatively related to the switching point, with changes ranging between -6% and -14% (Figure 2B).

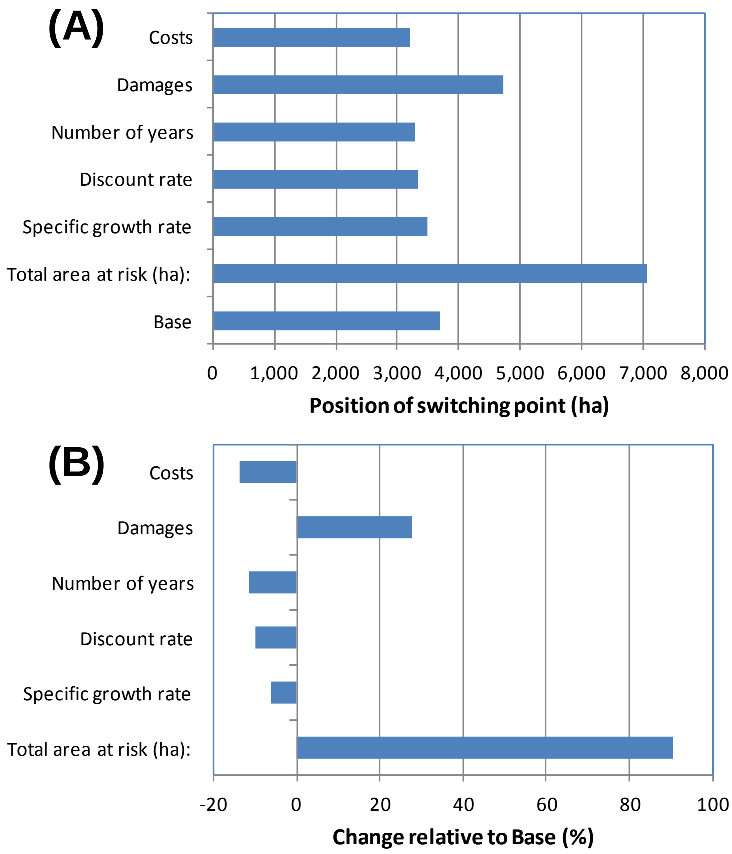

Figure 2. Sensitivity analysis. (A) the position of the switching point (in hectares) for the Base case and for a doubling of each of the key parameters in turn. (B) The percent change in the position of the switching point relative to the Base case in response to a doubling of each of the key model parameters.

As seen in Table 3, the maximum areas that should be eradicated are quite large according to our decision rule, they are higher than the 1,000 ha recommended by Rejmánek and Pitcairn (2002). This is because the model does not include a budget constraint. The decision is simply based on marginal benefits and marginal costs of control. The costs of control for the assumed parameter values (Table 3) vary between $4M and $10M. If these sorts of budgets are not available the optimal solution becomes infeasible. Figure 3 shows the area that could be treated with a budget of $2M for our example. The maximum area that could be treated ranges between 20% and 50% of the desired area.

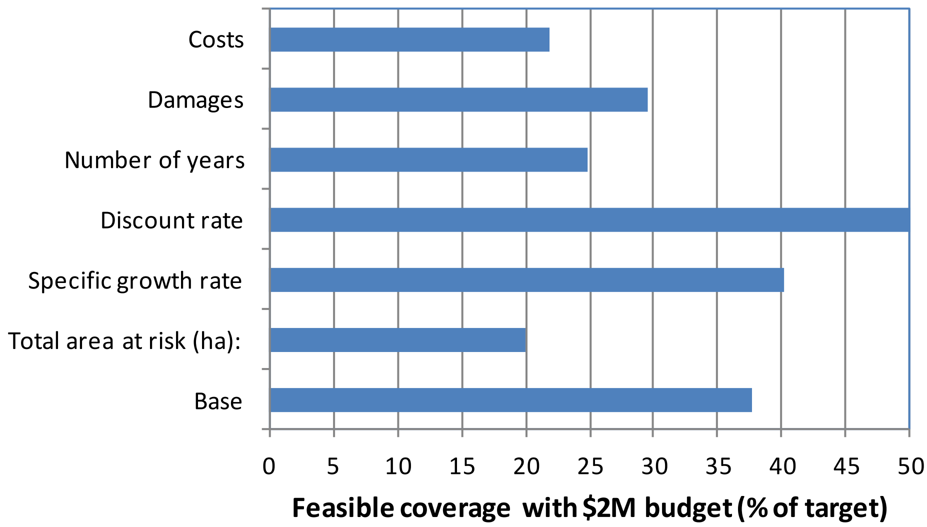

Figure 3. The effect of a budget constraint, expressed as the percent of the desired area that could be covered at the switching point for the Base case and for a doubling of each parameter, with a $2M budget in present-value terms. Note that for the assumed parameter values none of the cases could cover the whole area given by the switching point (see Figure 2A).

The correct way of dealing with the constrained case is to include the budget constraint in the mathematical model (Appendix A) and derive the optimal constrained solution, but this more complex case is out of the scope of the current project.

It is worth noting that the model is designed to be used for invaders that cause damages only. Its application to a 'benign' invader will still prescribe eradication. This is because the model includes avoided future control costs as part of the calculation of marginal benefit (left-hand side of equation 15 in Appendix A).[1]

3.4. Understanding the solution

The optimisation approach we use is state-based, where the optimal decision is expressed as a function of the area invaded at the time when the decision is made. This means that solution of the problem yields a decision rule rather than a single optimal value. The decision rule obtained for an infinite planning horizon can then be used to derive the optimal path that the invasion should follow through time for any given initial state.

To interpret the solution and identify useful management implications, it is necessary to understand three concepts: *optimal state transition*, *optimal control rule* and *optimal path*. To illustrate these concepts we will solve the problem for a set of parameter values scaled so that damages per hectare are equal to 1.0, so all costs are measured relative to one unit of

[1] An *if* statement was inserted in the Excel model to prevent eradication to be attempted when damages are zero.

damage. This allows us to abstract away from obtaining actual dollar values for damages in this exploratory phase. The parameters used are:

- Specific growth rate, $r = 0.2$
- Area at risk $K = 100$
- Damage $\beta_D = 1$
- Control Cost $\beta_C = 40$
- Discount rate $\delta = 0.07$

The problem from Appendix A was solved numerically using a stochastic dynamic programming (SDP) algorithm with the parameter values listed above. The problem is:

$$V(x_t) = \min_{u_t}\left(C(u_t) + D(x_t) + \eta \cdot V\left(x_{t+1}\right)\right) \quad (2)$$

subject to:

$$x_{t+1} = \left(x_t + rx_t\left(1 - \frac{x_t}{K}\right)\right) - u_t \quad (3)$$

$$D(x_t) = \beta_D x_t \quad (4)$$

$$C(u_t) = \beta_C u_t \quad (5)$$

Where η is a discount factor for the discount rate δ, defined as:

$$\eta = \frac{1}{1+\delta} \quad (6)$$

Equation (2) is the value function representing the total cost of the managed invasion (control costs plus damages). Equation (3) is the state transition equation, composed of the logistic growth function (the term in brackets) reduced by the control (u_t). Equations (4) and (5) are the damage and cost function respectively. Note that damage is a function of the area invaded (x_t) whereas control cost is a function of the control applied (u_t).

Equation (2) is solved recursively backwards in time for a discrete set of possible states x_t until the value of V converges. At that point the value of u_t that satisfies $V(x_0)$ is the optimal control rule, sometimes expressed as $u^*(x)$. For other applications of this technique to invasive species see Shea and Possingham (2000); Odom et al. (2003); Cacho (2006); Regan et al. (2006); Bogich and Shea (2008) and Hyder et al. (2008).

In this case the damage and cost functions (equations 4 and 5) are linear and the model is deterministic. The nonlinear and stochastic cases are considered in the next section.

The optimal state transition is represented as a curve that prescribes the state of the invasion at time t+1, given the current state at time t, when the invasion is managed optimally (Figure 4). Comparing this curve to a 45^o line indicates whether it is optimal to allow growth or force

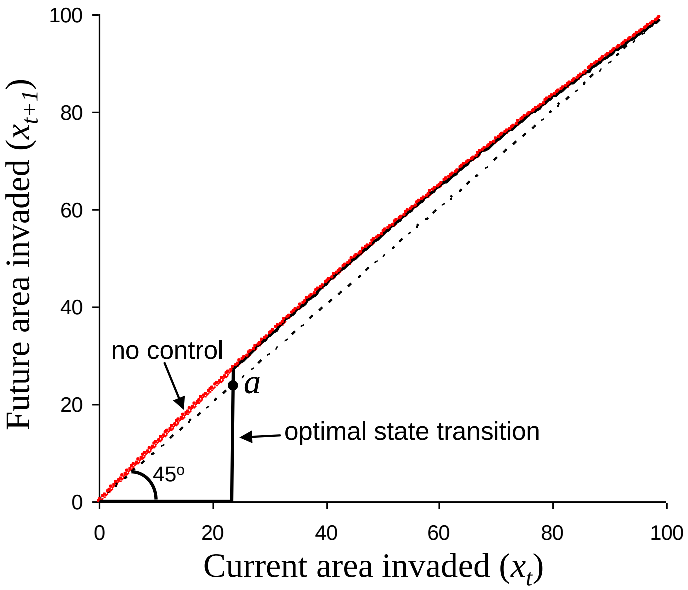

Figure 4. The optimal state transition (black solid line), the no-control case (red thin line) and a 45-degree line (black dotted) indicating the steady state where the area invaded at time *t* equals the area invaded at time *t*+1. The switching point (labelled *a*) shows the area at which it is optimal to give up on eradication.

shrinkage of the invasion. The switching point is located where the optimal state transition intercepts the 45° line (labeled *a* in Figure 4), this is the infested area at which the optimal action switches from eradication to no control.

The solution in Figure 4 represents what is called bang-bang control (i.e. Chiang, 1992), where the switch is from eradication to no action, with no intermediate solutions prescribing partial control. The reason for this result is the linear nature of costs and damages in equations (4) and (5), which results in corner solutions.

In reality, eradication is not immediate, it occurs over several years because of the need to revisit the site to eliminate any organisms that were missed in previous searches, and to treat new seedlings in the process of eliminating the seedbank in the case of weeds. This multi-year process is not treated explicitly in the model to avoid unnecessary complexity. Instead, the total cost of eradication is calculated in present value terms based on the expected number of repeat visits required. This calculation was explained in Section 3.2.

The optimal solution can also be presented as a plot of the current state against the optimal *change* in state (Figure 5). This shows how the optimal control (expressed as the area by which the invasion should be reduced) drops abruptly at the switching point, and this is

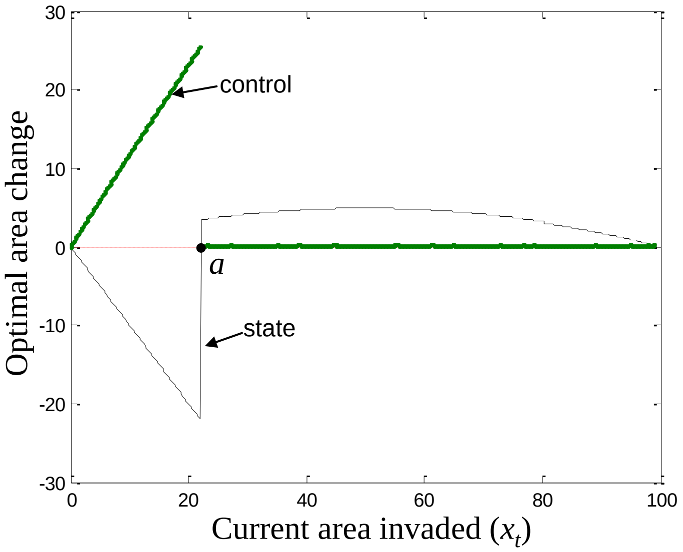

Figure 5. The optimal control rule (green dots) and the corresponding state change (black solid line) derived from the optimal state transition in Figure 4. The switching point (labelled a) shows the area at which it is optimal to give up on eradication and corresponds to a drop in amount of control applied and an increase in the area invaded.

followed by a rapid increase in the size of the invasion. Once again this illustrates the bang-bang nature of the solution.

The optimal control rule illustrated in Figure 5 can be applied repeatedly to derive an optimal path for any initial condition (Figure 6). In this case the switching point appears as a bifurcation in the optimal state path. In reality, an invasion managed according to the optimal rule will not follow the optimal path because of random variations in the spread process. This is addressed in the following section.

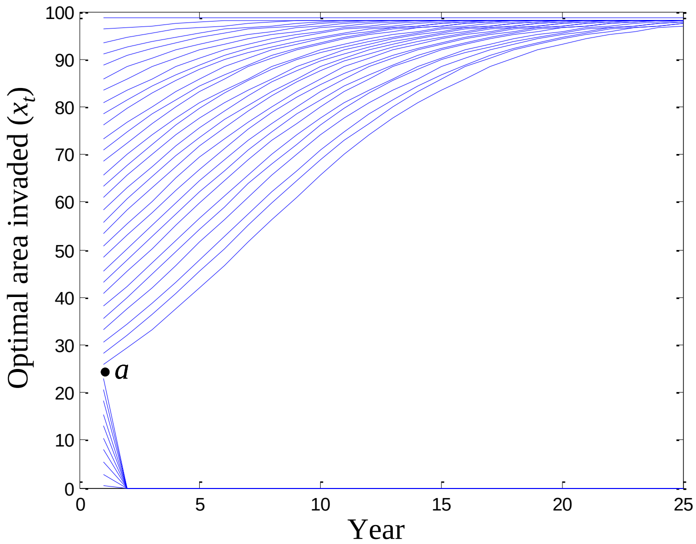

Figure 6. The optimal path in area invaded for several initial conditions. These paths are derived by repeatedly applying the decision rule in Figure 5 as the state changes through time. The switching point (labelled a) shows a bifurcation in the paths as eradication ceases to be attempted.

4. Introducing uncertainty and nonlinearity

In this section we extend the model to account for uncertainty regarding the state transition by introducing a stochastic factor represented by the parameter ρ below. We also introduce the possibility of nonlinear damages and control costs by adding an exponents to equations (3) and (4). The new model is:

$$V(x_t) = \min_{u_t}\left(C(u_t) + D(x_t) + \eta \cdot E\left[V\left(x_{t+1}\right)\right]\right) \qquad (2a)$$

subject to:

$$x_{t+1} = \left(x_t + r x_t\left(1 - \frac{x_t}{K}\right)\right)\rho - u_t \qquad (3a)$$

$$D(x_t) = \beta_D x_t^{\gamma_D} \qquad (4a)$$

$$C(u_t) = \beta_C u_t^{\gamma_C} \qquad (5a)$$

The objective function in equation (2a) contains the expected future value *E(V),* because the future state is now a random variable. The parameter ρ represents a random environmental disturbance, and the damage and control cost exponents (γ_C and γ_D) introduce the possibility of nonlinear damages and control costs. When $\gamma > 1$ the function is convex (increases at an increasing rate) and when $\gamma < 1$ the function is concave (increases at a decreasing rate). In this section we will deal with the convex case.

Convexity in costs implies increasing marginal costs as the area treated increases, which means that treatment costs increase at an increasing rate. This may occur when there are diminishing returns to inputs such as labour and chemicals. Convexity in damages may occur for the environment, for example, where remaining pristine areas becomes more valuable as they decrease in size and number (i.e. they exhibit scarcity value).

Once nonlinearity and randomness are introduced it is no longer possible to solve the problem analytically and the Excel version of the model cannot be used. The solution is now obtained with a stochastic dynamic programming (SDP) algorithm (Cacho, 2006).

The optimal control rule for the deterministic case is shown for 4 different sets of damage and cost parameter values in Figure 7. The first plot represents the linear case, where bang-bang control occurs as explained above. The remaining plots represent nonlinear (convex) cases. The switching point is obvious in all cases, as the intersection between the optimal state curve and the line y=0, but only when the former approaches the latter from below. This is a switch from shrinkage to growth of the invasion as before, but the switch is more gradual for the convex case, indicating that bang-bang control no longer applies. When both costs and damages are convex (bottom two charts in Figure 7) a *containment point*

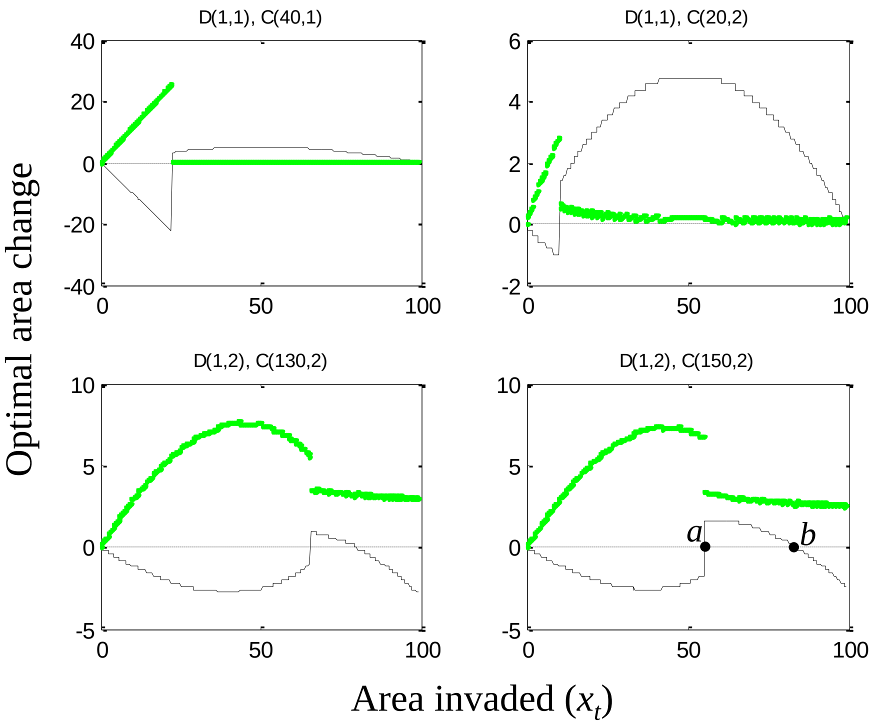

Figure 7. The optimal control rule (green dots) and the corresponding state change (solid line) for four different sets of parameter values. The dotted line at y=0 indicates the steady state; when the black curve is below the dotted line the invasion size decreases with time and when it is above the dotted line the invasion size increases. Parameter values were set at r=0.2, K=100, δ=0.07, ρ=1, the damage parameters are indicated for each chart as *D(βD, γD)* and the cost parameters as *C(βC, γC).*

emerges (labeled *b*) in addition to the switching point (labeled *a*). A containment point occurs where the optimal state curve crosses the horizontal axis from above. This is an equilibrium point that results in converging paths for certain initial conditions (see below).

To introduce uncertainty we let ρ become a normal random variable, with mean 1.0 and an arbitrary standard deviation (SD), denoted as ρ~N(1,SD). When SD=0.01 (Figure 8) the optimal solution patterns do not differ substantially from the deterministic case, but there is a tendency to become more cautious, as indicated by the switching point (*a*) shifting right towards larger areas and the containment point (*b*) shifting left towards smaller areas (compare Figures 7 and 8).

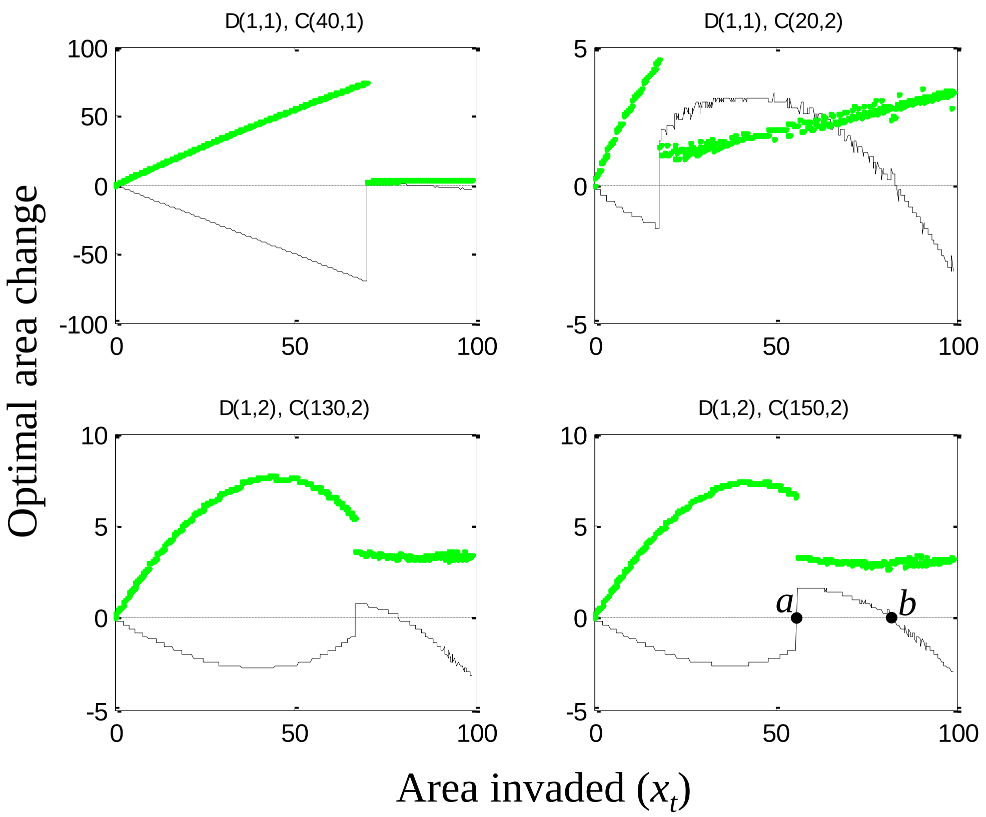

Figure 8. The optimal control rule when uncertainty is introduced, ρ~N(1,0.01). Compared to the deterministic case (Figure 7) the optimal decision involves caution, with the switching points shifting right towards larger eradication areas. Parameter values were set at r=0.2, K=100, δ=0.07, the damage parameters are indicated for each chart as $D(\beta D, \gamma D)$ and the cost parameters as $C(\beta C, \gamma C)$.

When stochasticity increases (SD=0.05) the optimal prescription is to always eradicate for the four sets of parameter values tested, even if the whole area at risk has been invaded (Figure 9). So when uncertainty is high extreme caution is advised by the optimization algorithm in the absence of a budget constraint. The budget constraint will then dictate what can be achieved.

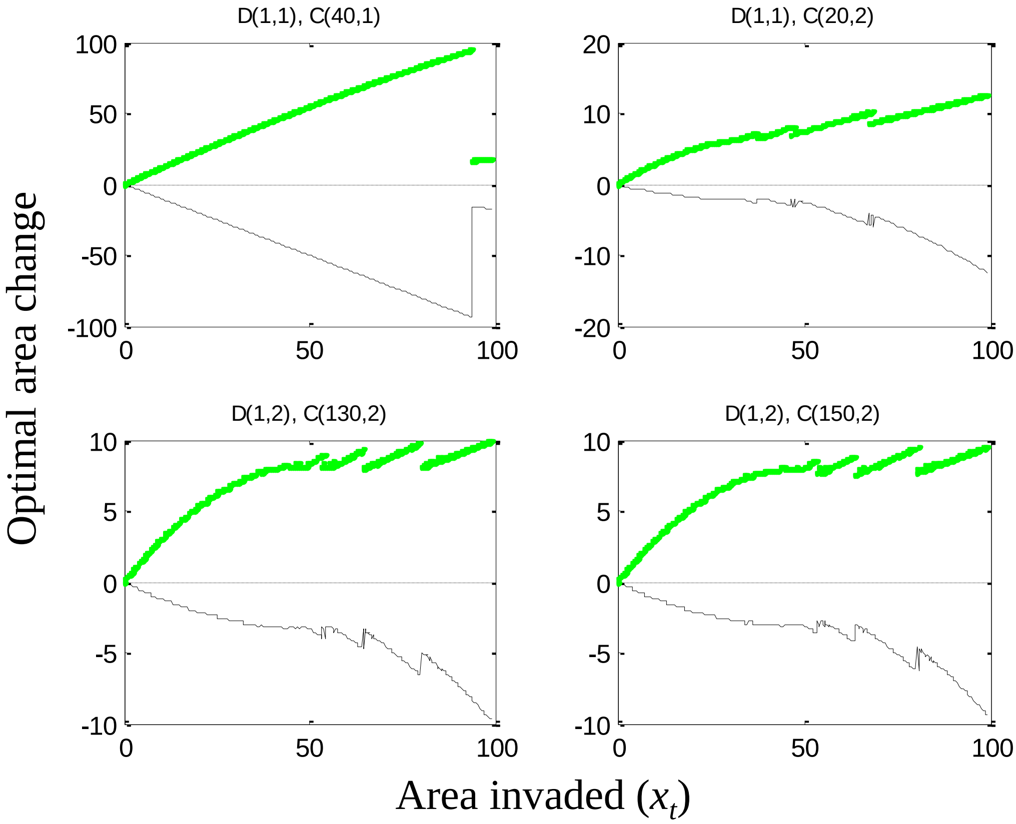

Figure 9. The optimal control rule with ρ~N(1,0.05), indicating that when uncertainty becomes high enough it is optimal to always eradicate. Parameter values were set at r =0.2, K=100, δ=0.07, the damage parameters are indicated for each chart as D(β_D, γ_D) and the cost parameters as C(β_C, γ_C).[2]

The optimal paths arising for two of our cases are presented in Figure 10. These paths show two absorbing states: x=0 and x=b, corresponding to the eradication and containment decisions. A real invasion managed according to the optimal rule would not follow one of the actual paths illustrated in Figure 10 because of random events. However, the optimal rule is applied to new states as they are observed; therefore the SDP technique provides a true tactical management tool that is robust to uncertainty.

[2] The discontinuities in the optimal control rule are caused by the jumps in the state (black line), which in turn are caused by the use of random numbers to obtain a numerical solution.

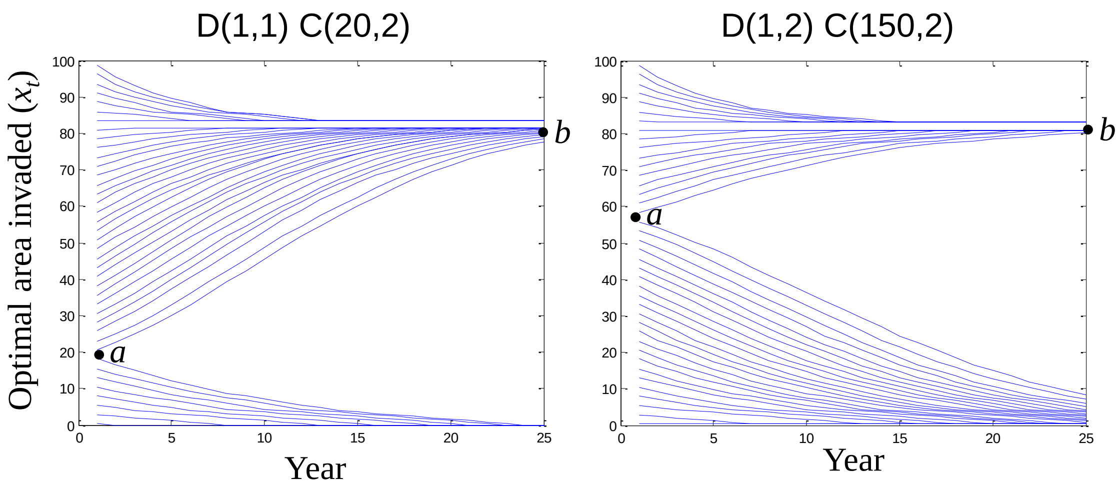

Figure 10. The optimal path for two cases where containment becomes part of the optimal solution. The switching point (a) is associated with a bifurcation of paths whereas the containment point (b) represents a stable equilibrium. Parameter values were set at SD=0.01 r=0.2, K=100, δ=0.07, the damage parameters are indicated for each chart as *D(βD, γD)* and the cost parameters as *C(βC, γC)*. Note that the paths represent expected values of a stochastic process, the actual path followed by a particular realisation of the process will vary randomly but adapting towards the target path.

Table 4 shows the position of the switching and the containment points for the four cases discussed above. Note how the introduction of stochasticity causes the switching area to increase and the containment area to decrease as already shown graphically.

Table 4. Position of the switching point and the containment point for four combinations of damage and cost parameters and for deterministic (SD=0) and stochastic (SD=0.01) cases

Parameter values				Eradicate below (ha)		Contain at (ha)	
β_D	γ_D	β_C	γ_C	SD=0	SD=0.01	SD=0	SD=0.01
1	1	40	1	22	69	-	82
1	1	20	2	10	18	-	82
1	2	130	2	65	67	80	78
1	2	150	2	55	56	84	81

The results presented in this section for a simplified case, where all parameters are scaled relative to damage per hectare invaded, has allowed us to draw some general conclusions. A significant feature of the optimal solution is the prescription of increasing caution as the stochastic disturbance increases. In the remainder of this report two case studies are presented to help us gain insights into the applicability of our model to actual invasions.

5. Case-study 1: Siam Weed in Queensland

5.1. Background and history in Australia

Siam weed (*Chromolaena odorata*) is considered one of the world's worst weeds. It is a fast growing perennial shrub, often forming dense, tangled thickets and can attain heights up to 20 m by scrambling on supporting vegetation. It thrives in disturbed habitats such as pastures, roadsides and riverbanks and can completely dominate the landscape it invades, smothering and suppressing the growth of other species. Siam weed is a prolific seeder, with seeds easily dispersed after becoming attached to clothing, animal fur and machinery. It is also easily spread when soil or stock are moved from infested areas and to some extent it is spread by wind.

Siam weed is native to tropical and subtropical Central and South America, but is now widespread throughout Africa, Asia and parts of the western Pacific, where it is a major pest in crops such as coconuts, rubber, oil palm, cotton, tobacco and sugar cane (Hardwick and Waterhouse 1996). It is also a significant environmental weed, can have allergic effects on humans and becomes a fire hazard in the dry season when it dies back after flowering.

Siam Weed was first detected in Australia in 1994, around the Tully River catchment south of Cairns, most likely introduced via contaminated pasture seed (Waterhouse 1994). In 1995 Siam weed became the target of a national cost-shared eradication programme. The programme continues, with an annual budget in 2009/10 of $1.3million (DEEDI 2009). The area currently surveyed for Siam weed is over 16,400 hectares and in 2008, 159 hectares of

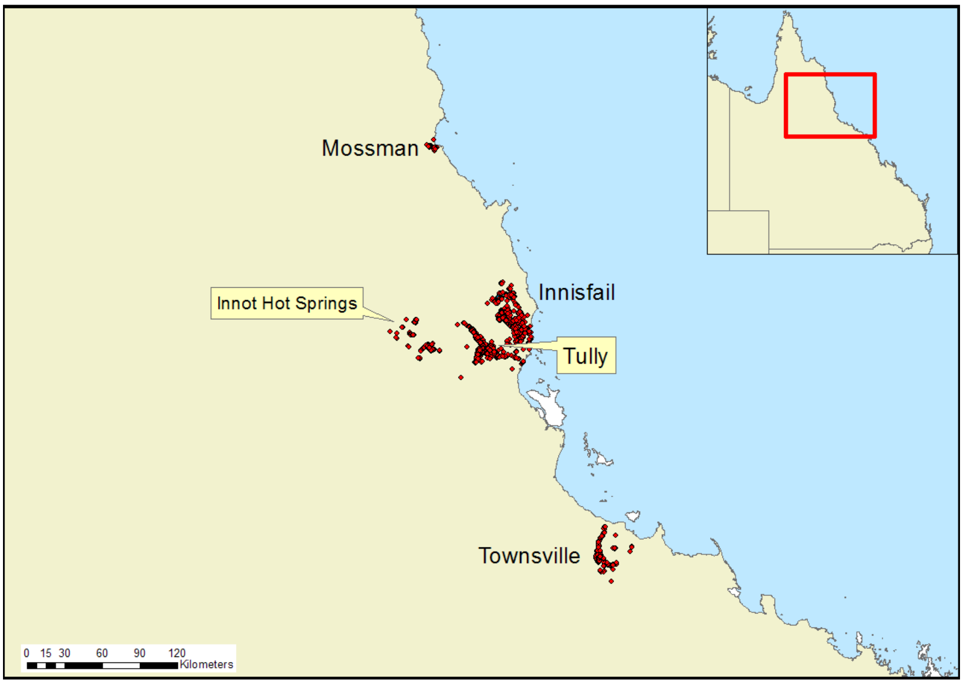

Figure 11. The current distribution of Siam weed on mainland Australia. Infestations are in red and are not to scale. Source: DEEDI (2009)

Siam weed were found and treated across 418 infested sites (DEEDI 2009). While the majority of the infestations are restricted to the Tully/Johnstone catchments and the Townsville/Thuringowa region (DEEDI 2009) (Figure 11), Siam weed has the potential to infest large areas of coastal land in New South Wales, the Northern Territory, Western Australia and Queensland (McFadyen and Skarratt 1996).

A recent benefit-cost analysis of the Siam weed eradication programme found it has resulted in accumulated benefits to agriculture of $2.9 billion, and combined benefits to agriculture and the environment (in terms of maintenance of ecosystem services) of $4.5 billion between 1994-5 and 2007-8 (Goswami 2008).

5.2. Modelling the spread and management of Siam weed

The original optimisation model developed in this project (Appendix A) was suitable for use with Siam weed with little modification. Below we explain the process of selecting parameter values.

5.2.1. Spread and Control

In the absence of control, Siam weed is assumed to spread according to a logistic function (equation 11 in Appendix A) with an asymptote representing the maximum area of land at risk. This area includes land used for agriculture and land that has high environmental value.

Application of chemical control to Siam weed infestations will reduce the size of the invasion.

5.2.2. Costs and Damages

When control measures are implemented they will largely be those that have existed under the Siam weed eradication programme as explained below.

5.3. Scenarios and parameter values

Model parameters and their values are given in Table 5 and are described in more detail below. Values come from a range of sources: the cost-benefit analysis of the national Siam Weed Eradication Programmme (SWEP) and associated bioeconomic model (Goswami 2008); annual reports from the eradication program (e.g DEEDI 2009), reviews of the SWEP (Carter and Dodd 2003, Wicks and Burley 2008) and personal communication with members of the Siam weed eradication team. Where no information was available on parameter values we use hypothetical but plausible values.

5.3.1. Invasion parameters

Siam weed has the potential to invade pastures and plantation crops and well as the natural environment. If Siam weed is left to spread uncontrolled it has the potential to infest the east coast of Queensland and the northern parts of the Northern Territory and Western Australia

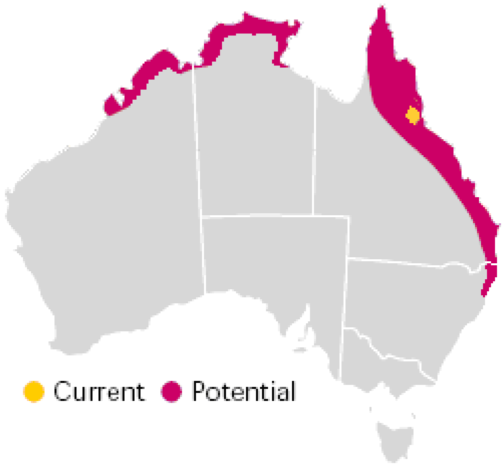

Figure 12. Current and Possible Extent of *Chromolaena odorata* (adapted from Kriticos et al. 2005; CRC Australian Weed Management, 2003)

(Figure 12), invading productive agricultural land and ecosystems known for their high environmental values (Goswami 2008).

Total area at risk

In calculating the total area at risk of Siam weed we follow the 'cease government investment' scenario of Goswami (2008) in which all control operations ceased in 2008 and the weed spread unhindered from all known infestations until a maximum infestation area was assumed to occur in year 25. Their area of spread is based on modeling with CLIMEX (DPI&F 2008), Kriticos et al. (2005) and Adamson et al. (2000). Potential future spread was then matched to Local Government Area (LGA) boundaries and reported in the bioeconomic model of Goswami (2008) as a percentage of LGA infested. For our analysis this percentage infested was converted to area for each LGA and summed. The (maximum) area infested in year 25 was calculated as 27,860,960 ha.

Specific growth rate of Siam weed

The specific growth rate (α) of Siam weed is used in the logistic equation to determine area infested over time. This means that the parameter α represents population growth as spread rate rather than biomass growth. No information was available on the specific growth rate of Siam weed, so two plausible values for this parameter, 0.05 and 0.09, were used in the simulations. Based on the current (known) extent of the infestation, when the value of α is 0.05, almost 179,000 ha would be invaded after 50 years. Whereas with a value of α = 0.09, about 1.27 million ha would be invaded after 50 years. Experts would be required to decide which scenario is more likely.

5.3.2. Control-costs parameters

Control costs are assumed to be those of the SWEP. Annual expenditure of the SWEP is divided between operational activities, research, extension, and project management. For the purposes of modelling eradication costs over time, we categorised this expenditure into control costs, on-ground search costs, helicopter search costs, research and communication costs and costs of programme administration. Data from annual reports for the years 2005/06, 2006/07, and 2007/08 were used to derive average values for expenditure in each cost category.

Control costs

A range of control methods are available under the SWEP. Siam weed may be removed by hand if plants are small, otherwise plants are sprayed with herbicides, either from the ground or by helicopter. Control costs have been calculated as $272/ha. This covers the salaries of searching crews, the cost of training search teams, the cost of chemicals and other necessary plant and equipment as well as the cost associated with travelling to infested sites.

Search costs

Searching for Siam weed is undertaken through ground searching and in recent years, via helicopter. Helicopter searching is used during the flowering season and is able to detect large flowering plants that are visible above the forest canopy, and detect Siam weed on rugged, inaccessible terrain (Carter and Dodd 2003). Ground and helicopter search costs vary each year as unit costs and area surveyed changed. Helicopter searching takes place using 3 different sized helicopters, all of which survey at a range of rates (in ha/day) and at a range of costs (in $/hr) (M. Jeffery unpubl. data). We took the average rate of searching and cost to determine the cost per area of both types of searching: $22.40/ha for ground searching and $2.50/ha for helicopter searching.

Research and Communications

Average annual costs for research and communication are considered fixed (they do not vary with area) and are assumed to be $37,715. Examples of research projects undertaken as part of the SWEP are the development of a polymerase chain reaction test for Siam weed DNA, a trial to provide empirical data for water dispersal modeling, experiments that enable the effects of burning Siam weed to be investigated and analysed, and seed longevity trials (DEEDI 2011).

Administration

Average annual costs for administration are also considered fixed and reflect the cost of maintaining an office with internet and phone access, and the salaries of a project manager and administration staff for the purposes of managing the SWEP. Average annual administration costs are assumed to be $143,231.

5.3.3. Invasion Damages

Siam weed has damaged plantation crops overseas by forming dense tangled masses up to 20m high (Adamson et al. 2000). It has reduced carrying capacity of agricultural land and has impacted on ecosystem services produced by the natural environment. In Queensland it is a threat to cattle, horticultural industries, forestry and to the natural environment.

Damages to livestock

Cattle grazing in Queensland has been impacted by Siam weed through reduced carrying capacity of grazing land, and because it has caused cattle deaths and abortions (Adamson et al. 2000). Under the ‘cease Government investment’ scenario Goswami (2008) estimates 631,860 cattle and calves will be impacted upon by Siam weed, at a unit value of $980/hd.

Table 5. Siam Weed base parameter values

Parameter	Description	Value
Invasion parameters		
	Maximum amount of area at risk (ha)	27,860,959
	Specific growth rate	0.05, 0.09
Control Costs parameters		
	Control ($/ha)	272
	Search – ground ($/ha)	22
	Search – helicopter ($/ha)	2.5
	Research and Communications ($)	37,715
	Administration ($)	143,231
Damages		
	Livestock (hd)	631,857
	Value of livestock ($/hd)	980
	Damage to horticulture ($/year)	324,494,649
	Area of affected forestry plantations (ha)	1,839
	Value of forestry ($/ha)	491
	Area of National Parks (ha)	167,166
	Value of ecosystem services ($)	3,786
Economic parameters		
δ	Discount rate (%)	7

Damages to horticulture and other agriculture

The horticultural and agricultural industries in Queensland at risk from Siam weed, in order of value of impact when maximum area is infested, are sugar cane, bananas, citrus, avocado, mango and papaya. Goswami (2008) estimates that the value of damages caused to these industries by Siam weed will reach a maximum of $325m in year 25.

Damages to forestry

We assume that 1,839 ha of forest will be affected by Siam weed when it reaches it maximum spread, and this is valued at $491/ha (Goswami 2008).

Loss of ecosystem services

To estimate the value of lost ecosystem services Goswami (2008) used a benefit transfer method, based on estimates undertaken by Costanza (2006) where the value of New Jersey's ecosystem services were estimated. This method assumes that ecosystem services derived from the natural environment in New Jersey can be transferred to the Wet Tropics World Heritage Area of Queensland.

To determine the impact of Siam weed on the natural environment in Queensland, Goswami took into account all the services that will be impacted (gas/climate stabilization, water supply, soil formation, waste treatment, pollination, biological control, habitat/refugia/, recreation/aesthetic and cultural/spiritual) and the degree to which they will be impacted. The estimate of the unit value of damage is $3786/ha and it is assumed that a maximum of 167,166 hectares of the natural environment will be affected by Siam weed.

5.4. Results

With base parameter values the switching point values are 7.4 and 10.2 million ha out of about 27 million ha at risk for $\alpha = 0.05$ and $\alpha = 0.09$, respectively (Table 6). It may be economically desirable to eradicate areas as large as these based only on a benefit-cost evaluation with no budget constraints and with linear costs. But clearly budgets to eradicate millions of hectares will not be available and hence budget constraints render the switching point calculation irrelevant.

The area estimated to be currently invaded could be eradicated at a cost of $18 million according to the model (Table 6), but this does not account for stochastic disturbances. At the switching point, it would cost between $9 billion and $13 billion, to eradicate Siam Weed from between 7 million and 10 million hectares depending on the specific growth rates. These sorts of budgets will never be available, so it is important to develop the budget-constrained version of the model in future work. Still, it is of interest to evaluate the effects of changes in costs and damages on the optimal solution. The effect of changing costs on the

Table 6. Siam weed results for the two values of specific growth rate

	Specific growth rate	
	α = 0.05	α = 0.09
Damages (\$/ha, β_D)[a]	57	57
Control costs (\$/ha, β_C)[a]	1,219	1,219
Switching point (1,000 ha)	7,369	10,285
Control cost (\$m PV) at switching point:	8,982	12,538
MB = 0 (1,000 ha)	26,871	21,120
Control cost (\$m PV) at current area invaded:	18	18

[a] β_D was estimated from the damage parameters in Table 5 as explained in Section 3.1 and β_C was estimated from the cost parameters in Table 5 as explained in Section 3.2.

position of the switching point is illustrated in Figure 13. As the costs of control per hectare increase the switching point decreases – the area up to which it is optimal to eradicate is reduced. This relationship is shown for two specific growth rates (α). Interestingly, when α = 0.05, the switching point is 0 if control costs reach \$2850 per hectare at base damage values (Figure 13A). This means that when costs are ≥ \$2850 (with other parameter values in Table 6 held constant) then it is never optimal to attempt eradication. When α = 0.09, the switching point remains at relatively high values even at very high control costs (> \$7,000/ha, which is about 16% of the area at risk in Figure 13A). The same patterns are observed when damages increase, but the curves shift up and to the right (Figure 13B).

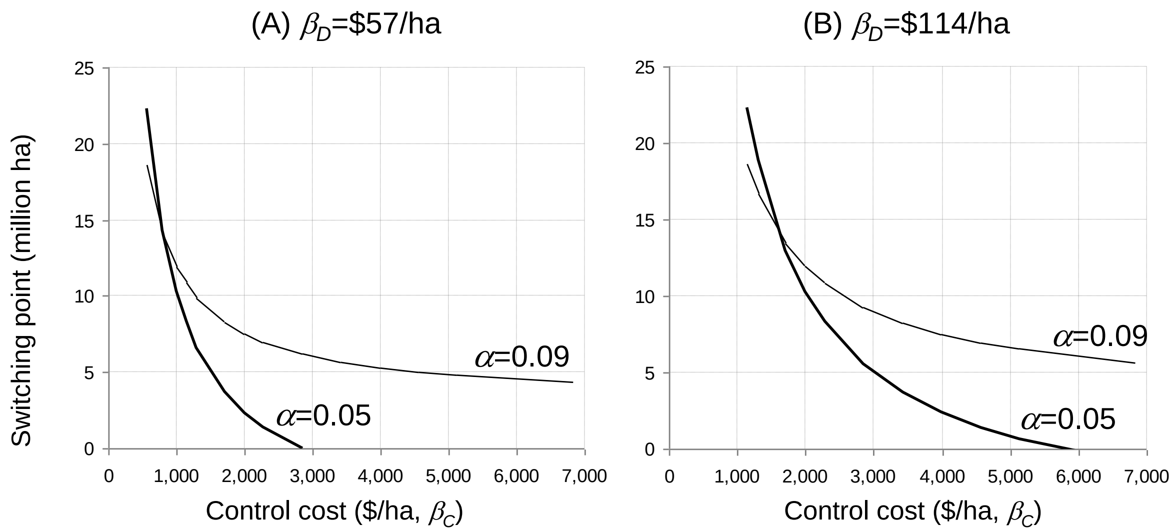

Figure 13. Switching point results for Siam weed for two different values of the specific growth rate (α)

The reasons for the patterns observed in Figure 13 can be understood by looking at the switching point equation (eq. 16 in Appendix A) in some detail:

$$x_S = \frac{\beta_D + (\alpha - \delta)\beta_C}{2\beta_C \alpha}\kappa \tag{7}$$

Here x_s is the area at which the switching point occurs and the other parameters have been described before. The growth rate of the invasion (α) compared to the discount rate (δ) determines the influence of future costs on the position of the switching point. The term $(\alpha - \delta)\beta_C$ represents the future costs of not controlling the invasion today. The parameter α represents the growth of the invasion on the ground and δ represents the opportunity cost of the funds used to control the invasion (the growth rate of these funds if they were invested at a rate δ).

If the growth rate of control costs is lower than the growth rate of funds saved by not controlling today ($\alpha < \delta$), it makes sense to not control but save the funds and use them in the future, when they will be able to buy more control. Conversely, if the growth rate of control costs is higher than the growth rate of funds saved by not controlling today ($\alpha > \delta$), it makes sense to control today, as the same funds would not be able to cover the costs required to control in the future. The value of the numerator in the equation above increases in proportion with the cost parameter (β_C) when $\alpha > \delta$ whereas it decreases in proportion to β_C when $\alpha < \delta$. This means that the former case ($\alpha > \delta$) will tend to result in higher values of x_s than the latter. However, this is not always the case because α and β_C also appear in the denominator of the equation, so lower values of α will tend to make x_s larger, especially at low values of β_C. This explains the pattern observed in Figure 13, where the curve for α=0.05 crosses the curve for α=0.09 from above, and where the curve becomes flatter as β_C increases, especially when $\alpha > \delta$.

6.3.1 Comparing the analytical and numerical solution

The results presented above were obtained using the Excel model (Cacho and Hester 2013), which is based on the analytical solution presented in Appendix A. We were able to obtain a closed solution for the switching point problem (see equation 7) because of the functional forms we used (linear damages, linear control costs and logistic population growth). The analytical solution is convenient for three reasons; it produces and exact solution; it is easy to implement on a spreadsheet; and it allows general inferences about the decision problem to be drawn as shown above. However, the analytical solution ignores the presence of stochastic environmental effects that may affect future invasion trajectories. Also, as discussed in Chapter 3, the analytical model cannot deal with nonlinear costs and damages (Refer to Section 3.4 for the reasons we may want to use nonlinear functions).

In contrast to the analytical model, the numerical (Matlab) model can incorporate stochastic events and nonlinear functions, but it does produce an approximation rather than an exact answer. The numerical model approximates the optimal solution using a state transition matrix that is based on a limited set of discrete values (see section 3.4 for a description of the stochastic dynamic programming model). We used a 500 $\times$ 500 matrix with rows and columns representing current and future states respectively. The set of possible invasion sizes contains 500 equally-spaced values in the range (0, κ). The stochastic model is solved by randomly drawing 10,000 points from a normal distribution, to represent random environmental shocks on the invasion, to estimate transition probabilities. The model is solved by backward recursion until the value function converges, at this point the optimal state transition matrix is obtained.

We tested the numerical solution against the analytical solution for the cases shown in Figure 13. The results from this comparison are presented in Figure 14. In all cases the numerical solution produced results that were consistent with the analytical solution: the switching point

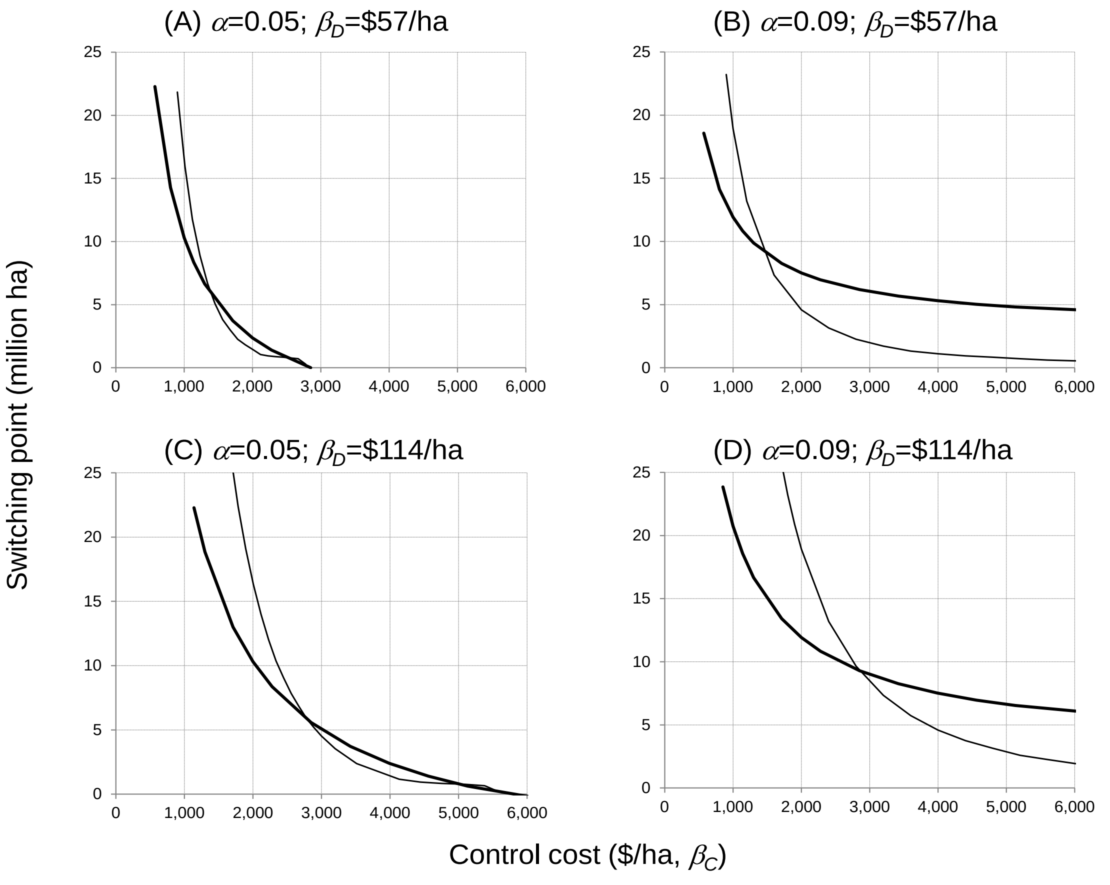

Figure 14. Comparison of Siam weed results with analytical model (heavy lines) and numerical model (light lines) for combinations of low and high values of growth (α) and damage (β_D) parameters.

(x_s) decreases at a decreasing rate as control cost increases. However, the numerical solution tended to overestimate the value of x_s at low control costs and underestimate it at high control costs. This seems to be more severe when the growth rate is high (compare Figures 14A and 14C against Figures 14B and 14D). Improving the numerical algorithm will require an understanding of the reasons behind these differences between analytical and numerical solutions. These are interesting questions left for future work.

In Chapter 4 we showed that introducing stochasticity results in cautious behavior. This was reflected in higher x_s values when future states were uncertain. This cautious behavior is shown for the Siam weed example in Figure 15. The solutions of the stochastic case are above those of the deterministic case for all combinations of α, β_D and β_C, indicating that the level of control should be intensified when random shocks cause future invasion states to be uncertain.

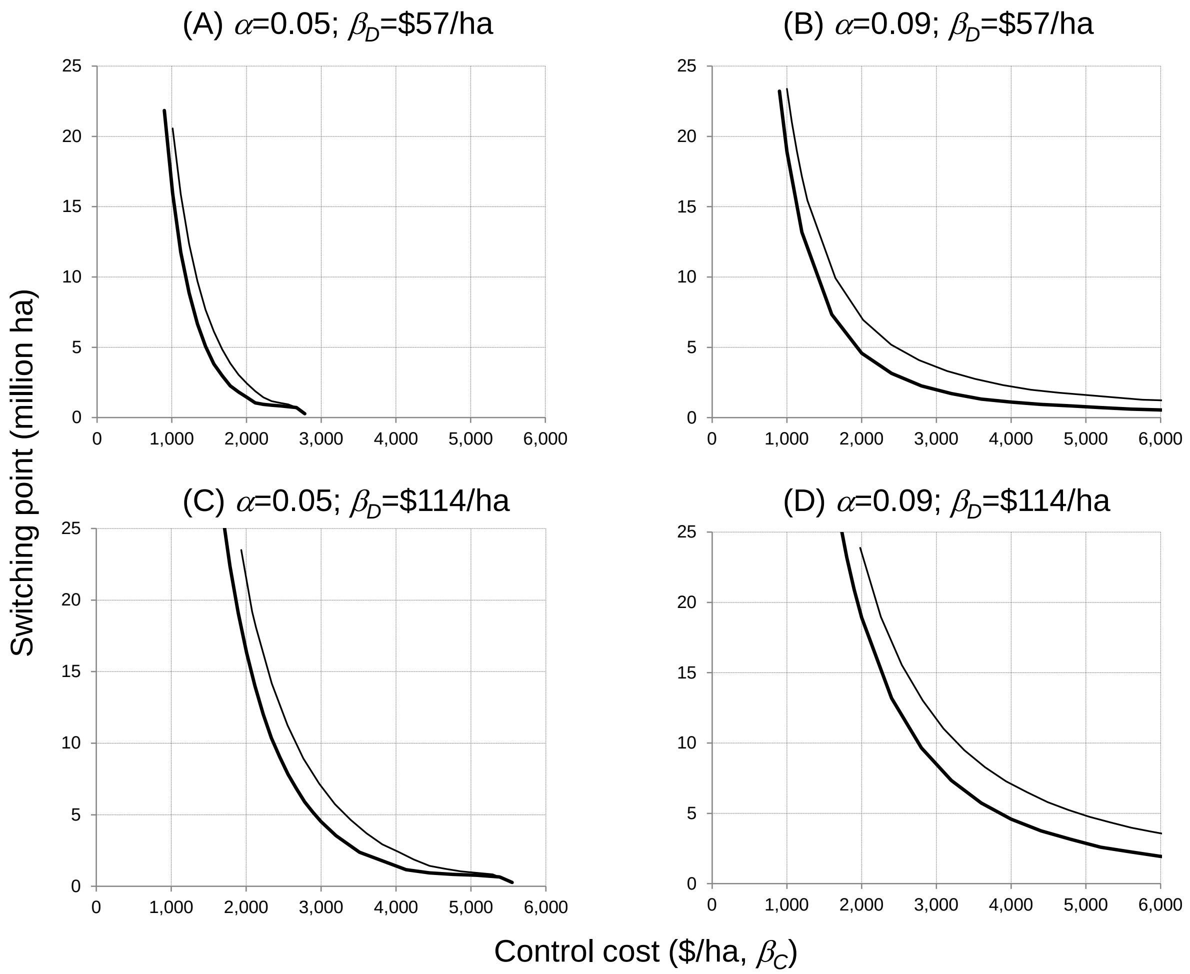

Figure 15. Numerical solution of Siam weed model results with deterministic model (heavy line) and stochastic model with SD=0.01 (light lines) for combinations of low and high values of growth (α) and damage (β_D) parameters

6. Case-study 2: European House Borer in Western Australia

6.1. Background and history in Australia

European House Borer (EHB) (*Hylotrupes bajulus*) is a serious insect pest of untreated dry softwood, including, pine, fir and spruce. EHB is native to Europe, but is now found in South Africa, Asia, USA and Canada, becoming a serious pest of seasoned softwood timbers in all countries where it has become established. In Western Australia, the pest has been found in dead pinewood or the dead parts of live pine trees (dried out branch stubs, damaged branches and trunks), dead trees and logs, and untreated manufactured articles derived from pine timber (DAFWA 2010). The adult beetle lays its eggs into cracks and holes in the deadwood, with larvae subsequently hatching from the eggs and causing damage by feeding on the timber. When found in timber in buildings, serious structural damage can occur when 2-3 generations have infested the same piece of wood.

Natural spread of EHB is slow – the pest can live in its larval state for 2-12 years before it matures and emerges from the timber as an adult beetle, to begin the life cycle again (DAFWA 2008a). An adult EHB beetle usually travels only a minimal distance if its food source has not yet been exhausted, which can take more than 10 years (DAFWA 2010). While it is possible for migrating beetles to fly and be dispersed by winds, there is great potential for EHB to be spread large distances by human assisted transport of infested pine wood.

Australia's most recent incursion of EHB was detected in Western Australia in January 2004 in a private residence - it is thought that EHB had been in the infested areas for 15 to 30 years prior to detection (Blanchard et al. 2006). When subsequent surveillance uncovered EHB at 27 properties in 10 Perth suburbs the State Government began an EHB Emergency Plant Pest Response Plan (EHB EPPRP) with a view to eradication, approved by the Primary Industries Ministerial Council in November 2006 (DAFWA 2008b). The Response Programme involves a mix of surveillance, regulations on the movement of untreated pinewood, research and education activities. By September 2010, there were 178 EHB infested sites across 50 suburbs in the greater Perth metropolitan area and one infested site in Albany (WA Dept of Agriculture and Food 2010). While most infestations have been found in pine waste material and dead parts of live pine trees, the pest has been found in structural material in a home which is thought to have become infested after EHB dispersed from nearby pine trees. Other infestations in structural materials have occurred but timber was found to be infested prior to installation in homes. Details of the current infestation of EHB are shown in Figure 16.

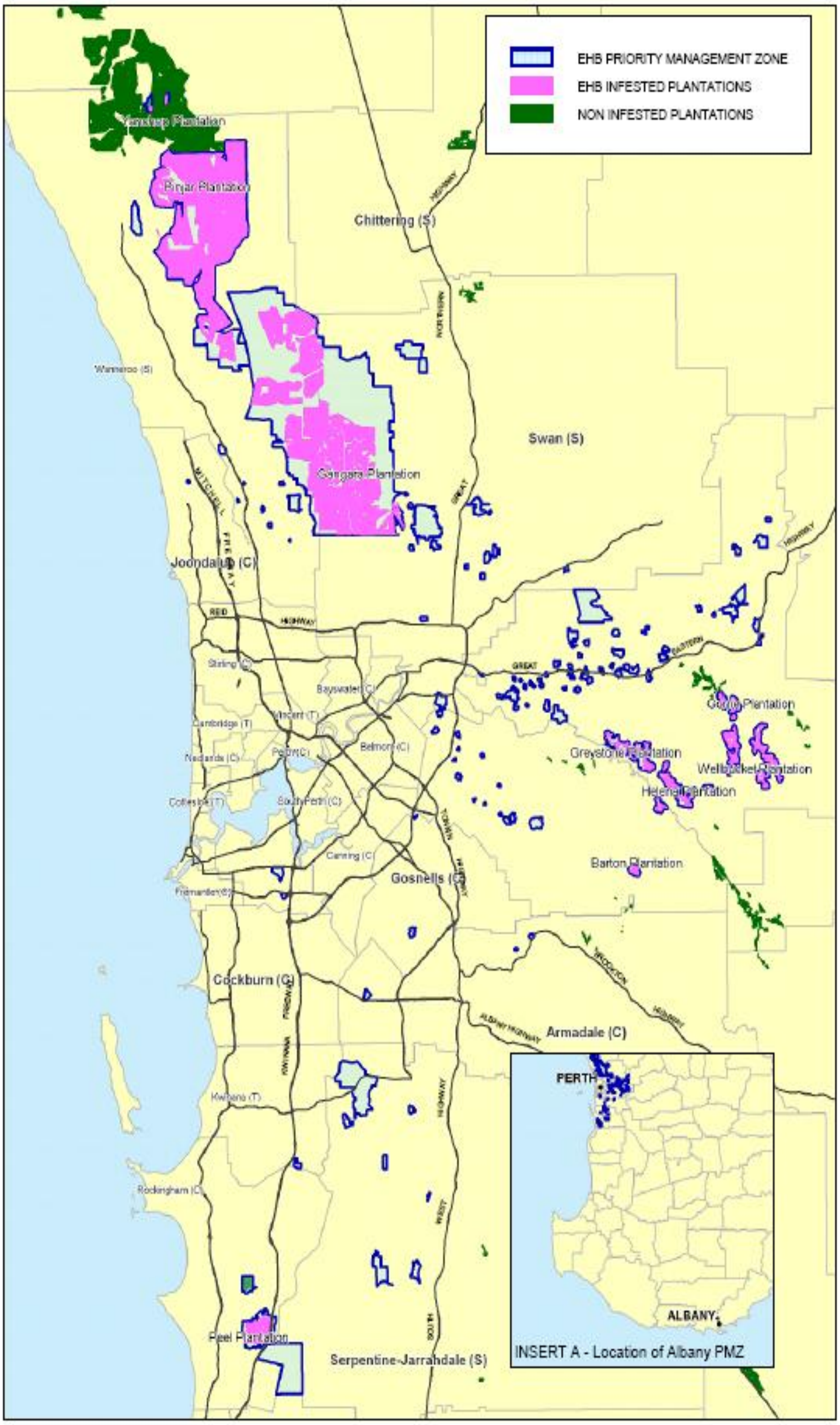

Figure 16. EHB Priority Management Zones. Source: EHB Response program (J. van Schagen)

Data on detections of EHB throughout the programme shows a rapid growth in the number of properties detected as invaded between 2004 and 2006, followed by a slower increase. Given that the latter occurred with no reduction in search effort, it indicates that the surveillance and control effort was succeeding in delimiting the incursion (Figure 17).

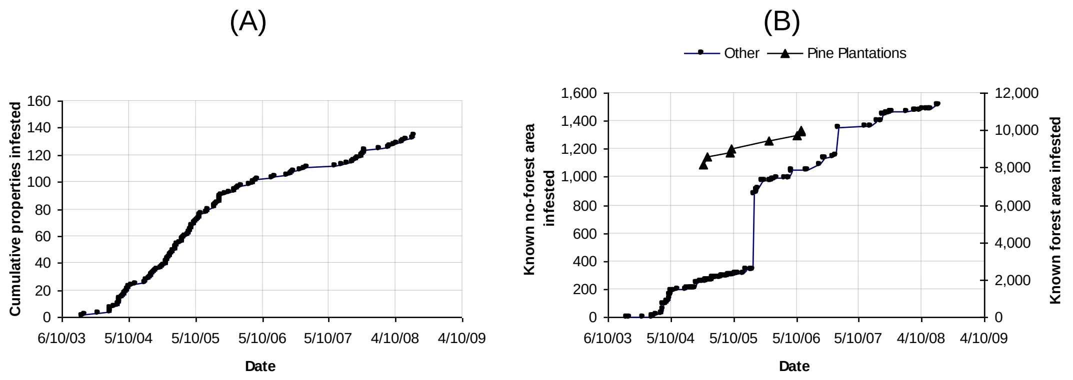

Figure 17. EHB-infested properties (A) and number of hectares (B) in forest and non-forest areas. Data from EHB Response Programme

The existing EHB Response Programme is in a transition from eradication to a management programme (ie. containment in WA), and it is likely that other states and territories will introduce legislation that places restrictions on the movement of pinewood out of Western Australia (see DAFWA, 2008c for proposed legislation).

6.2. Modelling the spread and management of EHB

The basic optimisation model described earlier (see Appendix A) proved to be of limited applicability for EHB because this pest not only infests the dead parts of pine trees in pine plantations, it also infests buildings. Pine forests are the main habitat of EHB but the damage occurs mostly in residential areas. This means that knowledge of the extent of the invasion (infested area) does not provide enough information to describe the state of the system for management purposes. We need at least two state variables: forest area invaded and number of susceptible houses in the infested area. Another complication relative to the original model is that control of the invasion involves “packages” of actions, including building restrictions, early harvest of infested plantations and enhanced forest ‘hygiene’. These actions cannot be easily related to reductions in area invaded as continuous variables.

A two-state-variable model was developed and shared with the EHB Control Team (see Milestone 2 Progress Report for this project). Feedback from the team through a teleconference led to modification of the model involving the introduction of a third state variable. This was done to differentiate between susceptible houses and houses at risk, whose relative values may change depending on whether the invasion is being contained, eradicated or allowed to spread.

Susceptible houses are those that contain untreated pine. Houses at risk are susceptible houses that are also within an infested area.

The European House Borer problem is illustrated in Figure 18. The state of the infestation at any time is described by the number of houses infested (y_t), the number of houses at risk (h_t) and the area of forest infested (x_t). Cross infection may occur from forest to houses (m_x) and from houses to forests (m_h). The risk of cross infection will depend on proximity between forests and houses. The total area of forest (θ_x) changes through time depending of the rates of forest planting (γ_{plant}) and harvesting ($\gamma_{harvest}$). The number of susceptible houses changes through time depending on the rate at which new houses are built using untreated softwood (γ_{new}), and the rate at which existing susceptible houses are protected (γ_{prot}) through timber replacement.

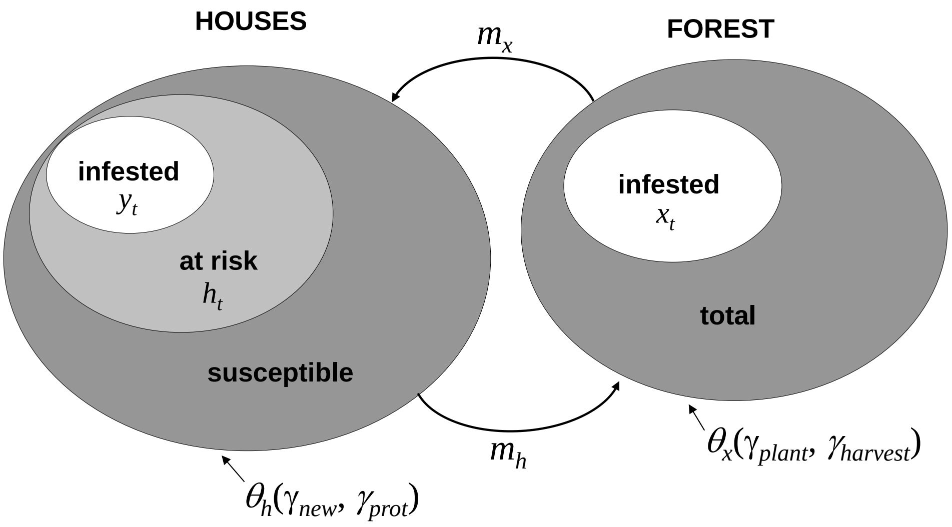

Figure 18. Diagrammatic representation of the European House Borer model

The final EHB mathematical model is presented in Appendix C. The model accounts for three state variables and uses discrete control actions. The output of this model is the sum of the damages caused by the invasion and the costs of managing it, in present-value terms. Note that, unlike in previous chapters, this is not an optimisation model, as the complexity introduced by the three state variables precludes its analytical solution. This means that the conditions for optimization cannot be reduced to the intersection of two lines, as in the base model. The ultimate objective will still be to minimize the present cost of the invasion, but this will require additional work once an acceptable set of parameter values is agreed upon.

For short we will refer to this objective function as the total cost of the invasion (*TC*). The value of *TC* depends on the time trajectory of three state variables and a control variable. The state variables are the number of houses infested (y_t), the number of houses at risk (h_t) and the area of forest infested (x_t). The control variable ($\mathbf{u}_t$) is a binary string of four digits representing a given package of control options. The options are:

1. building restrictions within RMZ
2. early harvest of softwood plantations
3. forest hygiene activities
4. fixed-cost activities

An option is turned on or off by setting its value to 1 or 0 in the appropriate position within $\mathbf{u}_t$. For example $\mathbf{u}_t$ = [0,0,0,0] represents no control and $\mathbf{u}_t$ = [1,0,0,1] represents a situation with building restrictions but no early harvest or forest hygiene. In the latter case the final digit is set to 1 to account for the fixed annual costs of running the programme.

6.2.1. Spread and Control

In the absence of control, forest area invaded (x_t) and houses at risk (h_t) are assumed to grow according to a logistic function (equations 5 and 6 in Appendix C), with an asymptote representing the maximum forest area at risk (in hectares) in the case of x_t and the maximum number of susceptible houses in the case of h_t. It is assumed that the rate of house infestation is a constant proportion of the houses at risk (equation 7 in Appendix C). These growth functions also include cross-infection risk, given by the parameters μ_x, μ_h and μ_y whose values are unknown at present.

A control package may reduce the size of one or more state variables. The control effects are given by equations11 to 13 in Appendix C. The forest area invaded (x_t) decreases as a result of early harvest (u_2) and forest hygiene actions (u_3) and the strength of these effects is given by the rate at which forest is harvested (γ_{harv}) and the proportion of infested forest that is cleaned (γ_{hyg}) annually.

The number of houses at risk (h_t) and houses infested (y_t) decreases according to the proportion of houses that are protected per year (γ_{prot}) and houses that are repaired (γ_{repair}) and these actions are activated through control variable u_4.

6.2.2. Costs and Damages

Control costs (C_t) are only incurred when $\mathbf{u}_t \neq$ [0,0,0,0]. When u_1=1, the cost of building restrictions depends on the fraction of new susceptible houses that would have been built in the absence of restrictions (γ_{new}). When u_2=1, the cost of early harvest is given by the loss experienced by forest owners and depends on the fraction of forest that is harvested early each year (γ_{harv}). When u_3=1, the cost of forest hygiene is given by the expense of clearing deadwood and debris and depends on the fraction of forest that is cleaned each year (γ_{hyg}). (For details see equation 14 in Appendix C). Note that u_4 should be set = 1 when any of the other control options in $\mathbf{u}_t$ is on, to indicate that a control programme exists.

Most damages occur in residential areas and hence depend on the number of houses at risk and houses infested. These include costs of additional pest inspections required within the area at risk; the cost of protecting existing houses at risk; possible loss in property values and costs of repairing infested public buildings. In addition to these property damages, the transportation industry faces the cost of treating pallets and crates used for interstate trade. (For details see equation 15 in Appendix C).

6.4 The Numerical EHB Model

Numerical implementation of the EHB model requires estimates of several parameters. Ideally these estimates should come from actual data. Unfortunately very limited data are available, this is partly because of the lack of GIS expertise in the EHB team to extract additional data. An alternative to overcome this limitation within the limited time left in the project was to let the EHB team come up with parameter values based on their experience, assisted by a simulation model for scenario analysis. For this purpose a numerical simulation model was developed in Excel (EHB_model_v2) and distributed to the EHB team. This would allow the EHB team to come up with parameter estimates that could then form the basis of optimisation analysis in the future.

The EHB Excel model performs the numerical solution of the mathematical model described in Appendix C. It simulates the three state variables (x_t, h_t and y_t) forward in time based on the control $\mathbf{u}_t$ applied. The management strategy (the 4 entries contained in $\mathbf{u}_t$) is kept fixed within a simulation run. This is a deterministic model and does not perform optimization, but allows the user to explore alternative control scenarios. The model is designed to allow managers to compare the consequences of alternative actions.

The simulation model is written in Visual Basic within Excel. The user can modify parameter values and click the *Run* button to solve the model and evaluate the consequences of any given parameter combination (Figure 19). The *Run* button is attached to a macro that performs one run of the simulation based on the parameters entered by the user.

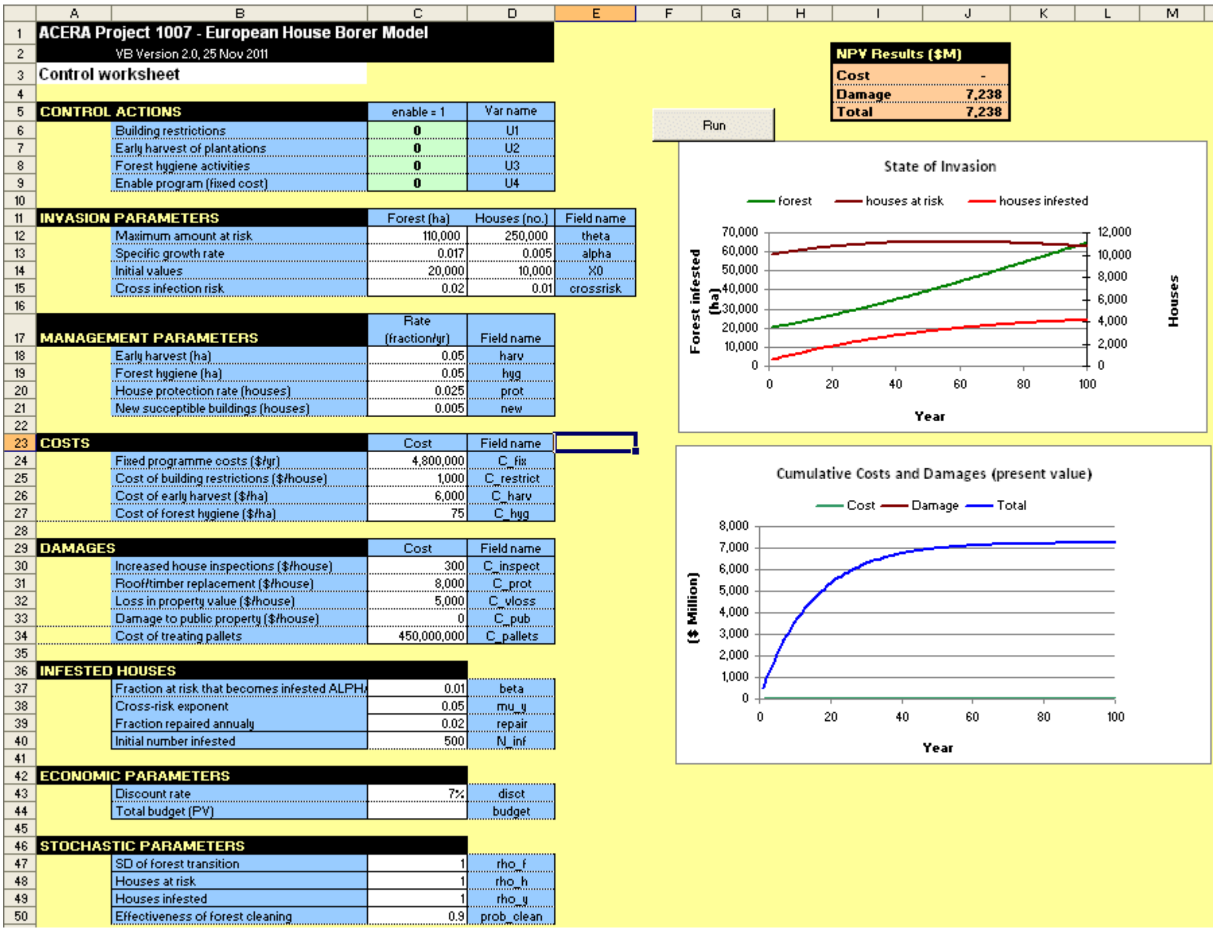

Figure 19. The EHB model for a set of arbitrary parameter values. The total budget and stochastic parameters are not used in this version of the model.

6.5 Scenarios and parameter values

The EHB model can be used to investigate a number of scenarios, including the option of no control ($\mathbf{u}_t$ =[0,0,0,0]) and full control ($\mathbf{u}_t$ =[1,1,1,1]).

Under the no control scenario the current EHB control zones are not maintained resulting in the pest potentially spreading throughout WA. Affected parties are assumed to be:

- Householders, who bear the cost of inspections and the cost of replacing roofs or affected timber should their homes become infected. Owners of susceptible homes are also likely to face a drop in property value because of this susceptibility;
- Transport companies involved in interstate trade, because all softwood leaving WA would need to be treated to allow entry into other Australian states and territories. The value of the damage appears largest for softwood pallets that are commonly used in transportation of goods.

- The taxpayers, who bear the cost of inspections and treatment of public infrastructure such as schools, halls, hospitals etc.

We do not consider the cost of surveillance for EHB in the eastern States that is likely to be implemented to confirm EHB freedom under the no-control scenario. It should be noted that the stock of EHB-susceptible housing in the eastern states of Australia is of several magnitudes higher than that existing in WA (R. Cunningham pers. comm.)

Under the full control scenario, the current EHB management zones are maintained. Affected parties are assumed to be:

- Those planning to build homes within the management zones, who bear the cost of complying with building restrictions mandating the use of materials that are not susceptible to EHB;
- Softwood plantation owners, who bear the cost of early harvest of pine plantations and who must increase forest hygiene, and clean-up affected areas after harvest.
- The WA government, who must bear the cost of maintaining the EHB response programme including maintaining high levels of surveillance.

We do not consider the effect of fumigation and other treatments on homes and softwood on the environment, nor the effects on the pest control industry whose members stand to benefit from increased inspections for EHB.

Model parameters and their values are given in Table 7 and are described in more detail below. Values come from a range of sources: the cost-benefit analysis of EHB management options and detailed bioeconomic model undertaken by Blanchard et al. (2006); the Regulatory Impact Statement on Building Regulations for European House Borer (The Allen Consulting Group 2006) and personal communication with members of the EHB eradication team. Where no information was available on parameter values we use hypothetical but plausible values.

6.5.1 Invasion parameters

Softwood (pine) plantations and dwellings/buildings built from softwood materials are at risk from EHB. While pine trees/plantations are not actually killed or damaged by EHB, the pest can infest the dead parts of pine trees and pine waste in the plantation. Many plantations to the north and east of Perth are infested with EHB and are contained within the current EHB management zones (Figure 16). Importantly, the presence of EHB in plantations becomes a source of infestation for nearby susceptible dwellings. As explained above, these features are accounted for thorough the three state variables x_t (infested forest), h_t (houses at risk) and y_t (houses infested).

Table 7. EHB Model Parameter values

Parameter	Description	Value
Invasion parameters		
θ_x	Maximum amount of forest area at risk (ha)	110,000
θ_h	Total number of homes at risk in WA	250,000
α_x	Specific growth rate of EHB in forests	0.017
α_h	Specific growth rate of EHB in houses	0.005
μ_x	Parameter for increased risk of house invasion as area of forest invaded increases	0.0002
μ_h	Parameter for increased risk of forest invasion as number of houses invaded increases	0.0001
Management parameters		
γ_{harv}	Fraction of forest area harvested each year	0.05
γ_{hyg}	Fraction of forest area subject to hygiene activities	0.05
γ_{prot}	Fraction of susceptible houses where timber is replaced	0.025
γ_{new}	Fraction of new EHB susceptible houses built relative to the total housing stock.	0.005
Control Costs parameters		
C_{fix}	Costs of eradication programme ($/yr)	4,800,000
$C_{restrict}$	Cost of building restrictions on new houses built in EHB zones ($/hh)	1000
C_{harv}	Early harvest and clean-up of pine plantations in EHB zones ($/ha)	6000
C_{hyg}	Increased forest hygiene ($/ha)	75
Damage Parameters		
$C_{inspect}$	Cost of pest inspections ($/hh)	300
C_{prot}	Cost of replacing affected timber ($/hh)	8,000
C_{vloss}	Reduction in property values ($/hh)	5000
C_{public}	Damages to public property ($/ha)	na
C_{pallet}	Replacement of pallets ($/yr)	45,000,000
Infested houses parameters		
αy	Fraction of houses at risk that become infested	0.01
μy	Cross infection parameter	0.05
γy	Fraction of infested houses repaired annually	0.02
Economic parameters		
δ	Discount rate (%)	7

Total area of forest at risk

If the EHB management programme ends as planned, all softwood plantations would need to be considered as susceptible to infestation by the pest, and building restrictions would be extended to apply across WA as much of the inhabited areas of the state are thought to match the suitable habitat for the pest. As part of the EHB EPPRP, Climex was used to find areas in Australia that have the same characteristics as areas in South Africa that have been infested by EHB, and for WA this is thought to be the bottom half of the state where most people live (unpublished Figure). In 2010, WA had 110,000 hectares of softwood plantation (DAFF 2008), and this is used as the value of θ_x, the maximum amount of forest at risk from EHB. The amount of forest currently within the management zones is approximately 21,000 hectares (Blanchard et al. 2006) and this was used as the initial value of infested forest in the model.

Total houses at risk

Between 2000 and the present, new homes in WA were allowed to be constructed from untreated softwood materials. Approximately 250,000 new homes were built in WA during this time period from untreated pinewood, so this is assumed to be the value of θ_h, the total number of houses at risk in WA. Since the discovery of EHB in pine plantations and in several suburbs in Perth, all new homes in EHB RMZ need to be constructed from steel and/or hardwood (Building Commission WA 2009). The number of susceptible houses in the current management zones is assumed to be 12,000 (Blanchard et al. 2006) and this was used as the initial value of affected houses in the model.

Specific growth rate of EHB

There is still much uncertainty about the natural spread rate of EHB, although it is known to be slow – the pest can live in its larval state for 2-12 years before it matures and emerges from the timber as an adult beetle, to begin the life cycle again (DAFWA 2008a). An adult EHB beetle will travel only a minimal distance if its food source has not yet been exhausted, which can take more than 10 years (WA Agricultural Authority 2010). Blanchard et al. (2006) assume two distinct growth rates for EHB in forests and houses and we also adopt this approach and use their values. The specific growth rate of EHB in forests, α_x, is assumed to be 0.017 and in houses, α_h, is assumed to be 0.005.

6.5.2 Management parameters

EHB managers can influence the ‘strength’ of the effects of early harvest and forest hygiene through the variables γ_{harv} and γ_{hyg} which represent the fraction of forest harvested each year and the fraction of forest area subject to forest hygiene activities, respectively.

In a sense, EHB managers can also influence the stock of susceptible houses through the variables γ_{prot} and γ_{new} which represent the proportion of houses that are protected each year and the fraction of new susceptible houses that would have been built in the absence of restrictions, respectively.

6.5.3 Control costs parameters

When control measures are implemented, there will be additional costs of building new homes in EHB infested zones, of improved forest hygiene, of early harvest and clean up of plantations, and of maintaining the eradication programme.

Annual costs of eradication programme

The current cost of the EHB eradication programme is $4.8m per year and includes the cost of administration, research and development, communication, surveillance and control. While we assume that this fixed cost, C_{fix}, applies each year until EHB is eradicated, it is likely that this fixed cost will be reduced in line with the severity of the infestation.

Restrictions on building materials

Cost of using treated timber, $C_{restrict}$ is mandatory in EHB management zones and is estimated to be at least $1000 per new home (Blanchard et al 2006, John van Schagen pers. comm).

Accelerated harvest costs

The harvesting of infested pine plantations will be brought forward for some plantations in order to assist with eradication of the pest, resulting in the harvest of a small percentage of trees before their optimal harvesting age, thus reducing the value of the timber. Once trees are harvested, pine tree waste would need to be cleaned up. Using information on plantation age, early harvest plans at various plantation and clean-up costs from Blanchard et al. (2006) we assume the cost of early harvest, C_{harv}, is $6000/ha.

Increased hygiene practices

Since EHB are found in the dead pine trees and pine material within the plantation, this material needs to be regularly removed from plantations. Using information provided in the bioeconomic model of Blanchard et al. (2006) we assume the cost of increased hygiene, C_{hyg}, is $75/ha.

6.5.4 Invasion Damages

This set of parameters describes the damages caused by the spread of the invasion as the areas infested by EHB grow over time, potentially spreading throughout WA, and affecting owners of EHB susceptible homes, and transport companies involved in interstate trade.

Household damages and cost of private control

Owners of EHB-susceptible homes will bear the cost of annual pest inspections, $C_{inspect}$, and we assume each inspection costs $300 per house. If a home is found to be infested with EHB, there are three options available to owners of infested homes: fumigation; reroofing, or replacement of the affected timber with non-susceptible materials. Fumigation is an expensive option, and does not remove the risk of future infection by EHB while complete roof replacement would only be necessary in a small number of heavily infested properties. Replacement of affected timber is thought to be the most likely way that homeowners would protect their homes from the pest (John van Schagen pers. comm.). The cost of undertaking timber replacement, C_{prot}, was assumed to be $8,000 in the model.

Currently there is no public disclosure of which houses have been infested by EHB (and subsequently treated). If the EHB eradication programme ends and the pests spreads more widely it could be reasonably assumed that all houses built with untreated pine would experience a loss in value. We assume that the loss in value for EHB susceptible homes is $5,000.

Damages to public property

Public property such as schools, halls and offices made from EHB-susceptible materials face the same treatment costs as private dwellings in residential areas infested. The state government would bear the costs of inspections of this property and the costs of protecting it should it become infested. In the initial model simulations, however, we do not consider the damages to public property from EHB.

Lost trade opportunities

Under the no-control scenario, WA companies wishing to trade interstate would need to use non-EHB susceptible pallets, or to treat all softwood products that leave the state, including pallets, timber and furniture with insecticide to ensure no EHB are carried interstate. The legislation on interstate movement on timber has recently been circulated for comment (http://www.ehb.wa.gov.au/html/newregs.htm). It appears that the largest costs will accrue from treatment or replacement of pallets. For existing softwood pallets, transport companies can use a preservative insecticide, where pine material is impregnated, dipped or sprayed, with long-lasting effects. The cost of permanently treating each pallet with insecticide is around $3 and there are 12 million pine pallets that would potentially need treating. The lifespan of each pallet is around 8 years, and replacement of each pallet with hardwood or plastic is assumed to be $30. For the purposes of the model we assume that an eighth of the 12 million pallets are replaced each year, so the cost of pallet replacement, C_{pallet}, is $45 million each year.

6.5.5 Infested houses

The parameters for infested houses were given arbitrary values as no information is available to calculate them. These are important parameters to be explored by the EHB team with the simulation model and to be considered for statistical analysis if suitable data can be obtained. We used conservative numbers by assuming that that the fraction of houses at risk that become infested each year (α_y) is 0.01, and the rate of repair of infested houses (γ_y) is 0.02 per year. The cross-infection risk parameter (μ_y) was set at 0.05.

6.6 Results

The model was run for a planning horizon of 100 years using the parameter values presented in Table 7. A factorial design was used to test the effects of all possible combinations of control options. The first three elements of **u** (building restrictions, early harvest and forest hygiene) can take values of 0 or 1, the fourth element of **u** (enable program) is not part of the experimental design because its value must be 1 when any other element in **u** is 1 (to account for the fixed costs of the program) and 0 if there is no program. Therefore this design resulted in 2^3=8 experiments with values of **u** ranging from [0,0,0,0] to [1,1,1,1]. State variable trajectories are presented in Figure 19. The full list of control packages is presented in Table 8.

Table 8. Control packages tested with the EHB model.

	Control actions			
Treatment package	1. Building restrictions	2. Early harvest	3. Forest hygiene	4. Fixed programme costs
A	0	0	0	0
B	1	0	0	1
C	0	1	0	1
D	1	1	0	1
E	0	0	1	1
F	1	0	1	1
G	0	1	1	1
H	1	1	1	1

Under the no-control scenario (Figure 20A) the forest area infested continues to grow throughout the 100 years simulated. The stock of houses at risk stabilises and then decreases slightly as susceptible houses are protected at private expense. The number of infested houses continues to increase throughout the 100 years but at a decreasing rate as number of houses at risk stabilises. Under the full control scenario (Figure 20H) forest area infested and houses at risk decrease rapidly as control actions and building restrictions are implemented. The number of houses infested increases for about 40 years before starting to decrease in response to the control actions. Other control packages result in intermediate results, but all the control packages result in a gradual reduction of the infestation (Figure 20).

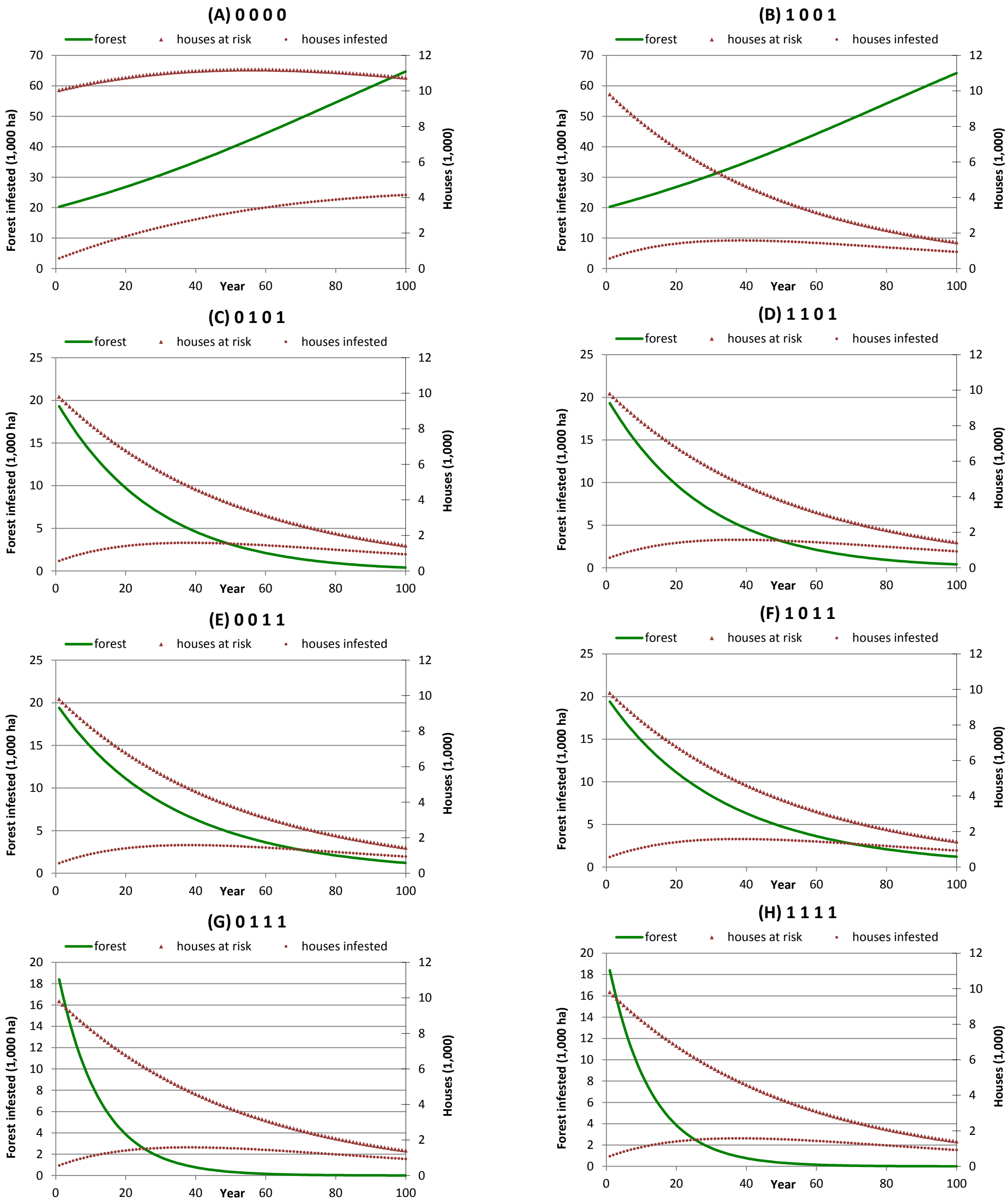

Figure 20. Simulated trajectory of the two state variables: forest area (dotted line) and susceptible houses (solid line) using the base parameter values. Figure headings indicate the control package used. Note differences in vertical axis ranges to enhance readability.

Under the base assumptions any form of control is preferred to no control (Figure 21). The present value of total cost (damages plus control costs over 100 years) is around $7 billion under no control and $800 million under full control. These results are roughly consistent with the benefit cost analysis of Blanchard et al. (2006).

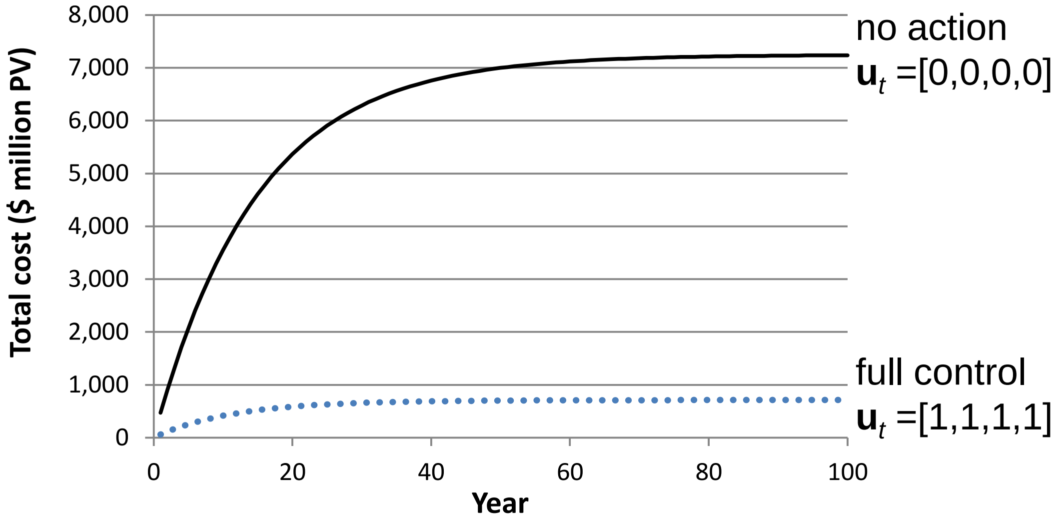

Figure 21. Cumulative total cost of control plus damage over 100 years in present value terms for two control packages

None of the control actions simulated resulted in eradication within 100 years. This is because the rates of house protection and forest cleaning where not high enough to accomplish earlier eradication. This raises the question of which combinations and magnitudes of control actions would achieve a high likelihood of eradication within an acceptable time period. To address this question we doubled γ_{prot} and γ_{hyg} from their base values and repeated the experiment. The higher rates of house protection and forest hygiene resulted in lower total cost because they caused all state variables to decrease more rapidly. The total costs of the no control action and the full control package are $1.2 billion and $663 million respectively, compared to $1.4 billion and $800 million with the (lower control) values in the base case.

Doubling the values of γ_{prot} and γ_{hyg} again results in further savings (Table 9) and allows eradication to be achieved within the period simulated (Figure 22).

Table 9. Total cost ($ million present value over 100 years) of two control packages under three different scenarios based on the rate of house protection (γ_{prot}) and forest hygiene (γ_{hyg}). Other parameters were kept at their base values as in Table 2

Scenario	Control package	
($\gamma_{prot}\gamma_{hyg}$)	[0,0,0,0]	[1,1,1,1]
Base (0.025, 0.05)	7,238	711
Base×2 (0.05, 0.1)	7,238	574
Base×4 (0.1 0.2	7,238	423

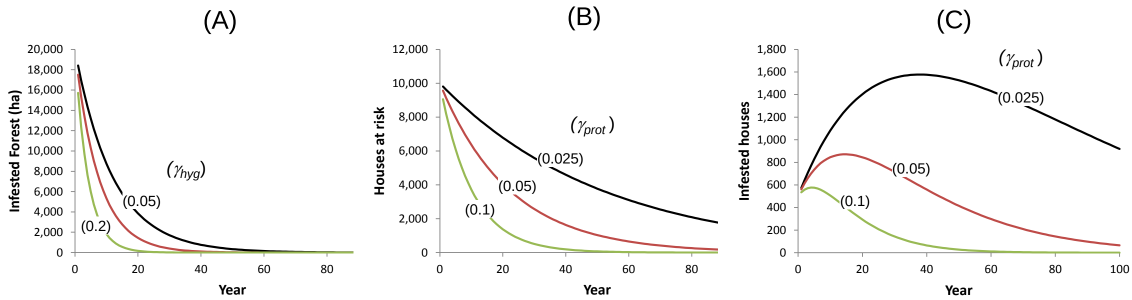

Figure 22. Simulated trajectory of the three state variables: forest area (A) houses at risk (B) and infested houses (C) with different control intensities in terms of house protection rate (*γprot*) and forest hygiene (*γhyg*), other parameters were kept at their base values.

The higher rates of house protection and forest hygiene illustrated in Figure 22 may be unrealistic when there are limits on the biosecurity budget, the number of builders available to change timber in susceptible houses, and non-susceptible building materials available. Further work should focus on refining parameter values and finding realistic rates of control based on skills and budgets available.

6.7 Spatial analysis with limited data

Point coordinates of the EHB data presented in Figure 17 were available. Each point in the dataset represents the location of an infested site. Properties differ in size and shape and point data provide limited information when vector data of the sites are not available. Spatial data on susceptible forest and susceptible houses were also unavailable. Given these limitations, we only undertook exploratory spatial analysis. This is work in progress which will be submitted as a journal article

7. Conclusions and recommendations

The original switching point model was built as the simplest possible representation of a managed invasion (see Appendix A) and was tested with two case-studies of relevance to biosecurity agencies in Australia – Siam weed in Queensland and EHB in Western Australia. While the generic model was successfully applied to Siam weed with little modification, the EHB application required a different model to be designed to account for important features in this type of invasion, where the main habitat of the pest is pine forest but the damage occurs to households.

Results of the Siam weed application indicated that, given our best estimates of costs and damages and without a budget constraint, it would be optimal to eradicate the invasion even when it covers several million hectares. The model prescribes that the current extent of the invasion (about 15,000 hectares) should be the target of eradication and the estimated cost is $18 million in present-value terms. However this is a deterministic estimate and does not account for the probability of failure.

Our findings from the EHB application indicate that any form of control of the current outbreak is preferable to no control at all, based on the damages to Western Australia relative to the cost of control. This result is based on a combination of best estimates available and plausible values for unknown parameters due to the difficulty in deriving some values. It should be noted that results are compatible with an existing benefit-cost analysis of the EHB EPPRP.

An issue for discussion with the EHB team is the treatment of fixed annual costs and the prospect for them to decrease based on the extent of the invasion. For all control packages we assumed a constant expenditure of $4.8 million per year throughout the 100-year simulations. This is based on current programme costs but it could decrease as eradication is approached.

The reduction over time in infested forest and susceptible houses exhibits an exponential decay pattern (i.e. Figure 20H). This is because the parameters that drive these changes (γ_{prot}, γ_{harv} and γ_{hyg}) are expressed as proportions of the state variables. An alternative would be to express them as absolute quantities, this would allow them to be related more directly to the budget available.

In this report we have presented simulation results for EHB with no optimisation. Analytical solution of the EHB model in not possible and numerical solution is not trivial because of the presence of three state variables. But this should be pursued when the EHB team agrees on parameter sets to be used.

The EHB mathematical model (Appendix C) contains stochastic-shock parameters (ρ_x , ρ_h and ρ_x) that affect the magnitude of state transitions. In our deterministic simulations we kept those parameters constant at a value of 1. Future work should involve stochastic simulations to derive the transition probability matrices required to solve the stochastic dynamic programming model. This will require us to understand the types of stochastic shocks that need to be considered and possible correlations between them.

Recommendations:

1. We recommend that the decision tool developed here be used by managers before considering a full benefit-cost analysis of an invasion to identify the kinds of costs and damages involved and the sorts of budgets that may be required for eradication.
2. The basic decision model has solid scientific foundations, but it prescribes eradication even for very large infested areas, as it is based on minimising damages + costs with no budget constraint. The constrained version of the optimisation model needs to be developed to make the model more applicable to the real world where biosecurity resources can be severely limited.
3. Once the constrained model is derived it should be applied to Siam Weed in close collaboration with the programme team to help develop a tactical management approach. This would benefit the Siam Weed programme but is also likely to have spinoffs that improve the management of invasions in general.
4. Regarding European House Borer (EHB), we recommend that the EHB team, with the assistance of the simulation model developed in this project, agree on sets of parameter values to be used in further analysis. This should be followed by scenario analysis of alternative policies in stochastic mode, so that realistic expectations are derived that account for the probability of failure.
5. Following up from 4 but requiring additional effort is the recommendation that the state-based optimization model for EHB be developed. This will provide the EHB team with a tactical management tool that is robust to random shocks in the state of the invasion.
6. At a more general level, the difficulty of extracting data, even when they exist in internal databases, needs to be addressed. This is a common problem in State and Commonwealth agencies, which is caused by the limited availability of staff with the required skills to manage and extract spatio-temporal data. This can be addressed by developing protocols for data sharing that account for security concerns while at the

same time allowing data access to teams with the specialised skills needed to make the best out of the information available.

7. Finally, the information required for decision models is often unavailable and the reason is that it was not recorded at the time, even when this would have been easy. It would be worth holding a series of workshops to come up with lists of data that should be recorded and protocols for storing and sharing them.

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9. Appendix A: The Switching Point Model

Consider the case of a managed invasion of size x_t at time t and a control that can reduce the invasion by an amount u_t per unit applied. The total invasion cost at any time (R_t) is the sum of damages (D_t) plus control costs (C_t):

$$R_t = C_t + D_t \equiv R(x_t, u_t) \qquad (1)$$

This indicates the assumption that the total invasion cost at any time can be fully described by the values of the state (x_t) and control (u_t) variables during that time period.

The objective is to minimize the present value of an infinite stream of future total costs

$$\min_{u_t} J = \sum_{t=0}^{\infty} R(x_t, u_t)\eta^t \qquad (2)$$

subject to the state transition

$$x_{t+1} - x_t = f(x_t) - u_t \qquad (3)$$

x_o Given

where:

$$\eta = \frac{1}{(1+\delta)} \qquad (4)$$

is the discount factor for the given discount rate δ.

The growth function $f(x_t)$ and the total cost function $R(\bullet)$ are later given explicit functional forms, but first we will derive the first order conditions for optimisation for the general case. The Lagrangean for this problem is:

$$L = \sum_t \eta^t \left[R(x_t, u_t) + \eta\lambda_{t+1}\left[x_t + f(x_t) - u_t - x_{t+1}\right]\right] \qquad (5)$$

The first order conditions are:

$$\frac{\partial L}{\partial u_t} = \eta^t \left[\frac{\partial R}{\partial u_t} - \eta\lambda_{t+1} \right] = 0 \qquad (6)$$

$$\frac{\partial L}{\partial x_t} = \eta^t \left[\frac{\partial R}{\partial x_t} - \eta\lambda_{t+1}\left[1 + \frac{df}{dx_t}\right] - \lambda_t \right] = 0 \qquad (7)$$

$$\frac{\partial L}{\partial [\eta\lambda_{t+1}]} = \eta^t \left[x_t + f(x_t) - u_t - x_{t+1}\right] = 0 \qquad (8)$$

The term $\eta_t\lambda_t$ in (7) comes from backing up one time period, when all terms have t-1 subscripts except for the last term in (5).

Rearranging we obtain:

$$\frac{\partial R}{\partial u_t} = \eta \lambda_{t+1} \qquad (6a)$$

$$\eta \lambda_{t+1} = \frac{\lambda_t - \dfrac{\partial R}{\partial x_t}}{1 + \dfrac{df}{dt}} \qquad (7a)$$

$$x_{t+1} - x_t = f\left(x_t\right) - u_t \qquad (8a)$$

The left-hand side of (6a) is the marginal invasion cost of an additional unit of control and under optimal management this must equal the marginal invasion cost of an additional unit of invasion in the following time period (discounted to the present). (See below for the interpretation of λ)

Setting (6a) = (7a) and rearranging we obtain:

$$\lambda_t = \frac{\partial R}{\partial x_t} + \frac{\partial R}{\partial u_t}\left[1 + \frac{df}{dx_t}\right] \qquad (9)$$

The first term on the RHS of this equation is the marginal cost of an increment in the invasion size at time *t*, the second term on the RHS captures the future costs by considering the effect of control on future population size. The lagrangean multiplier λ_t represents the cost of a unit of invasion (measured in area, biomass or whatever) when the invasion is optimally managed.

In the economics literature λ is interpreted as a “shadow price”, representing the ‘true’ price of a unit of a resource that considers future consequences of present actions. In our case λ is a “shadow cost” that represents the marginal cost of the invasion now plus the future marginal cost of allowing the invasion to grow.

The left-hand side of (7a) is the total invasion cost cost of an additional unit area invaded, the first term on the right-hand side is the marginal net cost of an additional are invaded and the second term is the (discounted) future net cost of an additional area invaded.

In steady state $\lambda_t = \lambda_{t+1} = \lambda$ and the first order conditions (6a) to (8a) simplify to:

$$\eta \lambda = \frac{\partial R}{\partial u} \qquad (6b)$$

$$\eta \lambda \left[\delta - \frac{df}{dx}\right] = \frac{\partial R}{\partial x} \qquad (7b)$$

$$u_t = \max\left\{f\left(x\right), 0\right\} \qquad (8b)$$

Equation (7b) was obtained by substituting (4) into (7a) and rearranging. Equation (8b) states that in order to maintain a steady state the control must exactly equal the growth rate (for the case $f(x) \geq 0$), if $f(x) < 0$ the population is on its way to natural extinction and no control is required (u_t=0).

Substituting (6b) into (7b) and rearranging we obtain:

$$\frac{df}{dx}+\frac{\partial R/\partial x}{\partial R/\partial u}=\delta \tag{10}$$

This is the equivalent to the fundamental relation of natural resources (Conrad 1999, p14) and along with equation (8b) it defines the optimal steady state values of *x* and *u*.

Now consider the following simple but plausible functional forms for the growth, damage and control cost functions:

$$f(x_t)=\alpha x_t\left(1-\frac{x_t}{\kappa}\right) \tag{11}$$

$$D_t=\beta_D x_t \tag{12}$$

$$C_t=\beta_C u_t \tag{13}$$

$$\Rightarrow R_t=\beta_D x_t+\beta_c u_t \tag{14}$$

The spread function is given by (11) as a logistic equation with specific growth rate α and carrying capacity κ. The cost and damage functions are linear in (12) and (13), the simplest possible form. If we measure the state of the invasion (x_t) in hectares, then cost and damage coefficients (β_C and β_D) are expressed as $/ha and are independent of the size of the invasion. Substituting (14) into the fundamental equation (10) yields:

$$\alpha\left[1-\frac{2x_S}{\kappa}\right]+\frac{\beta_D}{\beta_C}=\delta$$

Rearranging:

$$\beta_D+\alpha\left[1-\frac{2x_S}{\kappa}\right]\beta_C=\delta\beta_C \tag{15}$$

The LHS of (15) is the marginal benefit of removing one extra unit of pest. It consists of the avoided damage (β_D) and the avoided cost of removing the pest in the future. The RHS of (15) is the marginal cost of removing one extra unit of pest; it is also the opportunity cost (forgone interest) of the removal expense.

The switching point (also known as a Skiba point in the literature), is given by the intersection of the marginal benefit (MB) and the marginal cost (MC) curves as represented in Figure A1. That intersection corresponds to the equality in (15).

The switching point is derived from equation (15) as:

$$x_S=\frac{\beta_D+(\alpha-\delta)\beta_C}{2\beta_C\alpha}\kappa \tag{16}$$

Under the linear cost and damage assumptions, the objective function is not convex so the FOC do not result in an interior minimum. The solution results in bang-bang control, where control switches between corner solutions.

At any given time, if the infestation is at $x_t < x_S$, then MB > MC and the pest should be removed, leading to eradication.

At any given time, if the infestation is at $x_t > x_S$, then MB < MC and the pest should be allowed to spread.

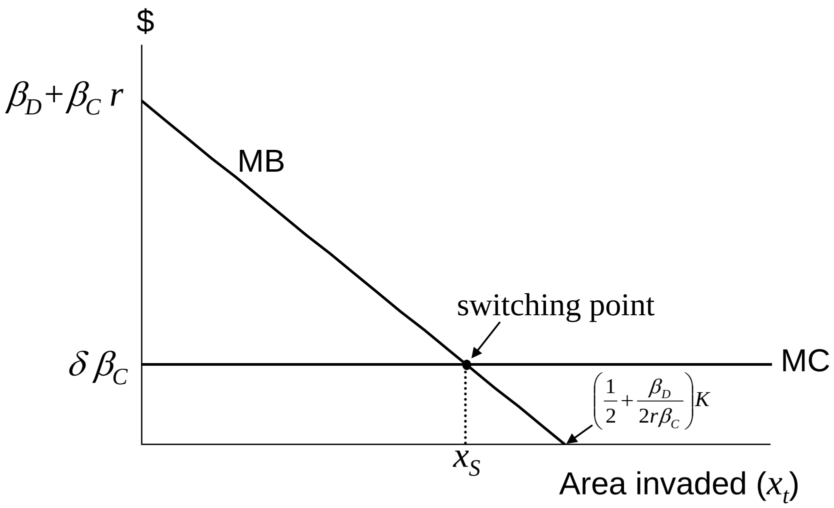

Figure A 1. Graphical representation of equation (12) and the location of the switching point

10. Appendix B: Derivation of the present value of eradication cost

Because control costs and damages caused by invasive species occur in the future, their values must be discounted into *present values* to accurately assess the opportunity cost connected with future spread and control of the pest. The present value is the equivalent value today of a future payment, *FV*. The standard formula for calculating the present value, *PV,* of a series of constant future payments is:

$$PV = FV\left(\frac{1-(1+\delta)^{-t}}{\delta}\right) \qquad (1)$$

where δ is the discount rate (%) and t is time, generally measured in years. In our model t represents the number of years that a site needs to be re-visited after the initial treatment.

To calculate (1) from standard discounting formula $PV_t = FV\frac{1}{(1+\delta)^t}$:

Expand standard formula to show the terms as a finite geometric series, note that FV is constant:

$$PV = FV\frac{1}{(1+\delta)} + FV\frac{1}{(1+\delta)^2} + \ldots + FV\frac{1}{(1+\delta)^t} \qquad (2)$$

For simplicity, $\eta = \frac{1}{(1+\delta)}$:

$$\rightarrow PV = FV\eta + FV\eta^2 + \ldots + FV\eta^t \qquad (2a)$$

Multiply both sides of the above by α (this is the geometric series trick):

$$PV\eta = \eta(FV\eta + FV\eta^2 + \ldots + FV\eta^t)$$

$$\rightarrow PV\eta = FV\eta^2 + FV\eta^3 + \ldots + FV\eta^{t+1}) \qquad (3)$$

Subtract (3) from (2a) and get:

$$PV - PV\eta = FV\eta - FV\eta^{t+1}$$

$$\rightarrow PV(1-\eta) = FV\eta\,(1-\eta^t)$$

$$\rightarrow PV = \frac{FV\eta\,(1-\eta^t)}{(1-\eta)}$$

Substitute for η:

$$PV = \frac{FV\left(\frac{1}{1+\delta}\right)\left[1-\left(\frac{1}{1+\delta}\right)^{t}\right]}{1-\left(\frac{1}{1+\delta}\right)} \tag{4}$$

Equation (4) can be simplified as follows:

$$PV = FV\,\frac{\left(\frac{1}{1+\delta}\right)\left[1-\frac{1}{(1+\delta)^{t}}\right]}{\frac{1+\delta-1}{1+\delta}}$$

$$\rightarrow PV = FV\,\frac{\left(\frac{1}{1+\delta}\right)\left[1-\frac{1}{(1+\delta)^{t}}\right]}{\frac{\delta}{1+\delta}}$$

$$\rightarrow PV = FV\,\frac{1-\frac{1}{(1+\delta)^{t}}}{\delta}$$

$$\rightarrow PV = FV\left(\frac{1-(1+\delta)^{-t}}{\delta}\right) \text{ which is the same as (1)}$$

11. Appendix C: The European House Borer Model

The present value of the total cost of the infestation for a planning period of T years is:

$$TC(T) = \sum_{t=1}^{T} \left[C_t(x_t, h_t, \mathbf{u}_t) + D_t(x_t, h_t, y_t, \mathbf{u}_t) \right] (1+\delta)^{-t} \tag{1}$$

Where Annual costs (C) and damages (D) are functions of the three state variables (x_t, h_t and y_t) and a control vector $\mathbf{u}_t$; and δ is the discount rate. The control variables contained in vector $\mathbf{u}_t$ are:

u_1 = building restrictions within area at risk
u_2 = early harvest of softwood plantations
u_3 = forest hygiene activities
u_4 = house protection (timber replacement)

The changes of x_t, h_t and y_t through time are described by state transition equations, one equation per variable:

$$x_{t+1} - x_t = f_x(x_t, h_t) - g_x(\mathbf{u}_t) \tag{2}$$

$$h_{t+1} - h_t = f_h(x_t, h_t) - g_h(\mathbf{u}_t) \tag{3}$$

$$y_{t+1} - y_t = f_y(h_t) - g_y \tag{4}$$

x_0, h_0, y_0 given

The growth rates of the state variables are given by:

$$f_x = \alpha_x x_t \left(1 - \frac{x_t}{\theta_x}\right) m_h \rho_x \tag{5}$$

$$f_h = \alpha_h h_t \left(1 - \frac{h_t}{\theta_h}\right) m_x \rho_h \tag{6}$$

$$f_y = \alpha_y h_t m_y \rho_y \tag{7}$$

Where α_i and ρ_i are growth rates and random disturbances, respectively, for $i=x, h,$ or y; θ_x is the total area of softwood forests; θ_h is the total number of susceptible houses; and m_x, m_h and m_y are multipliers that account for risk of cross infestation between forests and houses. Equations (5) and (6) are standard logistic growth functions that are subject to random variation and scaled based on cross-infestation risk. Equation (7) differs from others, as the growth parameter (α_y) represents the fraction of houses at risk that will become infested at saturation (when $h_t = \theta_h$).

We have no information on the shape of the cross-infection risk multiplier functions. We assume plausible monotonically increasing nonlinear functions to make the model operational:

$$m_h = h^{\mu_h} \tag{8}$$

$$m_x = x^{\mu_x} \tag{9}$$

$$m_y = \left(\frac{h_t}{\theta_h} \right)^{\mu_y} \quad (10)$$

with μ_x, μ_x, $\mu_x > 0$.

The functional forms of (8) and (9) imply that the multiplier $m_i = 1$ when its corresponding state variable $i = 1$. This is not correct for the case when $i = 0$ because equations (5) and (6) would result in zero growth, but this problem does not arise in the simulations presented here. A better understanding of the risk of cross-infection is required to refine this relationship. Equation (10) implies that the probability of a house within the area at risk becoming infested (m_y) increases as the proportion of susceptible houses that are at risk increases. This is also an arbitrary but plausible function.

The control functions from (5), (6) and (7) are:

$$g_x = u_2 \gamma_{harv} x_t + u_3 \gamma_{hyg} x_t \quad (11)$$

$$g_h = u_4 \gamma_{prot} h_t + (1\text{-}u_4) \gamma_{repair} y_t \quad (12)$$

$$g_y = (1 - u_4) \gamma_{repair} y_t + u_4 \gamma_{prot} y_t \quad (13)$$

Where γ_{harv} is the fraction of forest area that is harvested per year, γ_{hyg} is the fraction of forest that is subject to hygiene activities (clearing of dead wood) and γ_{prot} is the fraction of houses at risk that becomes protected from infestation because of roof/timber replacement each year.

The cost function applies when a control program exists and is defined as:

$$C_t = u_1 \gamma_{new} C_{restrict} h_t + u_2 \gamma_{harv} C_{harv} x_t + u_3 \gamma_{hyg} C_{hyg} x_t + u_4 C_{fix} \quad (14)$$

The components of this equation in order of appearance are:

- the cost of building restrictions in the area at risk;
- the cost of early forest harvest;
- the cost of forest hygiene; and
- fixed program costs.

The damage function is:

$$D_t = (1 - u_1) \gamma_{new} C_{restrict} \theta_h + C_{inspect} h_t + \gamma_{prot} C_{prot} h_t + C_{Vloss} h_t + C_{pub} h_t + (1 - u_4) \gamma_{repair} C_{prot} y_t + (1 - u_4) C_{pallet} \quad (15)$$

The components of this equation in order of appearance are:

- the cost of building restrictions throughout WA that would apply if a control program does not exist, which means the stock of susceptible houses will not be allowed to grow;
- the cost of house inspections in the area at risk;
- the cost of house protection by replacing softwood in the area at risk;

- the loss of land value within the area at risk;
- the cost of damage to public property within the area at risk;
- the cost of repairing infested houses when a control program does not exist;
- the cost of replacing pallets for interstate trade when a control program does not exist.

The cost and damage parameters are:

$C_{restrict}$: the cost of building restrictions (\$/house) measured as the additional of building a non-susceptible house.

C_{harv}: the cost of early harvest of pine plantations (\$/ha infested)

C_{hyg}: the cost of increased forest hygiene and clean-up of affected areas

C_{fix}: fixed annual costs (admin etc) (\$/yr)

$C_{inspect}$: cost of annual house inspections (\$/hh)

C_{prot}: cost of protecting houses through timber replacement (\$/hh)

C_{vloss}: loss in property value for houses located within are at risk (\$/hh)

C_{pub}: cost of fixing and protecting public infrastructure, such as hospitals, school and halls, in area at risk (\$/hh)

C_{pallet}: cost of treating pallets (\$/pallet)

One of the largest damages comes from the implications of an EHB incursion on interstate trade – all softwood leaving WA would need to be treated to allow entry into other Australian states and territories. The value of the damage appears largest for softwood pallets that are commonly used in transportation of goods. A number of these pallets would need to be permanently treated at a cost of C_{pallet} (\$/yr) for use in interstate trade.

Finally, actions by the public and government will affect the maximum areas at risk θ_i. The amount of forest will change depending on the rate of harvest relative to the rate of replanting:

$$\theta_x = (1 + \gamma_{plant} - u_2 \gamma_{harv})\theta_x \qquad (16)$$

The maximum number of susceptible houses will change depending on the number of new houses built with untreated pine, the number of existing houses that become protected, and the number of infested houses that are repaired.

$$\theta_h = \theta_h + u_1 \gamma_{new}(\theta_h - h_t) - u_4 \gamma_{prot} h_t - (1 - u_4)\gamma_{repair} y_t \qquad (17)$$