SCENARIOS FOR ALIEN INVADING WOODY PLANTS

RA Chapman • DC Le Maitre

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SCENARIOS FOR ALIEN INVADING WOODY PLANTS

Compiled by :
RA Chapman and DC Le Maitre
Division of Water, Environment and Forestry Technology,
CSIR
P O Box 395, Pretoria 0001

and

DM Richardson
Institute for Plant Conservation
University of Cape Town

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EXECUTIVE SUMMARY

Previous research has shown that there are approximately 10 million hectares , or 8% of South Africa, invaded to some extent by alien woody plants. The invaded area is expanding rapidly, at a rate of perhaps 5% per year, leading to a doubling of invaded area in 15 years. Their impact in South Africa is particularly deleterious, using an additional 3300 million cubic metres of water per year, or 7% of South Africa's runoff.

Control and removal of the aliens is enormously expensive according to some relatively crude calculations, upwards of R600 million per year over 20 years will be required in order to bring the problem under control using current removal practices. Financial resources will be quite limited however and the use of any such money would have to be targeted carefully so as to maximize return on investment.

Purpose of This Study

The purpose of this study therefore is to investigate ways of achieving efficient use of limited resources. Principally, the aims of this project were to develop techniques for estimating:

1. How much money will be required to achieve effective control of water using invasive plants in the different provinces in South Africa?

2. How long will it take to achieve significant reductions in water lost due to alien invasion resulting from varying rates of expenditure on control?

3. What impact biological control will have on control costs in the long term.

In order to achieve these objectives one must know something about how fast the alien invaders are spreading and to what limits they can spread. These numbers are key parameters and variables of a modelling exercise. Different environmental conditions controlling the spread of aliens may operate in the future that do not operate at present. So a methodology was required to cope with changing futures. Apart from that, very little data exists on spread rates and it is very difficult to set a limit to what areas may be invaded. Consequently, the problem was approached by developing scenarios for alien invasion, in which the state of invasion in South

Africa 20 years hence was examined

The Process of Scenario Development

Scenarios are stories told about the future. Scenarios describe the possibilities of arriving in the future via a variety of trajectories or paths. These trajectories are influenced by "large scale forces" which "push the future" in different directions. The development of scenarios is not arbitrary or trivial, but involves a structured process, beginning with the focal issue, that is, the condition which South Africa finds itself in with regard to invasions by woody plants 20 years hence.

The process then included identification of all the driving forces which affect invasion. Those driving forces about whose direction of action (whether promoting invasion or retarding it) there exists uncertainty were extracted as key uncertainties. These key uncertainties became the logics around which the scenarios were developed. Logics control the themes in each scenario. The logics developed in this study are based on 1) the "strength of the South African economy" and 2) the "character of implementation of laws, policies and regulations" governing alien plant material (see Figure i).

Figure i. Scenario logics and the logic names.

Scenarios were written for each of the four quadrants created by the logics. These attempt to convey the essence of what the future would look like with regard to alien invasion. An attempt was then made at developing the implications of these scenarios and what they meant for the key questions in terms of limiting area and rate of spread.

Conclusions from the Scenario Development Process

Three key conclusions and recommendations arise from this study:

1) A coherent set of laws, policies and regulations that control the import and distribution of invasive species needs to be rigorously and comprehensively implemented. This could be developed through a national weeds strategy or the development of a National Weeds Act;
2) Biological countermeasures can offer a very cost-effective solution to continuing invasion, continued investment is required for this to take place;
3) Control measures should not be delayed but be implemented now, as delays lead to rapidly increasing costs of future control efforts and
4) The ecology and economics of invasions are not well understood and the subject requires further research.

The regulatory environment governing the import of foreign biota, and its implementation, is where South Africa has the potential for the greatest leverage on the arrival of new species. Strong economic conditions, while necessary to combat the spread of invasions, also encourages the arrival of new species through increased trade. A National Weeds Strategy should have its focus on managing the current alien problem in the country, but also as a means to prevent the arrival of additional potentially invasive species.

A Numerical Model for Simulating Alien Spread and Control Effort

A simulation model was also developed, which characterizes the alien invaders and the work directed at controlling them as being part of an "ecological" system, with significant feedback loops and modifiers, the key one being the amount of money spent on mechanical clearing operations. An important aspect of controlling alien invaders is that the priority for spending money within a clearing operation is on doing follow-up operations on land that has been initially cleared of aliens before continuing with initial clearing operations. Thus the larger the area that needs to be follow-up in any one year, the less money that can be apportioned to initial clearing.

Simulations show how spread progresses, and how the cost of clearing rises with time. As money is spent on initial clearing and follow-ups, the model shows how the spread of aliens is contained. By repeated simulations with varying quantities of money as input, different funding rates for clearing operations can be determined. However, this is based on the assumptions of the order in which clearing takes place - lighter infestations first, as this has been shown to be more effective than tackling the smaller dense infestations.

Applying the Simulation Model to South African Landscapes

Using the scenarios and applying these to key landscapes, such as mountain catchments, riparian zones, open commercial farmland and rural commons, "experimental" data sets are developed in which the limits and rate of invasion vary according to each scenario.

The rate of spread is highest in the riparian zones where disturbance along these linear features is caused by flooding and human influences. The mountain catchments are the next most vulnerable, especially those that are not burned very frequently (> 3-4 year cycle). In the rural commons the spread rate of woody species is low because of the intense use of alien plants by rural people for energy sources and building purposes.

The cost of clearing is tightly linked to the spread rate. Where clearing activities are delayed, future costs of clearing rise rapidly, as high as five times for a delay of 10 years in the case of riparian zone invasions. This is the primary reason why clearing should take place as early as possible. Note that in Table I, the Unit Reference Value, which is used as a means of project economic evaluation, clearly shows that there is a much higher economic efficiency to be obtained by clearing the fastest spreading alien invading plants.

Biological counter-measures (biocontrol) can have a big impact on future costs of clearing, even if biocontrol agents are not particularly efficient and only reduce the spread rate by half. Table I also illustrates this point. A point is also made that catchment managers should not rely on biocontrol agents being available to deal with invasions in situations where clearing has been delayed. Biological countermeasures should be considered as an area of research of and development of national importance.

Table I The relationship between spread rates, the investment rate to clear a specific area in 20 years and the Unit Reference Value. The simulations assume that at the end of the 20 year investment period the project area will be clear of aliens invading plants.

Spread rate r	Investment rate for clearing alien plants over 20 years (R million / yr)	URV (R / m^3)
0.38	0.35	0.01
0.33	0.32	0.02
0.25	0.27	0.02
0.15	0.20	0.05
0.09	0.17	0.07
0.04	0.14	0.10

Recommendations for Further Research

Several requirements for further research have become evident from this work. They can be broadly described as a need for a greater insight into the ecology, environmental impact, and the economics and management of invasions:

The key drivers of invasions. This includes both human dimensions as drivers of alien invasion, as well the biophysical drivers. The human dimensions include population growth, international trade links, global economic trends, the forestry and horticultural industries, land redistribution policies of government and laws, policies and regulations

Spread rates of the different species. The simulations of cost of control are sensitive to the rate of spread variable, yet there is very little data on which to develop better models. Data is also required on spread rates of species only partially controlled by biological countermeasures.

The hydrological impacts of different alien species. There are very few data on the streamflow reduction of alien species other than commercial forestry species.

The costs of clearing the different species. The simulations of the costs of control are also sensitive to alien clearing costs. Better data is required for a variety of clearing and control techniques. This includes the investment required for biological controls.

Different alien management control options. The extent of alien invasion is so large in South Africa that mechanical and chemical means will not be able to control the increase in the area invaded. Nor will biological controls solve all the problems. An example was given that judicious use of fire could be a useful technique, but this needs further research.

Further model development. The numerical simulation model has useful applications, but also requires refinement. This could come through trial use of the model and could include addition of graphics capabilities.

Conclusions

Four key conclusions and recommendations arise from this study:

1. A coherent set of laws, policies and regulations that control the import and distribution of invasive species needs to be rigorously and comprehensively implemented;
2. Biological countermeasures can offer a very cost-effective solution to continuing invasion, but other methods of control also need to be investigated,
3. Control measures should not be delayed because of the cost implications,
4. Projects for clearing alien plant invaders should use rate of spread as a means of prioritization, and
5. The ecology and economics of invasions are not well understood and the subjects need investment.
6. Both scenario development and simulation modelling offer powerful analytical techniques for better understanding alien invasion and the strategies necessary to combat invasion

Footnote

The numerical simulation model is available from RA Chapman as an executable. He can be contacted at the CSIR in Stellenbosch:

Telephone	: (021) 888 2446
Fax	: (021) 888 2684
e-mail	: achapman@csir.co.za

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Mr H Maaren	: Water Research Commission
Dr GR Backeberg	: Water Research Commission
Prof RE Schulze	: University of Natal, Pietermaritzburg
Dr G Preston	: Working for Water Programme, Cape Town
Dr J Scotcher	: SAPPI
Dr HG Zimmerman	: Plant Protection Research Institute
Mr T Willems	: Department of Water Affairs and Forestry
Ms J Coetzee	: Working for Water Programme, Cape Town

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1. INTRODUCTION

1.1 Background

Ecosystems provide vital services, such as fresh water, conservation of biodiversity, soil generation and aesthetic and cultural benefits (Ayensu *et al.* 1999). About 40 to 50% of Earth's landscape has however been transformed and irreversibly degraded by human activity (Vitousek *et al.* 1997).

In South Africa, approximately 10 million hectares, or 8% of the country, is invaded, and therefore transformed to some extent, by mostly unproductive alien woody plants (Versfeld *et al.* 1998). Their impact in South Africa is particularly deleterious, threatening biodiversity of the sub-continent (van Wilgen *et al.* 1996) and using an estimated additional 3300 million cubic metres of water per year, or 7% of South Africa's runoff (Versfeld *et al.* 1998). The country receives only half of the world average of rainfall and the region is subject to frequent droughts. Scarce water resources are already a constraint on the economic growth of the region. Sustainable development of the economy (which is so dependent on water) and protection of the environment is compromised when water consumption by invaders increases every year. The invaded area is expanding at a rate estimated at 5% per year (Versfeld *et al.* 1998), leading to a doubling of invaded area in 15 years.

Crude estimates of R600 million per year over 20 years in order to bring the problem under control using current removal practices (Versfeld *et al.* 1998). The task of control is made that much more difficult by the fact that once initial clearing of an area has taken place, the priority for expenditure switches to one of follow-up and maintenance of the already cleared area, - invading exotics are more prolific in cleared, and therefore disturbed, areas. Thus there is less money for the initial clearing of new areas.

Financial resources are quite limited in South Africa and investment in clearing would have to be targeted carefully so as to maximize return on investment. The benefits are not only water released from previously invaded areas, but also prevention of the problem worsening. The purpose of this study therefore is to investigate ways of achieving efficient use of limited financial resources.

1.2 Objectives of the Project

The aims of this project were to develop techniques for estimating:

- How much money will be required to achieve effective control of water using invasive plants in the different provinces in South Africa?
- How long will it take to achieve significant reductions in water lost due to alien invasion resulting from varying rates of expenditure on control activities?
- What impact could biocontrol have on control costs in the long term?

1.3 Research Approach

Key components of the first two objectives above are mostly characterised as rates of activity. These include the spread rate of invaders, the rate of spending on clearing programmes and the rate at which aliens can be cleared. Rate based activities suggest a modelling or numerical approach.

Alien invasions in South Africa are well established, but have not yet spread to the maximum area available. These limits are defined by a variety of factors. There are physical barriers such as mountain ranges, deserts and oceans. There are environmental controls such as moisture availability, temperature and edaphic factors. Disturbance regimes like fire can prevent spread (frequent fires kill the small shrubs). These limits can also be anthropogenic, for example the aliens are kept out of cultivated lands.

How, therefore, does one determine the area available to alien invasion? Determining this for large areas is a very difficult task. There are very few data from which to work. Further, such a study requires an insight into how fast invasions occur. It is well understood however that long distance rare events of movement of precursors is one of the prime mechanisms for invasions. Propagules of invaders must arrive in an area and survive before they can spread. The arrival of alien invaders in South Africa are a result of human activities. People have purposely brought a variety of foreign plants and propagated them here, others have arrived inadvertently.

Those brought purposely have been for their useful properties, for example timber from pines, tannins and dune covering abilities from a variety of acacias, and the aesthetic and ornamental appeal of other species like *Jacaranda mimosifolia* and *Lantana camara*. Their invasive characteristics were probably not known at the time, but some species were selected for their ability to propagate unaided. Thus the spread rates of these vegetation types has been extremely rapid because their spread has been facilitated by human interventions.

Invaders that have arrived inadvertently are a result of propagules accidentally being carried along with other materials. Examples of these include *Solanum mauritianum* (bugweed) and *Chromolaena odorata* (parafinbossie). However, once these alien plants have crossed the various barriers, they spread. Their rates of spread within the country may be deliberately acclerated or not, but they are able to do so because conditions are favourable. For example, disturbance is a common driving force for further recruitment by encouraging seed germination. Fire is a good example of this (although frequent fire can be used to control *Chromolaena odorata*).

Disturbance, human (or animal, as a result of human activity) movement of propagules, lack of competition from indigenous vegetation and other factors will play a part in aiding further spread. All these different factors lead to a high degree of uncertainty as to where and how fast aliens could establish themselves and we do not yet have the ability to predict this numerically. Further, modelling from current conditions into the future implies that the future is the same as the past, that environmental conditions influencing alien invasion will be the same in the future as they are now. We know this to be not true and need a technique to cope with changing future environments.

This report therefore presents two techniques:

- Scenarios, which describe the future environment with respect to invasion, and
- Simulations, which model the effects that varying rates of expenditure have on controlling alien invasion.

These scenarios are intended to analyse the forces that influence invasion, how they operate in South Africa and provide a picture of plausible outcomes. Scenarios are stories with a meaning, which helps explain why things happen in a certain way. They offer multiple perspectives and cope with complexity. The development of scenarios in this context is not an arbitrary process leading to uninformed predictions about the future. The scenario development process involves a consideration of many aspects of the invader problem in a disciplined way. They are developed using specific techniques that allow us to make informed predictions. An important part of this study is therefore devoted to the development of scenarios.

The objective in the simulations is to achieve optimum spending rates within a dynamic system. Aliens cannot be cleared in one single large effort in one year, they must be cleared over an extended period, during which spread and re-emergence continues. The simulation model accounts for the dynamics of this system. The scenarios will then be used to develop different "data sets" for different parts of the country, in key ecosystems. Predictions are then made on the costs of clearing according to the different scenarios.

1.4 Structure of the Report

In Chapter 2 an introduction to scenario theory and its origins is given. In this chapter we further develop reasons why scenarios can be applied to the problem of alien invaders. In Chapter 3 we then develop four scenarios for alien invaders in South Africa according to two key uncertainties. The process followed is clearly described.

In Chapters 4 and 5 we have attempted to further our understanding through computer simulation of possible futures in terms of monetary costs of removing invaders using present day technologies. In Chapter 4 the structure of the model is described and in Chapter 5 the outcomes of simulations are given. In our simulations we vary the rates of invasion, the rates being influenced by scenario outcomes.

In Chapter 6 the outcomes of the scenario developments and the simulations are discussed in terms of their implications. Chapter 7 lists a set of further research recommendations and Chapter 8 develops the conclusions.

2. DEALING WITH UNCERTAINTIES - SCENARIO DEVELOPMENT AS A TOOL

"It was ordained at the beginning of the world that certain signs should prefigure certain events" - Cicero (cited by Wilkinson 1995).

The word scenario has the same root as the word scene in the Greek word *skēnē* (Latin *scena*) meaning a covered place, or stage. In modern theatre, a scene is portion of a drama which is acted out and set in a particular location and time. Like theatrical productions, scenarios present bold and dramatic scenes within a setting that is directly relevant to the group being addressed (Wilkinson 1995). They are designed to identify and illustrate the effects of the fundamental forces that are perceived to shape the future in a world of uncertainty (Schwartz 1991). Scenarios may be dramatic but they must be plausible or creditable at the same time, because they must make the viewers recognise that their current preconceived idea or 'mental map' of the future is only one of several plausible futures (Wack 1985; Schwartz 1991). If the onlookers do not become participants then it is very difficult to get them to reconsider their mental maps thoroughly and to take appropriate actions (Wack 1985). Scenarios can be used for short-term planning, but most applications have been aimed at helping decision makers take a long-term view. The aim of scenarios is not to make precise predictions of the future but rather to create plausible futures and to help people "*make better decisions today*" for a likely future (Wilkinson 1995).

The next section gives more background on the development of scenario planning and why it is appropriate to use it to examine the problems posed by invading alien plants.

2.1 Development of Scenario Planning

Scenario planning has roots in the Second World War where it was used to develop new tactics for the military. The methodology later came to the fore through Royal Dutch/Shell, who developed the technique further in the 1970s as a tool for thinking about the future and adapting mental models of the oil industry (Leemhuis 1985, Wack 1985, De Geus 1988, Kahane 1992). Their scenario planning was successful in changing management attitudes towards the business environment of the oil industry at the time.

By the late 1960s managers of oil companies, including Royal Dutch/Shell, believed that the world demand for oil in the 1970s would continue to grow as rapidly as it had since World War II *and* that the producers would continuously increase supply to meet demand (Wack, 1985), i.e. the future would be the same as the past. The development of long-term planning processes in Royal Dutch/Shell showed, however, that (a) a number of producers could not continuously absorb the increasing oil revenues; and (b) the demand projections implicitly required "miracle" new oil-field discovery and development (Wack 1985). It would not make sense for the producers to invest oil revenues when inflationary processes would erode their value. Therefore it would be to their advantage to cut production, conserve their resources and let prices rise. This analysis identified all the warning signs, but failed to change company direction and thinking. It was only the subsequent adoption of the scenario approach and its development as scenario planning that initiated major changes in management attitudes and decisions. These enabled the company to anticipate and be better prepared for the oil crisis of 1973 than other companies (Wack 1985, De Geus 1988, Kahane 1992).

A well-known local use of scenarios are those developed by Sunter (1987), entitled "*The World and South Africa in the '90s*". These scenarios, named "*High road*" and "*Low road*", have now passed into everyday language of a significant portion of people concerned with high level decision-making in South Africa. They also enabled many people in South Africa to see a range of possible futures for the country and themselves, and allowed them to develop alternate views about what was needed to avoid a descent into economic and social chaos (Esterhuyse 1992). The *Mont Fleur* scenarios were developed by a South African team to look at possible political futures for the country depending on different outcomes of the transition process (Le Roux *et al.* 1992). These scenarios influenced the outcome of the negotiations and many of the features of the preferred *Flight of the flamingo* scenario, i.e. negotiated settlement, rapid transition, and a delicate balance between tight economic management and social delivery, have been achieved.

2.2 Features of the Scenario Planning Process

As a result of the Shell success story scenario planning has become an important technique for anticipating major shifts in the business environment (Wilkinson 1995). It differs from prediction, which has fallen out of favour, because prediction can only be effective when the future resembles the past, i.e. when the same forces that determine the shape of one period are still at work in the same way during some later period (Wack 1985). Scenarios describe possibilities only, and not certainties or probabilities (Sunter 1987). It also differs from prediction because the emphasis is on highlighting and understanding the effects of the large-scale forces that push the future in different directions rather than the details of that future (Wilkinson 1995). The range of possible future worlds described in a set of scenarios is thus defined by the outcomes of the important elements at work now that could create those worlds.

Scenario planning is a structured approach to a core or focal issue that is a major concern for a group or organisation (Wack 1985). It distinguishes between certainties, such as predetermined trends, and uncertainties in the social dynamics and economic, political and technological issues relevant to a major concern (focal issue) of that group or organisation. It is these uncertainties that make the future inherently unpredictable and are the *raison d'etre* of the scenario development process (Wilkinson 1995). This first stage is not sufficient though. Descriptions of the alternative outcomes of a wide range of uncertainties merely lead to "first generation" scenarios. These are not helpful to decision makers because they cannot assess and use this array of uncertainties as a basis for strategic thinking or making decisions (Wack 1985). However, they do help to develop a greater understanding of the system being studied and they are a necessary step in the development of "second generation" scenarios, the "decision scenarios". These decision scenarios are developed through a process of grouping and ranking the uncertainties to reduce their effects to a small, easily assimilated set of outcomes or plausible futures. In assessing risks, one needs to take a broad as well as a narrow focus. Focussing on narrow issues creates the possibility of missing the larger issues which contain key driving forces.

Truly effective scenarios must change the prevailing view of reality, and question assumptions about the way the world works (Wack 1985). In Schwartz's (1991) words: "*This approach [scenario development] is a more disciplined way of thinking than a formal methodology*". They should provide an effective framework within which people can ask themselves the right questions, debate the future and act upon their judgements (Sunter 1987). Scenarios are vehicles for helping people to learn, they allow people to act with a knowledge-based sense of risk and reward (Schwartz 1991). The test of a good scenario is whether it enables an organisation to adapt and learn; to do this it must challenge and change the decision-makers assumptions (de Geus 1988).

The successful use of scenarios in planning thus requires that: (a) they are based on a sound analysis of the existing realities; and (b) they challenge and change the decision makers' assumptions about how the world works. Scenarios should prepare people to approach the future with a more open mind, alert to the warning signals about the driving forces, in short, they are about rehearsing for the future (Wilkinson 1995).

2.3 How Are Scenarios Relevant to the Problem of Alien Invaders?

2.3.1 Uncertainties in invasions

Many features of biological invasion are highly uncertain, but have a number of features which however lend themselves to scenario analysis. Many species are introduced and may even grow well in cultivation, but few will become naturalised (Wells *et al.* 1986, Hughes 1995, Mack 1995). In some cases this can be explained in terms of the features or traits of the environment and the species involved, but in many cases it cannot and there are many uncertainties or apparently unpredictable factors involved in this phenomenon (Noble 1989, Richardson & Cowling 1992, Mack 1995, Mollison 1996, Rejmanek & Richardson 1996, Higgins & Richardson 1998). Most introductions are deliberate but many, including some of the most harmful and costly, have been accidental (Vitousek *et al.* 1996, 1997, Bright 1998). In some cases there are long delays between introductions and the first observations of invasive tendencies; the underlying causes of these delays are not always well understood (Hughes 1995). In some cases invasions have been quite idiosyncratic. For example, the establishment of mutualistic relationships with local pollinators, seed dispersers or mycorrhizal fungi has been critical for successful invasions (Richardson *et al.* 1999). In some cases the introduced species have had totally unanticipated side effects which are very difficult to predict (Vitousek *et al.* 1997, Bright 1998). Thus, although it is clear that introductions of exotics inevitably will lead to invasions by some species, the timing, nature and severity of those invasions and the identities of the species involved are not predictable.

The picture of alien invaders is not all uncertainties though. The major driving forces that influence invasions have been the subject of a number of studies and reviews (e.g. Kruger *et al.* 1986, Noble 1989, Vitousek *et al.* 1997a, Richardson *et al.* 1999). These analyses have identified a number of driving factors that facilitate invasions and have clarified their roles and dynamics, even if their outcome in a given situation is unpredictable. The driving forces will be dealt with in greater detail below.

Another feature of scenario analysis is that it lends to dealing with the 'big hairy problems' that are very difficult to grasp and that people are wary of even considering. Invasion by exotic species are a classic example of this kind of problem. Alien invaders have a wide range of impacts, often very severe (Bright 1998). One example is the direct and economic costs of invasions to society. Alien species in range (pasture) and crop lands in the USA are estimated to cost that country USA US$5 billion for control and $7 billion in lost productivity each year and the total costs to the USA economy may exceed $123 billion per year (OTA 1993, Bright 1998, USDOI 1998, USA 1999). The extent of invasions was estimated to be increasing at about 14% per year (USDOI 1998). The total costs on controlling invading plants in natural environments alone in South Africa could be as high as R5.4 billion over 20 years (NPV) or R600 million per year (Versfeld *et al.* 1998). The invaded area in South Africa is estimated to be increasing at about 5% per annum, which means that size problem could double in 15 years if nothing is done (Versfeld *et al.* 1998). Invading trees and shrubs are also estimated to be using about 6.7% of the total surface water resources of South Africa, more than twice that of commercial forestry which has been tightly regulated since 1972 because of its water use. These figures show that alien plants can, and do, have significant economic impacts (Versfeld *et al.* 1998).

2.3.2 "Long fuse - big bang problems"

Human beings are not very good at detecting gradual changes, they tend to overlook changes until the cumulative effects finally cause a reaction. Likewise, organisations often fail to detect obstacles that initially develop slowly or undergo an extended delay or gestation period before manifesting themselves. These have been aptly termed "*long fuse, big bang problems*" (Wilkinson 1995) and are often "*life or death*" to that organisation. For example, it can take years for one to learn whether the decisions made at a point in time were wise or not. These issues and the questions about them also don't lend themselves to traditional analysis because key uncertainties, which can determine the success or failure of decisions, cannot be resolved by research (Wilkinson 1995). However, these same uncertainties can lend themselves very well to a scenario analysis.

Invasions by exotic species often can be described as "*long fuse - big bang problems*" or as 'quiet opportunists, spreading in a slow motion explosion' (USDOI 1998); those with trained eyes may notice that odd individuals of an exotic species are appearing in areas where they were not planted; those with untrained eyes may not notice anything amiss at all. And then the species 'suddenly' starts cropping up all over the place. This 'surprise' phenomenon is typical of exponential growth patterns in many things such as populations or compound interest on a bank overdraft (Cronk 1995). One explanation for this apparent delay or lag is in the nature of the exponential growth process itself . In an exponential curve, the rate of change per unit time (i.e. the relative growth rate) is constant *but* the absolute change in total population size per unit time increases exponentially. For example, if one starts with 100 individuals, by year two there are 110 individuals, an increase of 10, but in year thirty the increase is 1600 individuals, more than 10 times greater. The initially slow net growth in numbers is deceptive (e.g. years 1-10) and gives the impression of a 'lag' between the start of the process and the present situation. Another explanation is that population growth sometimes does undergo a real lag phase which lasts until conditions favour rapid or mass recruitment. This may happen when seed banks build up and are cued to germinate and establish seedlings by infrequent events such as fires or floods. Invasions by *Mimosa pigra* in northern Australia followed the dispersal of seeds from a riparian population into overgrazed floodplain areas during the high rainfall years of the mid-1970s and the subsequent mass recruitment (Lonsdale & Braithwaite 1988, Lonsdale 1993). The net result was the replacement of about 45 000 ha of grassland by dense to scattered shrublands in about six years (Braithwaite *et al.* 1989, Lonsdale 1993). Similar rapid invasions during wet periods have been recorded for *Acacia nilotica* (Carter 1994) and *Tamarix aphylla* (Griffin *et al.* 1989) in Australia.

Invasions by *Sesbania punicea* and *Prosopis* species in South Africa show the same pattern of sudden expansions. *Sesbania* was known from several localities across the country by 1920, but it was not identified as a weed prior to the 1960's; yet by 1966 it was recognised as an invader and by the mid-1970s as a major invader (Hoffman & Moran 1991). The cause of this rapid change in status is not known. *Prosopis* species were introduced as fodder plants in the late 1800s and were widely planted by the 1930s (Keet 1929, Harding & Bate 1991). A botanical survey of part of the Northern Cape from 1957-63 did not mention *Prosopis* as being naturalised and invasions first became obvious after the mid-1970s (Henderson 1991). The rapid expansion seems to be related to the high rainfall years of 1974 and 1976 (MacDonald 1985, Harding & Bate 1991, Henderson 1991).

2.4 Understanding the driving forces and the associated uncertainties

In writing scenarios it is essential to develop or build a model of how the system is driven. In the case of invasions by exotic species there is a substantial body of literature on alien invasions which has attempted to identify why some invaders succeed and others do not (Kruger *et al.* 1986, Noble 1989, Richardson & Cowling 1992; Rejmanek & Richardson 1996, Higgins & Richardson 1998). Many of these reviews have examined the traits of the species itself or those of the environment or habitat that is invaded or both (e.g. Kruger *et al.* 1986, Noble 1989)). In simple terms, successful invaders are those that are able to overcome the geographic, habitat and biotic barriers (Kruger *et al.* 1986[1]). The geographic barrier is discussed in the next section. To surmount the habitat barrier the invading plant species generally must be pre-adapted, or be readily able to adapt, to the local or regional climate (growing conditions - mainly temperature and rainfall distribution), soils (water holding and nutrient availability), and natural disturbance regimes such as fire frequencies and flooding (Pickett & White 1985, Kruger *et al.* 1986). To overcome the biotic barrier the plants generally must have a suite of traits that enables them to become victors in biotic interactions with local species / communities (e.g. competition), produce and disperse large numbers of propagules (e.g. Gill & Neser 1984; Weiss & Milton 1984; Dean *et al.* 1986), which are widely dispersed (Kruger 1977; Richardson & Brown 1986; Richardson *et al.* 1992, Rejmanek & Richardson 1996), and become the dominant species (e.g.

[1] See Richardson *et al.* in press for a more detailed discussion of barriers.

Richardson & van Wilgen 1984). Because of the variety of habitats, each with their own combination of factors affecting spread rates, it is impossible to predict how fast and invasion can occur except in general terms and at landscape scales rather than field or "patch" scales.

We believe it is important not to just focus on these 'biological' factors that support or hinder invasion because the process of invasion ecology is driven by other equally important factors (Cronk 1995). Based on these studies, we recognise four closely linked and interacting, primary forces that drive the invasion process:

Arrival of new propagules - the seeds, cuttings or other parts needed for the plant to be able to establish itself; the main source of this is human activities such as colonisation, largely historical, and trade, especially during the 20^{th} century.

Disturbance regimes which are either (a) necessary to maintain the natural ecosystems but can make them more vulnerable to invasion when they are altered by human activities or climate change or (b) introduction of new forms of disturbance that disrupt natural communities.

Fragmentation of the landscape that creates extensive ecotones and corridors for invasions.

Changes in the availability of limiting factors, for example the supply of nutrients such as nitrogen or phosphorus which are often of anthropogenic origin.

Each of these is discussed in greater detail in the following sections.

2.4.1 Arrival of new propagules - the human factor

In order to colonise a new area, be it another part of a country or continent or a new continent, the propagules[2] of a species need to cross the geographic barriers that separate them (Kruger *et al.* 1986). In natural systems, propagule dispersal is typically restricted to distances of 10^2-10^3 metres and the number of propagules decreases rapidly and non-linearly, often exponentially, with increasing distance from the source (e.g. Harper 1977, Greene & Johnson 1989, 1995, Hengeveld 1989, Andersen 1991, Shigesada *et al.* 1995, Kot *et al.* 1996). The net result of this was that even 'small' geographic barriers such as mountain ranges or seaways could be highly effective at creating 'islands', each of which supported the evolution of a distinctive suite of organisms (Vitousek *et al.* 1997a, Holmes 1998). Our ancestors began to break down those geographic barriers in prehistoric times with the development of cultivated crops. For example the dispersal of rye and wheat from the Middle East across Europe and Asia with their associated weeds (Di Castri 1989, Pringle 1998). The Age of Exploration and the European colonial era accelerated this process and the pace has continued to increase ever since, especially during this century (Di Castri 1989, Heywood 1989, Bright 1998). Facilitation can be of two forms (Kruger *et al.* 1986;

[2] A propagule is the minimum component an organism requires for it to establish itself such as a seed, spore, cutting or a mature individual.

Bright 1998): (a) deliberate introduction and propagation, for example for forage, fibre, medicine, erosion or driftsand control, timber, tanbark; and (b) inadvertent introduction, for example via ship ballast, contaminated crop seeds, in or on domestic animals, soil, animal fodder 9hodginkinson & Thompson 1997). Most countries now have thousands of exotic species which have been introduced deliberately as crops for food or fibre, commercial forestry and horticulture and many species which were accidentally introduced - part of the "*MacDonaldisation*" of the world (Holmes 1998). Many of the accidental introductions have had significant economic and social impacts (Bright 1998; USA 1999).

Another of the key uncertainties is that only a small percentage (roughly 1% in Britain, Williamson & Brown 1986) of introduced species will become major invaders, even fewer succeed in natural systems and only a few of that remnant will be able to radically transform the systems they invade. For example, about 750 tree species have been introduced to South Africa (von Breitenbach 1989) and about 70 of these are considered major invaders (Henderson 1995). About 15 of these tree species (including some only named at the genus level) have invaded areas of more than one million ha (Versfeld *et al.* 1998). The problem is that it would have been very difficult to determine which ones of the 750 would become major invaders *a priori*, especially when considering the country as a whole with its diverse climates and habitats.

The critical role of anthropogenic factors in the introduction of new propagules makes the impacts incredibly difficult to predict or model because so many other factors are involved as well. Human activities are influenced by the state of the economy, political systems, international relations, cycles in climatic factors such as rainfall (droughts and floods) and markets for goods and products both local and international. Fads and fashions in the horticultural trade play a huge role in the introduction of new species. The degree of utilisation and manipulation of the environment for resources such as food, wood and fibre depends in turn on the degree of poverty, access to agricultural equipment or finance, stock management and grazing patterns. A recent trend is the development of international treaties or conventions which include some or address aspects of the problems caused by exotic species. There are currently at least 20 such treaties the best known of which is the Convention on Biological Diversity (CBD) which South Africa has signed (DEA&T 1997). The White Paper on the conservation and sustainable use of biodiversity commits the government to taking implementing the CBD and proposes a number of actions to deal with exotic organisms in line with the CBD. The problem is that there is a lack of political will to turn these words into effective actions and thus a major uncertainty about how much impact it will have. The Working for Water Programme of the Department of Water Affairs and Forestry is making a serious effort to deal with invading plants, primarily in order to conserve water. It has an annual budget of about R180 million and has generated many other benefits such as employment, training and improving the quality of community life in rural communities. There are two key uncertainties though: (a) there are many species whose control is not a high priority for this programme because they have little or no impact on water resources; and (b) the long-term political commitment is still not really in place and a change of government, or even ministers, could derail this programme. The rate of economic growth of the country could be the determining factor in the success of this programme because the money will be reallocated to other areas with higher priorities.

The history of invasions of exotic species in southern Africa is a good example of the importance of human activities. Migrations by humans have played a fundamental role in facilitating alien plant invasions with about 28 plant species, including *Ricinus communis*, probably being introduced during prehistoric times (Deacon 1986; Wells *et al.* 1986). European colonisation resulted in the introduction of a wide range of plant species for food and timber production and for horticultural purposes (Shaughnessy 1986). South Africa has always had a shortage of timber and many of the major invasive tree species in South Africa were introduced by the colonial governments and wealthy individuals in well meant attempts to find species suitable for use in commercial plantations, for example *Acacia mearnsii, Pinus pinaster, Eucalyptus grandis* (King 1943, Richardson 1996). Others were introduced and widely planted as ornamental species; these include *Melia azedarach, Jacaranda mimosifolia* and *Lantana camara* (Sim 1927). Wars have also facilitated the introduction of invaders as well as with importation of fodder (e.g. *Nicotiana glauca*) (Brown & Gubb 1986). The forestry department strongly favoured species which were able to establish with minimal, or no, site preparation (King 1943), a key trait of successful invaders. Invasions in some areas were already noted for wattle and pines (especially *P. pinaster*) within 10 years of their introduction (e.g. Anon 1902 for the Amatola and Pirie areas). Afforestation, particularly with *Acacia saligna* (and later *A. mearnsii*) for the production of tanbark, also was actively promoted during the late 1800's with competitions for the best stands (Shaughnessy 1986). By the 1930s forest nurseries were selling more than 4 million young trees per year (King 1943). State plantations were established at Tokai in 1884 using *Pinus radiata* (King 1943; Geldenhuys *et al.* 1986; Shaughnessy 1986), by 1891 in the southern Cape, and from 1882 in the Eastern Cape. In the Eastern Cape *Acacia, Pinus* and *Eucalyptus* species were promoted planted extensively and by 1900 there were 27 state plantations throughout the Eastern Cape including native trust lands (i.e. the former Transkei). Plantations are also colonised by many alien plant species, particularly *Caesalpinia, Solanum mauritianum, Rubus, Chromolaena, Lantana* and *Psidium* (Geldenhuys *et al.* 1986). The introduction of trees was undoubtedly necessary to ensure that South Africa had adequate supplies of wood, but the lack of effective mechanisms, and the political will, to deal with the consequences has resulted in a significant cost to the country as a whole (Versfeld *et al.* 1998).

2.4.2 Disturbance regimes

Disturbance regimes - namely the frequency, seasonality and intensity of the occurrence of events which perturb natural systems (Pickett & White 1985) - form part of the habitat barrier described earlier (Kruger *et al.* 1986). The 'Vital Attributes' model developed by Noble & Slatyer (1980) identifies a number of traits or attributes which are the key to surviving in environments with different disturbance factors and regimes:

(a) persistence seed banks *in situ* or the ability to colonise via effective dispersal <u>and</u> the ability to recover through vegetative means;

(b) the ability to establish immediately after disturbances, or between disturbances or both; and

(c) timing of reproductive maturation, length of the lifespan and longevity of seed (propagule) banks relative to the timing of disturbances.

Suites of attributes that guaranteed a species persistence include the ability to disperse into a disturbed area from adjacent areas and the ability to establish at any stage in the disturbance cycle. These traits are found in many successful invaders; for a recent summary of the attributes of successful invaders see Richardson *et al*. (1997). Rapid colonisation and increases in density of invasive plants are often tightly linked to disturbances. For example, fires, floods and overgrazing create areas of open soil, or reduce competition from other plants, providing open space which is ideal for colonisation by invasive plants (Hobbs & Huennecke 1992, Decamps 1995, Hobbs, 1988; Noble, 1988; Richardson & Cowling, 1992). Australian *Acacia* species - particularly *A. mearnsii, A. dealbata, A. cyclops* and *A saligna* - all have persistent seed banks, their seeds can be dispersed long distances by water or birds, establishment is favoured by - but not dependent on - disturbances such as fires and floods and they produce seeds at a relatively early age. Fires typically initiate expansions and increases in the density of invasive alien plants in fynbos (Richardson & Cowling, 1992), but the same may not necessarily be true of grasslands. The frequent fires which occur in grasslands in good condition may actually prevent regeneration, and factors which reduce fire frequencies, or exclude fires (e.g. overgrazing), may be needed to initiate invasion by species such as *Acacia mearnsii*. They are also undoubtedly South Africa's most pervasive and significant invaders as well as being among the most expensive to control (Versfeld *et al*. 1998).

Human activities again play a critical role by altering the natural disturbance regimes and by introducing new sources or agents of disturbance (Hobbs & Huennecke 1992, Vitousek *et al*. 1997a, b, Bright 1998). During the last century these impacts have increased at an unprecedented pace and human resource use is now dominant in much of the earth (see review Vitousek *et al*. 1997b; Matson *et al*. 1997). Human population size and degree of resource use drive enterprises such as agriculture, industry, recreation and international trade. The activities of these enterprises, in turn, drive land transformation which alters disturbance regimes. Humans can increase the frequency of fires and floods by changing the vegetation and causing land degradation through the loss of top-soils that promote infiltration. Increased fire frequencies can lead to the loss of soils and the associated nutrients and changes in hydrology and regional climate. Invasive alien species often are the main beneficiaries of these changes as they typically flourish in the human transformed systems and then penetrate the natural ecosystems, particularly when these are under stress (Cronk 1995, Vitousek *et al*. 1997b, Bright 1998). For example, land transformation facilitates invasions by exotic grasses in semi-arid and arid ecosystems, increasing the frequency, intensity and size of fires and reducing the biodiversity of savannas and seasonally dry, tropical forest and woodlands (D'antonio & Vitousek 1992). Climate change can also facilitate invasions where the invaders are more tolerant of, or better able to exploit, the altered conditions (e.g. increased frequency of droughts, increased nitrogen availability) (Cronk 1995). Islands with a high degree of visitation are relatively more heavily invaded (on a log area basis) than continents or less trafficked islands (Vitousek *et al*. 1997b).

A number of species are able to invade natural systems even though the disturbance regimes have not been significantly altered by human activity. A clear example is the shrubland communities, particularly fynbos, of the Cape Floristic Region (MacDonald *et al*. 1986, Richardson & Cowling 1992, Richardson *et al*. 1992). Shaughnessy (1986) found that the major invaders in the Western Cape could be divided into three groups:

(a) those where human assistance clearly facilitated invasion - *Acacia cyclops, A. saligna, Hakea drupaceae, Pinus pinaster*;

(b) those where the evidence for significant human facilitation was inconclusive – *Acacia mearnsii, A. melanoxylon, A. pycnantha, Hakea gibbosa, Leptospermum laevigatum, Pinus halepensis*; and

(c) those which succeeded despite limited or no propagation - *Acacia longifolia, Paraserianthes lophantha, Hakea sericea*.

More widespread species which would belong in group (c) above are *Solanum mauritianum, Sesbania punicea, Chromolaena odorata* and, possibly, *Rubus* species. The first two have become major weed species despite being accidentally introduced to limited areas, while *Rubus* has spread well beyond the initial area where it was introduced. *Sesbania* has been planted quite widely but has spread very rapidly, particularly since the 1960s. The reasons for the extensive and rapid invasions by these species must lie largely in their ability to overcome the biotic and the habitat barriers. These examples highlight the uncertainties that are inherent in attempting to predict invasive success.

2.4.3 Fragmentation of the landscape

As described above, land transformation by human enterprises is increasing steadily and it is estimated that 39-50% of the worlds land surface has been transformed in one way or another (Vitousek *et al.* 1997b). The transformations are also often patchy at a range of scales, resulting in a far greater fragmentation of the landscape than if all the transformed areas were contiguous. Fragmentation of natural vegetation leaves 'islands' or remnants of the natural communities in a 'sea' or matrix of the transformed land cover, sometimes linked by strips or corridors of untransformed vegetation (Shafer 1990). The first effect of this process is clear, the remnants which contain subsets of the original communities and species largely in proportion to their size and spatial distribution. The second effect is more subtle and that is in increase in the extent of the edge of these communities. Small patches are potentially affected more than larger ones because the ratio of the perimeter to the area increases non-linearly as the size decreases. In addition, the greater the contrast in structure between the island community and the inter-island matrix the greater the degree of disturbance this causes and the deeper these edge effects will penetrate into the island.

The converse of this effect, the relationship between the number of species and area, led to the development of the theory of 'island biogeography' by MacArthur & Wilson (1967). This postulates that there is an equilibrium between species immigration and extinction and the size of the island, that the number of species at equilibrium is related to island size, and that the immigration rate is in inverse proportion to the distance from the mainland (source of immigrants). As a general rule this theory fits observations well, both for actual islands and for fragments or remnants of natural vegetation although modern studies recognise that a wide variety of factors other than area *per se* determine the numbers of species on a given island (see Shafer 1990). For example, there is a large body of literature which shows that the likelihood of extinctions of many species increases as island size decreases, partly because of the risk of stochastic (random) extinction increases rapidly as population size decreases (Saunders *et al.* 1991, Mack 1995). Many invasive exotic species appear to be able to benefit from fragmentation by: (a) being able to invade the matrix and, in many cases, being the species that is grown in the matrix (e.g. plantations) and (b) exploiting the vulnerability of the edges of the natural remnants and the increased vulnerability of the remnant communities due to altered disturbance regimes, microclimates and other factors in the remnants (Hobbs & Huennecke 1992, Gentle & Duggin 1997; Rose 1997). The marked ability of many of the successful invaders to persist at low population sizes (see Mack 1995) and disperse over large distances (Higgins & Richardson 1999) also seems to enable them to invade and persist in islands more readily than indigenous counterparts. Comparisons of forest fragments left after forest clearing and natural forest fragments (e.g. gallery forests) have shown that fragments left after clearing are more vulnerable and maintain fewer species (Brokaw 1998). Natural patches have more trees per unit area, more species which are well dispersed, and have a well develop edge or ecotone with species adapted to those conditions. Newly formed fragments have exposed edges, often lack the species that can form a protective ecotone. This makes them highly vulnerable to invasions by exotic species, especially as the transformed land is heavily disturbed by frequent burning (to encourage grass cover for pasture) or cultivated.

2.4.4 Changes in the availability of limiting factors

Human population size and degree of resource use drive enterprises such as agriculture, industry, recreation and international trade (Vitousek *et al.* 1997b). The activities of these enterprises, in turn, alter of biogeochemical cycles (e.g. increasing CO_2, nitrogen availability) at local and global scales, resulting in climate change and the loss of biodiversity (Matson *et al.* 1997, Vitousek *et al.* 1997a, b). Land transformation also has the potential to directly and indirectly drive climate change, for example via net CO_2, methane and nitrous oxide losses and changing hydrological conditions. Climate change can also facilitate invasions where the invaders are more tolerant of, or better able to exploit, the altered conditions (e.g. increased frequency of droughts, increased nitrogen availability). Climate change may also allow invading exotic species to expand their ranges in areas where climatic factors such as temperature and rainfall limit their distributions and the changes could be rapid (Richardson *et al.* in prep).

Nitrogen is one of the major elements required by living organisms and nitrogen limitation is a key regulator of ecosystem functioning. Natural nitrogen fixation on land is estimated to have been 90-130 million metric tons per annum; fixation of nitrogen by industry and agricultural crops is at least 120 million tons per year and still increasing (Matson *et al.* 1997, Vitousek *et al.* 1997b). Some invaders may increase nitrogen availability at ecosystem levels; for example, the nitrogen fixer *Myrica faya* invades lavas on Hawaii and increases nitrogen levels, altering ecosystem process and favouring invasion by other exotics (Vitousek & Walker 1989). Invasions by exotic, nitrogen-fixing *Acacia* species increase soil organic matter, nitrogen, calcium, magnesium and phosphorus levels in the nutrient-poor soils in the Western Cape (see summary in Stock & Allsop 1992). Invasive alien species often are the main beneficiaries of increased nutrient levels as they typically flourish in the human transformed systems and then penetrate the natural ecosystems, particularly when these are under stress (Hobbs & Atkins 1988, Huennecke *et al.* 1990,Stock & Allsop 1992, Vitousek *et al.* 1997b, Bright 1998). Alien grass species appear to have been relatively unsuccessful at invading natural grasslands South Africa, perhaps because most invaders have the C_3 photosynthetic pathway and they are not able to compete in these C_4 grass dominated grasslands. An increase in nitrogen availability and in the efficiency of nitrogen use due to increasing atmospheric CO_2 concentrations could alter this balance, and favour invasions by the exotic grasses (Richardson *et al.* in prep). Another form of pollution that affects natural ecosystems is acid rain generated from pollutants produced largely by vehicles, industry and coal and oil-fired electricity generation plants. These pollutants combine to form acidic compounds which leach nutrients from the soils, acidify stream water and alter ecosystem functioning (Galloway *et al.* 1984, Kauppi *et al.* 1992, Blank *et al.* 1988, Loehle 1988, Vitousek *et al.* 1997b). These alterations could facilitate invasions by exotic species.

2.5 Discussion

Key strengths of the process of developing scenarios for long-term planning are its ability to (a) deal with uncertainties by proposing plausible alternative futures structured around the possible outcomes of those uncertainties; (b) to deal with "long-fuse - big bang" problems; and (c) because well developed scenarios highlight the underlying processes that drive the changes and will determine the trajectory that will be followed into the future. These features help decision makers to understand the consequences of different actions, to be better prepared for them and to make decisions now that will result in better outcomes in the future. Scenario planning also helps us spot the trends as they begin to unfold because the focus is on the driving forces and how they are changing and not simply on what is happening.

Invasions by alien organisms, in this case plants, have a number of features which are well-suited to scenario analysis. Although invasions will undoubtedly increase, it is not possible to predict with any detailed certainty how rapid the invasions will be, what species will be involved, what kinds of impacts they will have and how severe those impacts will be. Invasions are also often characterised by lag periods followed by very rapid increases in extent and impacts depending on infrequent events (e.g. high rainfall years). One the other hand numerous studies have shown that the major driving forces behind invasions are: those controlling the arrival of propagules, disturbances regimes (particularly changes in them), fragmentation of the landscape and changes in the availability of limiting factors. We are also not starting with a blank slate. A significant proportion of the country has already been invaded and these invasions are continuing to expand at least 5% per year. It is likely that, given a time frame of 20-30 years, the biggest problems that result from invading exotics will be caused by species already established in South Africa. New species will undoubtedly arrive and some may invade successfully and have significant impacts but the underlying forces that drive invasions will remain essentially similar to those operating already.

Human beings and their enterprises: agriculture (including forestry), industry, recreation and international commerce are clearly the main agents which will determine the direction and strength of action of those factors. The activities of these enterprises, in turn, are affected by economic trends (national and international), population growth (local and regional), political systems and institutions and legislation (local and international). Clearly, the driving forces and the factors that influence them operate on different scales (from local to national) and there are many links and feedbacks (positive and negative) between them. The South African economy has recently grown slower than expected because of events thousands of kilometres away in eastern Asian economies. This, in turn has a significant impact on South Africa's ability to support critical initiatives like the Working for Water Programme.

We believe we need to understand the trajectory of these invasions through time if we are to take decisions now that will result in the best possible outcome in the future. We cannot do it by analysing the biology of invaders on its own and will have to incorporate the forces acting at bigger scales and in other realms. We cannot understand the intricate interactions only by modelling as we need to address this in a manner which would take into account the extraordinary complexity of the human enterprises and human-dominated systems. These issues are examined in more detail in the following chapter where we identify the underlying forces such as economic growth in more detail and develop our scenarios.

3. BUILDING THE SCENARIOS

A brief history of scenario planning and a review of relevant aspects of the invasions process was given in Chapter 2. This showed that the key strengths of successful scenario planning - the ability to deal with uncertainty explicitly, to deal with "long-fuse big bang" problems and to reveal the underlying driving forces - are well suited to getting a grip on the problems posed by alien plant invasions. The invasion process is inherently uncertain because it is very difficult to predict which species will invade, when and how fast they will invade, and what and how severe the impacts will be.

Alien invasions are also strongly influenced by human activities such as land transformation for agriculture and commercial forestry and potentially by global climate change, both of which involve important uncertainties. Although the process of invasion is complex, the main influences come from just four driving forces that influence invasions - the primary driving forces. These, in turn, are influenced by secondary driving forces. The aim of this chapter is to explain the process that was followed for developing the scenarios, based on the information in Chapter 2.

3.1 The Scenario Development Process

Scenario planning is based on a systematic procedure with recognisable phases (Box 1), but it is not a straightforward, mechanistic, process; it is iterative and there are many points at which critical assessments are needed (Wack, 1985). Moreover, it is organic, in that the learning from one phase is used to feed into subsequent phases. In what follows, a definition of each of the phases, more detail on the processes and the derived information, is given.

Box 1: Phases in the scenario generation process (based on Wilkinson 1995):

1. Identify the focal issue (found by agreement and through consultation with relevant parties).
2. Identify the primary "driving forces" at work. (*Look past the everyday crises that typically occupy our minds and examine the long term forces that work well outside our concerns*).
3. Identify the predetermined driving forces, i.e. those that are completely outside our control and will play out in any story we tell about the future.
4. The remaining driving forces comprise the uncertainties, the things whose effect on the future (positive or negative) is unpredictable. Test each one to determine which ones are critical to the focal issue - these are the key uncertainties.
5. Reduce key uncertainties to groups that have a common thread or cause to a single spectrum, or axis of uncertainty (negative <-> positive). One way to simplify the groups of uncertainties is to form two major axes of uncertainties by identifying things that are independently uncertain. Arrange the two axes at right angles (with the intersection at the midpoint) to form a four-quadrant matrix. Each of the quadrants should now define a plausible and distinct group which describes a possible future or scenario.
6. Flesh out the scenarios to make a "story" using the list of driving forces generated earlier as "characters". The goal is not to tell four stories, one of which might be true because the "real" future will not be any of the four scenarios although it will contain elements of all the scenarios. The corners of the matrix are exaggerated - the outer limits of what is plausible - a near caricature quality.
7. Explore the implications of the scenarios and identify courses of action that will make sense across all of the futures. Those that make sense in all four scenarios are the decisions that should be implemented today. Work can proceed on the basis of these decisions, in the confidence that they are more or less likely to play out. Some will make sense across only one or two, these require more care. Attempt to identify "early warning signals", for example by tracking trends or shifts in the driving forces, that tell us those particular scenarios are beginning to unfold.

3.2 Identification of the focal issue

Scenarios have to be developed around a *focal issue*, the issue that encapsulates and lies at the heart of concerns about the future outcomes of the decisions currently being made by a particular group or organisation (Wack 1985, Schwartz 1991, Wilkinson 1995). The groups can range from small businesses to national or international governments. The questions can be broad: "what will the economic situation in southern Africa look like in 2010 AD?" Or narrow: "what will computer systems look like in 2005?" The key issue is that the focal question must (a) clearly identify a source of genuine concern to the group for whom the scenario is developed; and (b) provide a clear focus based on a shared understanding of the problem.

The findings of the report by Versfeld *et al.* (1998, see chapter 1) clearly show that invading alien plants are already having a significant impact on South African water resources and that controlling them will cost very large sums of money. The results of a number of other studies also show that invasion by alien plants are having a significant impact on agricultural productivity and on our natural ecosystems, their biodiversity and the ecosystem services they provide (see van Wilgen *et al.* 1996, Richardson *et al.* 1997, Hoffman *et al.* 1998 for recent reviews). The invaded area is also increasing rapidly and the invasions are becoming denser, so delayed or inappropriate actions, or both, could have a high cost in the long-term. We know that changes in the degree of invasion and in the distribution of alien invasions are certain, but the form of these changes is unclear and there are many unanswered questions. The key concerns that we have are about the future impacts of invading alien plants. To make this more specific, these concerns were reduced to the following question which addresses what we believe to be the focal issue:

What will the state of invasion by alien woody plants in South African catchments be in 20-30 years from now?

This focal question also leads logically to a number of subsidiary questions, for example:

- How much of the country will be invaded?
- What effect will invasions have on water and land resources and natural ecosystems?
- What effects will invasions have on sustainable development?
- What efficacy will biocontrol have in the same time period (20 - 30 years)?
- Will political and institutional support be maintained for eradication programmes?

It is clear that there are no simple answers to these questions, and that a range of players and driving forces are involved. Yet we need to make decisions now that will be effective over the long term, for a range of different plausible futures and for different regions. We need to maximize the benefits of control strategies irrespective of how the strengths of different driving forces might change. To do this we need to identify the forces that are driving invasions, and understand whether the outcome of their actions is to facilitate invasions, reverse or prevent them.

3.3 Identification of the Driving Forces Of Invasion

The driving forces behind alien invasions were identified by researching and collecting information on those activities which could promote or slow further invasion. This was undertaken in workshop mode, as well as by extracting information from the literature and a variety of sources such as the Internet. Examples of scenarios were also examined to identify driving forces that could affect invasions. We have made extensive use of the recent popular review of invasions and their impacts by Bright (1998) in this section. The driving forces are discussed below, firstly at the fundamental level and then within the context of those forces existing at global or international scales and then local or Southern African scales.

3.3.1 Primary driving forces

The review of alien plant invasions in chapter 2 identified four primary (genesis) driving forces which influence the speed and impacts of invasion:

Arrival of new propagules - the seeds, cuttings or other parts needed for the plant species to be able to establish itself; the main source of this is human activities such as colonisation (now largely historical), war refugees and trade, especially during the 20^{th} century.

Disturbance regimes which are either (a) necessary to maintain the natural ecosystems but can make them more vulnerable to invasion when they are altered by human activities or climate change or (b) introduction of new forms of disturbance that disrupt natural communities.

Fragmentation of the landscape which creates extensive ecotones and corridors for invasions by facilitating the dispersal of propagules and establishment of plants.

Changes in the availability of limiting factors, for example the supply of nutrients such as nitrogen or phosphorus, or climatic extremes caused by global climate change. Human activities are a key factor by adding nutrients through industrial and agricultural pollution, or leaching nutrients via acid rain, but in some cases the invading species themselves may alter nutrient availability.

The impact of each of the primary driving forces described above is, in turn, affected by secondary driving forces which are at work, ranging from local right up to global scales. These secondary forces, which are listed below, do not have a direct influence on the ecology of the plants but work by providing an environment which increasingly favours aspects of invader biology above that of plants within the natural ecosystems.

Wilkinson and Schwartz (1991) have argued for identification of the "primary" driving forces, which may be thought of as being represented by the genesis driving forces listed above. We would argue that these driving forces are essentially "predetermined", in that it is inconceivable that any of these driving forces would not continue to operate in the future. This can be explained by noting that the arrival of new propagules in an area will continue, that landscape disturbance and fragmentation would increase and nutrient enrichment and global climate change will continue, all being causative forces for further invasion. Nevertheless, each of them still contains many uncertainties in, for example, the timing and magnitude of their impacts. Much of this uncertainty can be clarified by improving our understanding of how each of the primary driving forces is influenced by the secondary driving forces, both individually and in various combinations. The issue of uncertainty will be discussed further in the section on "Selection of Predetermined Events".

3.3.2 Secondary driving forces

During our examination of the different forces acting on the primary driving forces it soon became evident that some were operating largely in the international context and thereby also exercising an influence over invasions by exotic species within South Africa. Other driving forces were acting exclusively or very largely within South Africa. We believe this to be a useful distinction and we have used it to group the driving forces we discuss below. Note the numbering system, ***I*** distinguishes the item as being of an international character, while ***S*** items are of local or southern African character.

INTERNATIONAL SECONDARY DRIVING FORCES

It is important to recognise that introductions may be deliberate as well as accidental and that both can have severe consequences. Some introductions have also been intended to solve the problems created by earlier introductions and have only compounded or aggravated the problem (Bright 1998).

I1. INCREASING HUMAN POPULATION AND FLUCTUATING MIGRATION PATTERNS

The general increase in the number of people in the world generally leads to greater demands for resources, foodstuffs and materials such as wood and fibre. Increased demand results in the development of existing resources to increase their productivity, adoption of new species and opening up of new areas to the existing and new species (Matson *et al.* 1997, Nobel & Dirzo 1997, Vitousek *et al.* 1996, 1997a). People also migrate, taking with them their old ways of doing things, including different plant and vegetable forms. The 20th Century has also seen an unprecedented increase in tourism and in the collection of 'souvenirs', some of which may be undesirable species (Bright 1998). In this way both the quantity of propagules and the variety of ways in which humans potentially increase the movement of propagules increases.

I2. EXPANDING NETWORK OF INTERNATIONAL TRADE AND TRAVEL LINKS

The number of international links, and therefore the number of potential invasion pathways, has increased dramatically during this century. Most of the significant invasions that originated through trade have been of marine organisms which are transported in ship ballast water (Vitousek *et al.* 1997a) but seeds of many plant species can be moved in containers, transporter vehicles, soil or contaminated seed lots (Hodgkinson & Thompson 1997, Bright 1998). Since 1994 and its reintroduction to international trade, South Africa has been opened to a multitude of new markets for trade and its importance as a hub for trade with the rest of Africa has also increased. This will increase the variety of new invaders that could be introduced.

I3. INCREASING MAGNITUDE OF INTERNATIONAL TRADE

As the quantity of trade increases, the number of alien species or propagules landing in a country increases (Bright 1998). This higher frequency leads to an increase in the probability of a successful establishment of an alien in its new habitat (Mack 1995). It also increases the sampling of the genetic diversity of the important aliens, which increases the fitness of an alien in its new environment.

I4. GLOBALIZATION OF ECONOMIES

The globalisation of the economies of the developed and developing countries is resulting in a marked shift in the distribution of industries. The comparative advantage of the economies of different countries is increasingly exploited, with industries being located so that production of certain items takes place where there are increased "*efficiencies*", for example cheap labour or comparatively weak environmental legislation and awareness. This can be an example of the "Not In My Back Yard" (NIMBY) syndrome, in which wealthier countries exploit the lack of *suitable controls against invasive species with agricultural value, or industrial pollution, in less* developed countries (Hughes 1995). Another example is the possibility of carbon banking or sequestration as recognised under the Kyoto protocol (IPCC 1996). This may be used as a method of debt reduction in poorer countries who sell their few resources of land and water for carbon sequestration purposes, thereby allowing the carbon producing nations to delay their spending on carbon emission reduction. One favoured route for this is through growing plantations of fast growing trees, many of which are highly invasive (Hughes 1995, Richardson 1999). Another example would be an artificial demand for "green tannins"[3] which can be grown in developing countries because of their greater land and water resources. This could revitalise the wattle growing industry in this country.

I5. *GLOBAL ECONOMIC TRENDS*

The events of the last year have shown clearly how vulnerable the South African economy is to turmoil in the international financial markets, especially in the 'emerging economies' (Finance 1999). South Africa also is undergoing a process of major economic reform and is vulnerable to volatile commodity price changes. This situation is likely to continue and could place strong limitations on South Africa's capacity to reform its economy and achieve sustainable growth. South Africa's concerns about international financial management and their implications for developing countries, including South Africa are being raised and discussed in international economic forums (Finance 1999).

I6. *GLOBALIZATION OF THE FORESTRY/AGRO-FORESTRY ENTERPRISE*

The demand for increased productivity by forestry and agricultural enterprises is continuously growing and these enterprises are consuming an ever increasing proportion of the world's resources (Matson *et al.* 1997, Vitousek *et al.* 1997b). The agricultural and forestry enterprises are searching for new species and varieties of plant with commercial value or potential. This search includes the exchange of plant material, the increasing use and development of hybrids, as well as genetic prospecting (the search for plant modifications and products with economic potential). Many developing countries are attempting to find ways to rehabilitate degraded land in order to provide for their growing populations (Dobson *et al.* 1997). This exchange and trade often involves species known to be invasive elsewhere in the world but this is ignored because of the perceived benefits of the 'miracle' species (Hughes 1995, Bright 1998).

This driving force is not necessarily only promoting invasions. The so-called "Green Certification" is a recent development that can limit the distribution of invader propagules and lead to control programmes for invasive species (IIED 1996, Kruger & Everard 1997, Olbrich *et al.* 1997). The approach was first developed for tropical forests and is aimed at ensuring that the timber products from the forest are harvested in a sustainable fashion. It was initially touted by environmental organisations using the environmental sentiments of the relatively wealthy countries, but has become accepted practice. In recent years it has been expanded to include the

3 These are derived from natural plant sources and not from by products of the coal and petroleum industries.

product of artificial plantations as well. The timber trade in many developed countries, for example the USA and countries belonging to the European Union, will not import products lacking this certification. A certified product will specify how that product was grown, and whether or not the product is invasive where it was produced and what control measures were utilised.

I7. *IMPROVED COMMUNICATION METHODS (INTERNET, GLOBAL DATABASES)*

Modern communication methods such as the Internet may speed the flow of information on the useful characteristics of a species, prompting producers to import these species without first considering their invasiveness. A large number of sites already contain information on plant species with agricultural, horticultural and herbal value, many of which are run by commercial companies. There are also several organisations which specialise in studying and researching the commercial potential of agricultural crops and tree species. One example is the CAMCORE co-operative to which some commercial forestry companies in South Africa belong (Dvorak and Donahue 1992). Genetic stock of pines and other species collected or developed by members of this co-operative is actively marketed to other members for them to test as well. Many of the recent introductions of new pine species to South Africa were sourced through this co-operative (Le Maitre 1998). Other institutions include the Oxford Forestry Institute and the Consultative Group on International Agricultural Research (CGIAR) which includes 16 research centres worldwide, many of which specialise in agroforestry systems (CGIAR 1999).

This trend may be countered however by the growing number of global databases on problem species (Frost *et al.* 1995 e.g. BOPRC 1998). These databases may include information useful for control purposes, such as pesticides and natural predators in their home ranges and which may be targets of biocontrol research. The databases are also used by organisations responsible for quarantine on imports, for example in Australia and New Zealand (see Hughes 1995). A number of countries also maintain internet sites which list their major invaders with information on how to identify and control them (e.g. BOPRC 1998, AWA 1998, HEAR 1999). There are also international e-mail groups which deal with information on, and queries about invasive species (e.g. the aliens-l list server maintained by the IUCN in Switzerland).

I8. *GROWTH AND MATURATION OF INVASION ECOLOGY INTO A ROBUST, PREDICTIVE SCIENCE*

Invasion ecology is still a growing science. The SCOPE invasives programme of the 1980s made some major steps forward in our understanding of invasions, their causes and their impacts (summarised by Drake *et al.* 1989, Dean 1998). This programme has recently been revived as new information on the enormous economic costs of alien invasions became available and as invasions have become more and more pervasive and evident (Bright 1998, Van Wilgen *et al.* 1998; Dean 1998). As the understanding of the processes of invasions and their impacts increases, there will be an increasing pressure to feed the ecological perspectives of alien invaders into policies, laws and regulations. The new insights will also lead to improved methods for screening species for invasive potential and for methods for controlling invading species.

I9. *GLOBAL CLIMATE CHANGE*

Most people have become aware of global climate change and the possible changes in mean temperatures and thus also in rainfall. More importantly, global climate changed is highly likely to lead to more frequent and intense extreme events, such as droughts and floods, that will create massive disturbance in the affected areas. Disturbance is one of the key driving forces of invasions. For example, floods disturb river banks and reroute water courses, providing recruitment sites for colonising species with water-borne propagules such as *Acacia mearnsii*, poplars, willows ands other invaders (Rowntree 1991, Pysek & Prach 1993, Decamps 1995).

The climates of areas may also change. In general, humid areas tend to be more favourable to invasion than drier ones (Versfeld *et al.* 1998), so any increase in long term rainfall in a region is likely to see an increase in the level of invasion. Similarly, a warming may also lead to conditions for invaders becoming more favourable at higher altitudes (an example might be woody invaders on the escarpment and in the headwater catchments of both sides of the Drakensberg) (Richardson in prep, Chapter 2).

20. *INTERNATIONAL TREATIES (EG BIODIVERSITY CONVENTION, AGENDA 21)*

There are a number of international agreements and conventions that attempt, directly and indirectly, to prevent the spread of invasive organisms (Bright 1998). South Africa has signed a number of these conventions. The most important one is the Convention on Biological Diversity" (CBD) which contains the following clause under Article 8: In-situ Conservation: "Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species". The CBD also contains a provision for dealing with genetically modified organisms. More information on the proposed implementation of this convention is given under S5 below. The government is also involved in developing an international Biosafety Protocol for the safe handling, use and transfer of genetically modified organisms. The government has also signed the Kyoto protocol which commits to reducing CO_2 emissions and also, possibly, to looking for ways to sequestrate carbon to offset carbon taxes.

Risks remain, however, where South Africa is a signatory to protocols on trade for example, such as those of the World Trade Organisation (WTO) as part of its drive to promote foreign investment. Restricting the import of goods for reasons of invasion risk might be construed as a special form of protection of local industries and businesses from foreign competition. An example of this is the dispute underway at present between Australia and the United States.

WITHIN SOUTHERN AFRICA

S1. *HUMAN POPULATION DYNAMICS*

South Africa has a population growth rate of about 2.4% (Stats SA). Much of the higher population growth rates are in the rural areas. Urban areas have lower population growth rates. There is a trend towards urbanization as people perceive that the potential for income in the urban areas is greater.

AIDS is one of the most serious diseases facing southern Africa, with infection rates reach 20-30% in some communities. This is bound to have an effect on the population growth rate in some areas. It will also lead to a severe demand on the medical services, which will not be able to meet other emergencies because of a lack of resources. Labour effort will decrease and this may have a marked impact in the rural area where livelihood strategies will be affected. The utilization of invaders as a fuel source may decrease.

S2. *ECONOMIC TRENDS*

The economic performance of South Africa is controlled by two constraints, one external and the other internal. The external constraint is the global economy discussed earlier. The internal constraint is a function of the local economy's efficiency, its balance as well as the level of good governance in the country. A collapse in the gold price for example may lead to massive unemployment and therefore increased disturbance and fragmentation of the land as people surge onto land as a survival mechanism. An economy which is more balanced may be able to weather global economic downturns with greater ease. In line with the GEAR strategy (Finance 1998), the economy is being redirected to support key industrial clusters, the small business sector, strategic trade links and attract foreign investment. The extent and rapidity of this economic reform towards a more stable and export-directed economy will be partly determined by global economic trends.

An economy that is performing well has scope to do things such as invest in research on invader controls (biocontrol for example). It also has the resources to undertake land management and do things in an orderly manner.

An economy which is not performing well is far more restricted in what it can do. For example, research funding might be limited to the major agricultural pests that threaten the more immediate food security concerns. The amount of money available to support programmes such as the current "Working for Water" will be reduced. Less money would be available to support the laws, policies and regulations that have put in place. An example might be the screening and quarantine services necessary to control the movement of invaders across the country's borders.

Politics also starts to play a much more important part of resource allocation. The immediate demands of significant parts of the electorate may tend to get preferential treatment.

S3. *EXPANDING INFRASTRUCTURE (ROAD, RAIL AND INTER-BASIN TRANSFERS)*

The development of new infrastructure such as road and rail networks provides a mechanism for the transport of propagules along new routes. Firstly, the building of the infrastructure provides new foci of disturbance by earth moving machinery. Seeds carried by earth moving equipment

around the country are a substantial source of invasion. Secondly, the road and rail networks also are routes of movement by propagules by the normal traffic operating along these routes. Inter-basin transfers of water are also a mechanism for the transport of seeds and plant material, as well as other organisms.

S4. *POST APARTHEID TRANSFORMATION (POLICY TRANSFORMATION)*

One of the stated aims of the post 1994 government is to conduct land reforms, in which there would be a substantial movement of dispossessed people back onto the land, as well as increasing the number of individual black farmers. This process can either be orderly or chaotic, depending on the manner in which the government conducts its operations. A chaotic situation might develop in such cases where land invasions are accepted after the fact. Little investment is likely to follow such activities and farming methods are likely to be poor. In such cases, invasion by woody aliens may take place. Orderly land redistribution however is likely to be accompanied by investment that should ensure greater productivity and care of the resources. In this case, alien invaders may be more controlled.

Following the lifting of the Influx Control laws in the '80s there has been an increase in urbanization and rural depopulation to some extent. If the urbanization removes enough rural people, there will be less use of alien invaders as a fuel resource, thus allowing them to spread at a faster rate. Land tenure practises may change. It is too early to say what the outcome of these changes would be, but the number of big farms with a single owner could reduce significantly. Land care practises are being encouraged. This will have a direct impact on the status of invasion as people understand the negative impact of aliens and therefore remove them.

S5. *CHANGES IN LAWS, POLICIES AND REGULATIONS*

Aliens may be declared a Stream Flow Reducing Activity under the new water law. This would require land owners to pay for the water used by aliens on their land. This payment would be an incentive for alien removal. New coherent laws, policies and regulations may be introduced, under the auspices of a National Weeds Strategy. These would control all aspects of aliens under a single Act or similar body of laws. Nothing of this nature exists at present.

S6. *CHANGING AGRICULTURAL PRACTICES*

Increasing fragmentation is a highly likely outcome as more land is settled through opening up of State land, or, more likely, farms will be subdivided into smaller units in order to accommodate more people. Thus there will be a changing regional mosaic, resulting from shifts between subsistence farming and intensive high tech agriculture. Subdivision is much more likely where the land is relatively fertile and there are good water resources. This will enable those settled on the land to make a living by farming cash crops without requiring large amounts of capital investment. Intensive use of the land in this way is likely to lead to a reduction in aliens. As agriculture is intensified in certain areas, the use of fertilizers is likely to increase - leading to changed nutrient regimes which may encourage aliens invaders.

With the introduction of water pricing policies under the new Water Law there will be an increased focus on the reduction of water waste. Invaders are likely to be targeted (see S5 above).

While more people may be settled on the land, some traditional practises may not change - the storage of wealth in livestock may continue, but within a smaller area - leading to increased soil disturbance and hence scope for invasion. Livestock movement will continue to be a vector of seed movement.

There is now a strong emphasis by biotechnology companies for the development of Genetically Modified Organisms (GMOs). One of the key concerns is the insertion into crops of genes for the production of insect and pest toxins. There are conflicting claims about the safety of these organisms. A threat is that these genes could spread into closely related crops, or even unrelated plants (although this occurrence is not seen as highly likely). If the movement of such genetic material should somehow find its way into alien plants, it will make their eradication by biocontrol that much harder.

S7. *OPTIONS AVAILABLE FOR ALIEN INVADER CONTROL*

Biocontrol is probably one of the most cost effective means of controlling alien invaders. Once the necessary agent has been released onto its target plants, little further investment is required. Nevertheless, significant research needs to be carried out before release of the agents and this can therefore take quite a number of years.

Screening and quarantine protocols are an effective method of preventing invader material from arriving in the country. There are controls in place in South Africa. We cannot say how effective they are. Australia, for example, has an wide ranging effort to prevent potentially invasive material from coming into the country. It does however require considerable investment to maintain the effort. An obvious way for controlling alien invaders is for land owners to control these things on their own land. However, because it can be an expensive process, various ways need to be found to encourage this.

S8. *FIRE*

Changes in land ownership patterns and use could lead to an increased frequency and altered seasonal patterns of fire. However, with the projected increase in fragmentation, the ability of fire to burn over large areas might be more restricted.

S9. *AFFORESTATION (COMMERCIAL FORESTRY, AGROFORESTRY, SOCIAL FORESTRY)*

Plantation forestry is potent source of invader species. Wherever plantation forestry occurs, significant numbers of species of invaders also occur. These weeds are not only a problem to the surrounding environment, but also detract from the forestry operations themselves.

The pattern of ownership of plantation forestry is changing. There is a movement, in new plantations, away from the ownership and control by the large forestry companies to those of small growers, but assisted by the large companies. This change means that new afforestation will move away from the large monolithic plantations that are a characteristic of the South African landscape in some places, to woodlot types of tree stands. The driving force behind these changes are the requirements for more social investment by the big forestry companies, as well as the way in which afforestation permits are granted. The result of this may be less incentive to manage aliens, and also a lack of resources to tackle the problem in a systematic manner.

More woodlots also mean more foci for spread of propagules, and a bigger perimeter to area ratio (contact zone) with the natural vegetation. With a smaller amount of trees, it will be relatively easy to insert plantations into large areas. These attributes favour the spread of invaders. New regions are being exposed the development of plantations as the land under forests increases. Thus plantations are now expanding through the North Eastern Cape, around Lake St Lucia and possibly on the Wild Coast and even the dry West Coast north of Cape Town. The history of the forest industry in South Africa (seeds were being brought into the country in the 19th Century) has meant a long residence time for some major forestry species, allowing acclimatization (development of landraces) and probably hybridization.

Long residence times (allowing for acclimatization) in conjunction with large planted areas increases the potential of an invader to capitalize on rare events that facilitate spread. Plantation forestry is characterised by the movement of heavy machinery. Seeds of problem invaders picked up with plantation soil are often spread extensively in this manner. Riparian zones also become conduits for rapid dispersal of seeds out of forestry zones. However, as the number and size of the invasion increases, an informal economic sector based on alien plant species utilization often develops. The utilization of *Acacia mearnsii,* for firewood is an example of this.

S10. *CHANGING PERSPECTIVES AND PARADIGMS IN NATURE CONSERVATION*

Attitudes towards the way in which wild life conservation in South Africa is approached is undergoing a change. National Parks, for example, cannot now operate in, and enforce, their isolation from surrounding communities, especially if those communities are poor and see no benefit from the conserved area.

A solution therefore has been one of limited access and specific use of materials (like thatching grass). Park fences thus become more permeable (more in and out movement for utilization) and thus the probability of transporting propagules across these boundaries increases. The same holds true for the proposed Peace Parks (which involves cross border transfer) and for biosphere reserves (core areas, buffers etc) and conservancies.

S11. *HORTICULTURE*

There is always a demand for alien plants for aesthetic purposes (flowers, trees, bushes and shrubs). This demand provides a ready mechanism for the spread of potential invaders. These often have the ability of bypassing normal controls at such places as air and sea ports. Increasing tourism and trade therefore may allow more propagules and new species to enter the country.

S12. *CHANGING PERSPECTIVES REGARDING ALIEN SPECIES*

As the impact of alien species becomes more evident and are publicized, so the attitude towards alien species has changed. Thus a "culture of non-tolerance" is developing and institutional approaches such as the Working for Water are making an impact on the problem. Nevertheless, there are people who take the alternative viewpoint and see alien invaders as valuable in their own right.

3.4 Ranking the Driving Forces and Their Interactions

We developed a matrix to explain whether a) there is a strong interaction between the driving forces *per se* (Table 3.1), and b) whether these interactions between driving forces could be stated as promoting invasion, retarding it, or as being uncertain. The reader should be reminded that we are looking for uncertainties, following the process laid out in Box 1 at the beginning of the chapter.

We are primarily concerned with the lower left portion of Table 3.1. These are rated as being either positive, negative or uncertain. Some are also rated as "don't know". Driving forces at the international scale generally strongly promote invasion. The influence activities which directly raise the number of propagules arriving in the country. This is mostly as a result of the increased trade and the opportunities for aliens to be imported or to inadvertently arrive at the ports of the country. All driving forces related to the movement of propagules such as the globalisation and expansion of trade links have a strong influence on intensifying invasion. Global climate change is a strong driving force for further disturbance and change.

At the local scale, the status of the driving forces are more variable. Agriculture and forestry are potent influences in promoting further invasion. Recent work (Nel *et al*, 1999), for example, show that there is a strong relationship of certain types of alien invaders and the forest industry. The linkages are shown diagrammatically in Fig 3.1.

3.5 Selection of Predetermined Events

One can arrive in the future via a variety of trajectories or pathways. The trajectory which will be followed is determined by the combination driving forces and how they vary in dominance over time. We need to get a comprehensive overview and thus need consider the range of driving forces in as broad a context as possible. This means including both the micro-environment (local, national) and the macro-environment (regional, international), and taking into account the social, political, economic, bio-physical and technological forces acting in these domains (Schwartz 1991, Wilkinson 1995).

Once this analysis is completed the next step in this phase is to divide these driving forces into two groups. If we can predict the direction and outcome of particular forces in the future with confidence, we can take actions that will mitigate their impacts. These predictable outcomes are also called predetermined events (Schwartz 1991, Wilkinson 1995). There will always be some forces whose outcome cannot be predicted with confidence or may even be totally unpredictable or may act in either a positive or negative fashion. Often these forces are significant and pivotal to the understanding of future crises that may arise. The most important ones comprise the key uncertainties around which the scenarios will be built.

We are looking for events which can be predetermined from our examination of the driving forces. The reason is that certain future events can be quite predictable and logical. For example, flooding is a predetermined event after very heavy rains in upper catchments. Our list of predetermined events includes all elements of the genesis forces listed earlier, amongst others.

Table 3.1: The interactions of the driving forces matrix. The column and row headings refer to the driving forces outlined in the text. The ranking of driving forces was achieved from the bottom left part of the matrix where the + and - signs indicate which way the driving force acts in promoting invasion or retarding it.

	i1	i2	i3	i4	i5	i6	i7	i8	i9	i10	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
i1	1	3	3	2	2	1	0	0	3	2	3	2	2	0	1	2	0	0	2	1	0	0
i2	++	3	3	3	3	2	3	3	0	2	0	1	2	0	1	2	1	0	2	0	3	3
i3	++	++	3	3	3	3	3	3	2	3	2	3	3	1	3	3	1	0	3	1	3	1
i4	++	++	++	2	3	3	3	1	1	3	2	3	2	1	3	3	0	1	3	0	3	1
i5	++	++	++	?	1	3	2	2	2	2	2	3	3	1	1	3	0	0	3	1	3	1
i6	++	++	++	+++	++	3	3	2	2	3	0	2	2	2	2	3	3	1	3	2	0	3
i7	++	++	++		?	++	2	3	0	1	0	0	0	0	1	2	3	0	2	1	3	3
i8							–	2	3	3	0	0	0	0	3	3	3	2	3	3	3	3
i9	++	++	++	+++	++	++	++	++	2	3	3	3	0	0	1	3	2	3	3	3	1	3
i10								–	++	1	0	1	0	2	3	3	2	0	3	3	2	3
S1	++	++	++	++	++	+++	++	++	++		2	3	3	3	3	3	0	3	3	3	3	3
S2	++	++	++		?	++	++		++		++	3	3	3	3	3	3	3	3	2	2	2
S3	++	++	++	++	++	+++	0		++		++	++	3	3	1	3	2	3	3	1	2	0
S4	++	++	++	+	+	++	?		++		++	++	++	2	3	3	1	2	3	3	1	2
S5								–							2	3	3	1	3	3	2	3
S6	++	++	++	++	?	++	++	?	++		++		++	++		3	3	3	3	3	2	3
S7	0	0	0	0	?	?	-	-	++		?		-	0		?	3	3	3	3	3	3
S8	0	0	0	0	0	0	0	-	++	0	+	+	+	++		+	-	3	3	1	0	1
S9	++	++	++	+++	+++	++	++		+++		++	+++	+++	+++		++	-	++	3	3	1	3
s10	++	++	++	+	?		?		++	–	?		++		-	++	?	-		2	1	3
s11	++	++	++	++	0	0	++		++		+	++	++	+		++	0	0	+	-	2	3
s12	-	0	+	+	+		-	—	++	–	0		0			-	-	-	-	-	-	3

+++	—
++	–
+	-

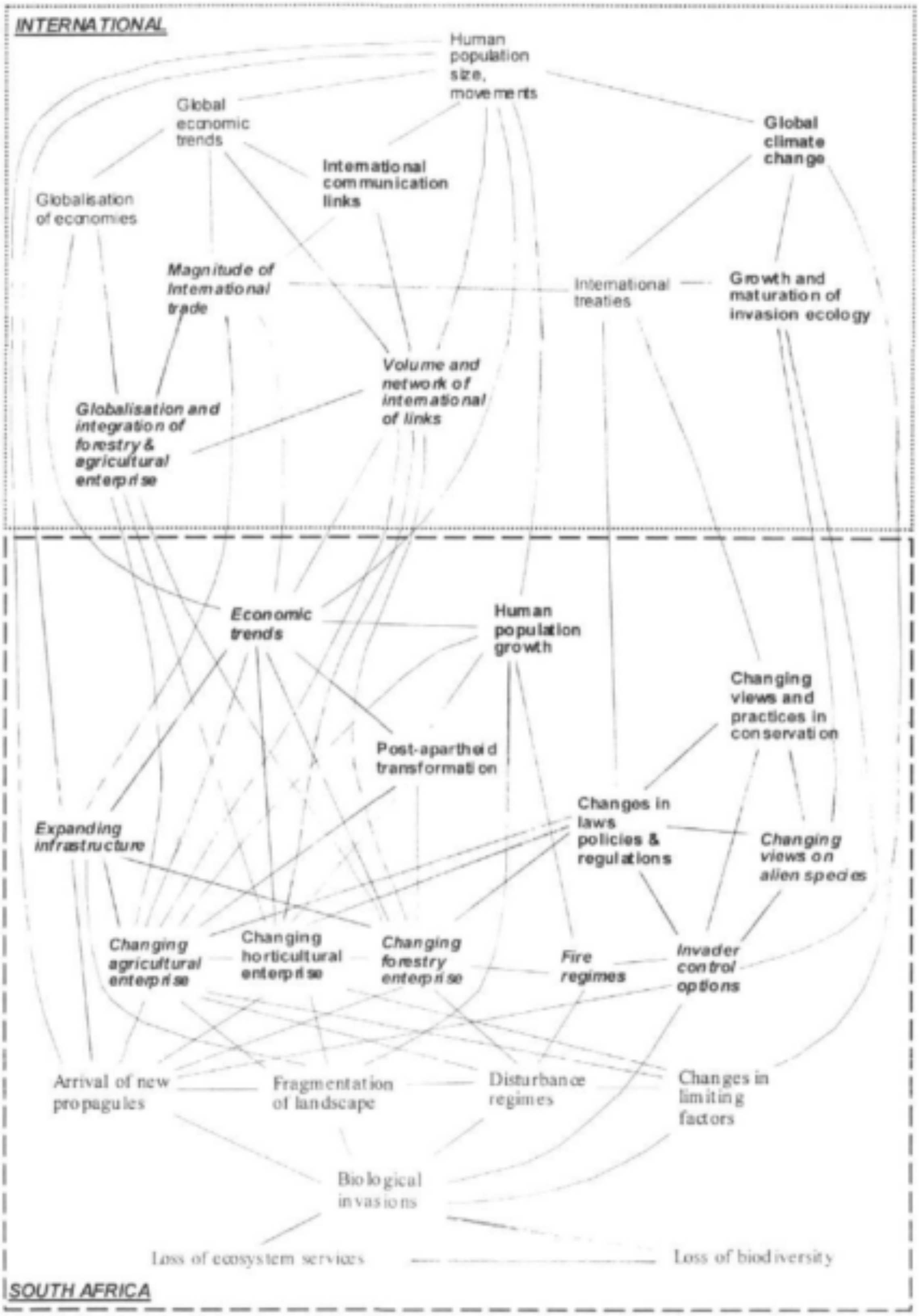

Figure 3.1: The secondary driving forces of invasion.

Population growth could be an easily identified predetermined event. Southern Africa has a relatively high population growth. Increased populations will mean increased pressure on the land in terms of disturbance and fragmentation. There is more and more evidence that AIDS (Acquired Immune Deficiency Syndrome) is expected to have a significant impact on the birth rate as an increasing number of young adults are infected by the disease. AIDS is expected to have a large effect on the health services and the economy (Dalal-Clayton, 1997).

We would argue that the arrival in South Africa of propagules of invasive species is a predetermined event. The pathways by which this will occur have long been established, and the country has already shown that it is vulnerable to invasion (see Macdonald, Kruger and Ferrar 1986 for a review).

Because of increasing population and the demand for land, both disturbance and further fragmentation are impossible to avoid. Overgrazing is likely to become heavier, while fire may become a more frequent feature of the landscape. From a fragmentation point of view, it seems that there is no doubt that firstly there cannot be a consolidation of the South African landscape into fewer management units or landscapes. There would be few exceptions to this. The implementation of land redistribution policies by the government will spread more people over some land, as well as opening up new state land for redistribution.

Similarly, the pressure on the land from agriculture and forestry will lead to nutrient changes and this will provide a further impetus to invasion.

We also suggest that global climate change is a predetermined event. Evidence that this is so is now becoming more irrefutable all the time. While it is indisputable that the quantity of CO_2 and methanes (both strong greenhouse gases) are increasing in the atmosphere, direct evidence that this will lead to a warming of the atmosphere has been scant in the past. However, recent and independent measurements show strong evidence for global warming (e.g. Mooney and Duke, 1999).

3.6 Identification of the Remaining Uncertainties

The next step in the process is the identification of the uncertainties (see Box 1). We looked for those things whose effect on the future (positive or negative) is unpredictable. These were obtained from the ranking system used in Table 3.2. The uncertainties identified there are listed here as

1. The outcome of the development of invasion ecology into a robust and predictive science.
2. The promulgation of international treaties aimed at preventing dispersal.
3. Economic trends in South Africa.
4. Changes in laws, policies and regulations governing alien species imported into South Africa.
5. Changing perspectives and paradigms of conservation.
6. The status of horticulture in South Africa.
7. Changing perspectives regarding alien species.

An external uncertainty in our matrix is the outcome of the development on invasion ecology into a robust and predictive science. Another is the sort of international treaties that may be promulgated. All other external driving forces were considered to be strong promoters of further invasion.

3.7 *Classification of Uncertainties: Developing the Scenario Axes*

Uncertainties 1 and 2 listed above are external to South Africa. It is useful to separate the internal uncertainties and the external uncertainties. The internal uncertainties are in some measure dependent on the external uncertainties, therefore we have chosen the internal uncertainties as key uncertainties. It is easier to see the relationship between these internal uncertainties and the changing status of invaders within the country. Thus we put aside Uncertainties 1 and 2. It is important to note that we do not ignore external uncertainties, only that they are considered in relation to the internal ones.

Considering the uncertainties 5, 6 and 7 of the previous section together, we felt that these were of less significant as uncertainties in comparison to those of 3 and 4. Economic trends (Uncertainty 3) have a large influence on what happens in the rest of the country. The economy has an important impact on most of the other driving forces. However, as should be obvious, the future state of the economy is quite unpredictable.

Strong laws, policies and regulations (Uncertainty 4), which are coherent and implemented well, could have a strong influence in retarding invasion by new species, and by enforcing activities that destroy these alien invaders. On the contrary, weak implementation of laws, policies and regulations which are also fragmented and fail to support one another would create very little resistance to further invasion. Because of the political nature of the regulatory environment, it is extremely difficult to predict an outcome. We feel therefore that the regulatory environment is a key uncertainty.

A number of key uncertainties were described in both the external and the internal driving forces. While external forces have significant effects, they are difficult to influence because of their global nature. We could not realistically expect to be able to make decisions today that could influence or change the outcome of the external forces. Where the local uncertainties are concerned, there are possibilities that the opposite holds true. There are opportunities for planning and making decisions today that could well influence the outcome of the uncertainties at some later stage. Therefore, we have chosen to use the internal uncertainties as the basis on which to develop our scenarios. Their relevant impact on the focal issue is high (ranked from the analysis of the interactions of the driving forces) and they have a low predictability relative to the other driving forces. Economic trends in South Africa is one of the remaining key uncertainties and therefore becomes one of the scenario logics. We call this "**The Strength of the Economy**" logic. The other key uncertainty are the changes in laws, policies and regulations. A number of these address alien invaders directly and indirectly. Thus the second scenario logic is "**Laws, Policies and Regulations**" logic.

The next step is to use these logics as a framework of reference in which to develop scenarios. The following section addresses this process.

3.8 Fleshing out the Scenarios

The power of scenarios comes through their way of presenting a story. These enable the reader to envision an outcome without trying to spell out each detail, in which case the message would get lost for trying to understand the consequences of each detail. In order to develop the stories that represent the scenarios, one needs to know the main themes (also known as logics) around which each scenario is developed. The themes have their basis in the driving force uncertainties and we have used the technique (described by Wilkinson (1995), Schwartz (1991) and others) of constructing two axes, vertical and horizontal, to represent the logics.

The scenario or story is developed in the following manner: using our matrix of interactions again - we developed for each quadrant of the scenario axes, or logics, the likely outcomes of the interactions, which were described earlier, in the form of cause and effect. These are described in Fig. 3.2, which outlines what happens in the future when the applicable logics become true.

3.8.1 Naming the scenarios

An important part of scenario development is the naming of scenarios. These should conjure up an image of what occurs within that scenario. A good example of this are the "*High Road*" and "*Low Road*" names given to the South African political scenarios by Sunter (1987). They convey immediately the essence of the scenario without having to spell out all the details. Using the same logics as in Fig 3.2, we have named our scenarios as follows:

Figure 3.2: Scenario logics and themes

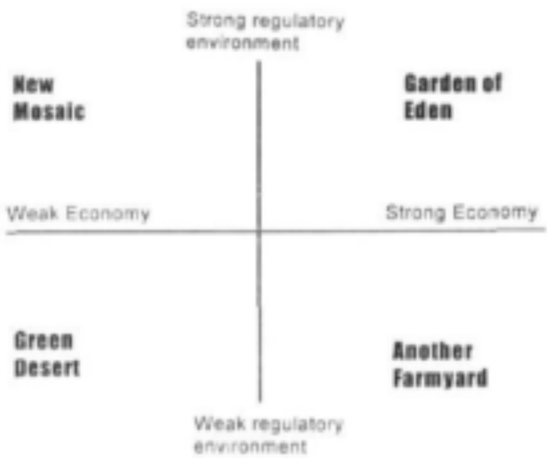

Figure 3.3: Scenario logics and the logic names

3.9 Developing the Implications of the Scenarios

Developing the implications of scenarios is one of the most important parts of scenario development. Unfortunately, this aspect is also one that too often gets ignored and the reader is left to interpret the scenarios themselves. The intention of developing the implications of scenarios is to create the context for the planning and actions that should follow in order to cope with each future should they happen. The implications of each of the scenarios developed in the previous sections are discussed below.

GARDEN OF EDEN, with its strongly performing economy and coherent and vigorously implemented laws, policies and regulations suggests a dichotomy of driving forces. Ongoing alien removal programmes are well funded by the strong economy. However, stronger trade links and higher frequency of trade movement increases the threat for the arrival of new propagules through serendipitous or deliberate means. The increased economic activity increases the rate of movement of propagules via more active seed companies, intensified agriculture and the transport of earth moving equipment. Thus control efforts need to be focussed at potential points of entry like the various ports, and the importers of alien plants such as the agricultural and forestry industries. Screening of imported materials is comprehensive and effectively enforced. Further afforestation takes place among small growers who could be subsidised as part of government development plans. Land redistribution and reforms within the country are orderly. The conservation ethic is strong at all levels of society. In order to slow the current invasions, research and development of biological countermeasures is required. There is widespread education on the dangers of importing potentially invasive material.

The rigorously implemented regulatory environment has an appropriate measure of incentives and coercion. For example, an economic charge for water is introduced and land-owners pay for the excess that woody invaders are estimated to use. This provides incentives for land-owners to control aliens on their land. This scenario has the most favourable outcome, with the least impact by alien plants

ANOTHER FARMYARD represents a strong South African economy but a weak regulatory/policy environment scenario. This scenario implies a *laissez faire* or free-for-all attitude by people and results in a variety of land uses and in the management of land resource issues. The landscape becomes highly fragmented with large numbers of small holdings. The general level of environmental ethics is poor, especially in agriculture. Timber for the export market is grown in well managed plantations relatively free of aliens, but those plantations used for local wood supplies and the pulp and paper industry are less disciplined. Although the economy may be doing well, government is sidetracked by other issues.

Laws, policies and regulations are weak and implementation non-existent. The lack of policies and regulations implies less knowledge and awareness of the dangers of aliens. The rate of introductions of propagules increases. People bring in new species for possible economic advantage. The environment becomes "dirty" because of the presence of numerous different species. The variety of alien plants is higher than in other scenarios. The strong economy shows little care for the environment. This is different from the *New Mosaic* scenario, which implies a land-care ethic that is hampered by a lack of funds. Biological counter-measures are more focussed on agricultural crops, where there is a direct economic impact. There is poor integration of weed control and land management. There is a continuous and expensive effort to contain the spread of invaders in some places, such as important catchments and conservation areas, but the problem is not addressed at a strategic and national scale. Costs rise as a result of more intense fires in the southern and western Cape.

GREEN DESERT represents a weak South African economy and a weak regulatory/policy environment. In this scenario, government sponsored control programmes have collapsed for lack of funding as a result of the weak economy, but fuel requirements of the rural poor place some woody invaders in check. The poor performing economy means that the frequency of international trade, and therefore frequency of arrival, is reduced. The threat of invaders in this scenario therefore originates from those plants already within the country. Low cost methods for alien control are especially required within this scenario, but lack of funding constrains research and development of biocontrol agents. A specific danger within this scenario is also the possibility of international organisations using the weak laws, policies and regulations and the financial attractions of foreign organisations investing in the country to test GMOs in South Africa. Both driving forces combine, resulting in a double jeopardy.

Mountain catchments are especially vulnerable and convert to pines in the western and southern Cape mountain catchments. Fires become very intense, dangerous and costly to combat. Financial losses are significant. The severe fires damage soils, resulting in erosion and sedimentation of reservoirs is increased. Significant loss of biodiversity occurs in places. On the eastern escarpment frequent fires in the grasslands keep out the woody invaders. However, riparian zones are also increasingly invaded and significant losses of water take place. Erosion occurs here too, leading to the increasing sedimen load. Loss of grazing occurs. Significant streamflow reduction by aliens in places is concomitant with a loss of biodiversity, a loss of habitat, an increase in fire hazard and a substantial loss of productivity of the land.

NEW MOZAIC represents a weak South African economy but a strong regulatory/policy environment. In this quadrant, the South African economy remains at the mercy of the international economic condition and local political and economic failings. But the internal development of policy relating to invaders is strong and coherent. The government knows what to do, but lacks the resources to do it. It concentrates on prioritizing the funding, and there are intense debates around which priority becomes dominant. The landscape is an irregular patchwork of large wealthy farms on one hand and a sprawl of small holdings which are a result of land redistribution on the other (which is where the scenario gets its name). In this scenario, attention is given to prioritising areas for clearing and control efforts. The government cares about the problem of alien invasions but doesn't always have the financial resources to do the job as a result of the weak economy. Invasion therefore occurs to some degree over the whole landscape. At the same time, the rate of introduction of invaders slows because of reduced trade, investment and the movement of propagules around the country.

Spread of aliens increases in general, but small amounts of money are available for controlling aliens in prioritised areas. The landscape takes on a patchwork nature with dense infestations of aliens in some places but not in others. The poor economy also puts pressure on the need for subsistence farming. Blocks of homogeneous land cover change into a patchwork of small and large land holdings. Invaders are declared as stream flow reducing activities but this is not enforced.

Arrival of new propagules

In all scenarios, the number of propagules arriving in South Africa continues to increase, both in quantity and variety of species. The number of new species arriving is largely influenced by external driving forces such as foreign trade. Under the strong-economy scenario logic, the quantity of new propagules arriving in South Africa increases because of the increased frequency of trade. Within the country, from the point of landing, their distribution through the rest of the country could be moderated by a strong policy framework - this would most likely take place at ports of entry through screening and quarantining activities. Under the weak policy framework logic, propagule distribution throughout the country increases because of the lax laws and their implementation.

Under a weak-economy scenario logic, the quantity of new propagules arriving in South Africa decreases because of a lower frequency of international trade and movement of people. However, screening and quarantine services diminish because of reduced capacity by government. Under the weak policy framework logic, this capacity is further reduced.

Fragmentation of the landscape

Fragmentation of the landscape increases in all scenarios. In a strongly performing economy but under a weak regulatory framework, fragmentation increases as more land is cleared in order to meet production and access (of new farmers given land) targets. Fragmentation is not as strong under a scenario of a strong policy framework, this is implied by a government with sufficient capacity to address the issues concerning alien invaders.

Under a weak economy scenario but a strong policy framework scenario, fragmentation decreases because of a lack of financial resources restricts the transferral of land that would result from the government's land reform policies. Fragmentation is most rapid within a weak economy and a weak policy framework. This scenario is one in which there is a high population growth where people are desperate for land to earn a living, there being few jobs to be had in the towns (although urbanisation continues).

Disturbance

The ***Green Desert*** scenario shows the greatest levels of disturbance, where a poorly functioning economy and a poor policy environment are conducive to poor land use practises. The increased use of fire as a means of improving grazing removes the shrubland in open areas - decreasing the spread of alien woody plants in these areas. However, this practise also encourages alien propagation in the less frequently burned riparian zones.

Nutrients

An increase in nutrients in the landscape occurs under a wealthy economy scenario logic, but mostly under the co-logic of a poor policy framework. This is implied by a lack of restrictions on point source pollution as fertilizers are applied indiscriminately to the landscape as a means of increasing production. These practises encourage the establishment of alien invaders. However, under the weak economy logic, an increasing nutrient application becomes expensive. A strong policy framework might tend to restrict nutrient applications to a level where there is far less evidence of fertiliser applications in catchment waters.

Global climate change

There are various projections of regional temperatures rising by a few degrees Celsius over the next 50 years. It is quite possible that this could lead to the intensification of climatic and meteorological events like droughts and floods. These are a form of disturbance, therefore climatically induced disturbance will increase. Floods are significant drivers of invasion where they disturb riverbanks.

3.10 Looking for the Warning Signals

An important aspect of scenarios is that they allow action to be taken before a particular scenario might play out. However, to do this, the warning signals or precursors of that particular scenario *must* be understood in advance. In this way, they are less open to interpretation later when there may be more contention about what one is seeing.

In our scenarios the most important warning signal is whether the government manages to get into place the appropriate laws, policies and regulations when it has the greatest opportunity for change, which the present. Failure to do this will activate the driving forces which will encourage a future in which a weak regulatory environment becomes a dominant force. Because of the nature of alien invasion, in which the problem gets worse the longer nothing is done, the lack of sufficient laws, policies and regulations will be especially invidious. The current laws and regulations *vis a vis* alien invaders should be revisited in the context of all driving forces and not just for the particular species.

Decisions still have to be made in spite of the uncertainties. Wilkinson (1995) notes that:

> *...a good decision or strategy to adopt is one that plays out well across several possible futures. To find that "robust" strategy, scenarios are created in plural, such that each scenario diverges markedly from the others...*

3.11 Discussion of Scenario Development

Why did development of biocontrol not become one of our uncertainties or even key uncertainties? Biocontrol is a technology which works well in controlling alien invaders in some cases, but the technology has to be developed before application. Schwartz (1991) notes that technology is a strong driving force, and crops up in many scenarios. If one looks at our list of driving forces and the matrix in Table 3.1, biocontrol is weakly interacting with other driving forces but does have a strong influence on invaders where it is successful. Also, biocontrol is a technology that has a specific internal characteristic because a key part of its research must be carried out within the country i.e. the testing of the biocontrol agents for potential to damage native biota. Biocontrol as an uncertainty may need to be revisited.

Curve balls

There may be some driving forces that can not be identified at this stage, let alone us be uncertain about whether they become dominant or not. An example that is very recent on the scene are carbon sequestration (or carbon banking) policies of world organisations. In exchange for carbon tax credits, some countries may fund others to afforest significant areas in order to create a carbon sink. Afforestation is a significant driving force of alien invasion in South Africa. This could become a threat in the *NEW MOZAIC* or *GREEN DESERT* scenarios where the financial attraction is great in a poorly performing economy.

In the scenarios, we have not gone as far as those who have developed other scenarios in other literature, in which they have written "stories". The reason is that they were considered not appropriate at this stage, and the themes described in Fig 3.2 suffice for this purpose.

Alternative scenario names

In our scenarios we also look for a scenario called the "*OFFICIAL FUTURE*", which is a set of implicit assumptions behind most institutional policies that say things will work out tomorrow - all that has to happen is that the right people put their policies into effect, or that current policies are the correct ones acceptable and all that needs to be done is implement them. The *OFFICIAL FUTURE* is often the line of government and bureaucracies, but it represents a significant danger because it pre-empts actions that could have important impacts at the later crucial stages (Schwartz, 1991). We believe the *GARDEN OF EDEN* scenario is equivalent to the South African *OFFICIAL FUTURE* scenario. Likewise there is also the scenario "*WORST NIGHTMARE*". This would mostly be equivalent to the *GREEN DESERT* scenario.

The Next Step

The important thing is how one uses a scenario. Firstly we have illustrated a number of possible futures, each of them having a different outcomes with respect to alien invasion. We use the scenarios to "set the scene" for simulations of alien invasion in different environments.

4. DEVELOPING A SYSTEMS MODEL

4.1 Rationale

Can we predict the financial implications of the scenarios and would these predictions help us make better decisions?

Previous work into aliens and their removal considered simple cause and effect models (Le Maitre, *et al.* 1996; van Wilgen *et al.* 1997). In these studies, estimates of costs of clearing and stream flow reduction were based on spread models that did not have clearing strategies factored into them, and the way in which regrowth of aliens (recruitment) developed from the cleared areas. They were used to calculate the "instantaneous" cost of clearing through time.

Environmental conditions influence spread rates. The level of disturbance, fragmentation, the influx of nutrients and the operating vectors for propagules will all cause it to vary. Thus we can use the scenarios generated in the previous sections to develop insight into how spread rates might vary in the future. From this, we can develop estimates of how costs of invader management will change under different futures. The value of doing this will enable the country to put in place those procedures necessary to manage the situation as best as possible.

Such a system, however, also tends to be amorphous and poorly defined, where processes and mechanisms are poorly understood and data are few. By building a model of the system, we intend to "*explore the consequences of what we believe to be true*" (Starfield and Bleloch, 1986). We have a small quantity of data and a moderate understanding of the system processes. Thus our model would tend to be somewhat speculative, but it allows us to further develop the scenarios.

4.2 The System Structure

Our model is one with significant feedbacks and includes the human interaction as part of its "ecosystem". There are the two key aspects to the system:

1) invasion and subsequent spread , and
2) mechanical clearing of invasions.

The spread of aliens drives the system, and the removal of aliens counteracts it. A diagram of this system is given in Figure 4.1. The area of alien invasion determines the amount of money that is needed to clear the invaders, as well as the amount of water used through transpiration. The system has the attributes that the area of invaders can get bigger through natural spread, up to some saturation point or limit, as well as get smaller through clearing activities. We have attempted to strike the right level of resolution (see Starfield and Bleloch, 1986, p6) by focussing only on the relevant detail and limiting the scope of the model. Thus the resolution of our model is guided by:

- simple spread model operating on a yearly time step,
- three vegetation density classes,
- a two stage follow-up programme to previously cleared areas,
- a simple species classification,
- a cost of clearing model based on density classes of different species, and
- an economic analysis model.

The model is deterministic, in that the same inputs will always lead to the same outputs. It is also strictly one-dimensional and cannot simulate spatial characteristics.

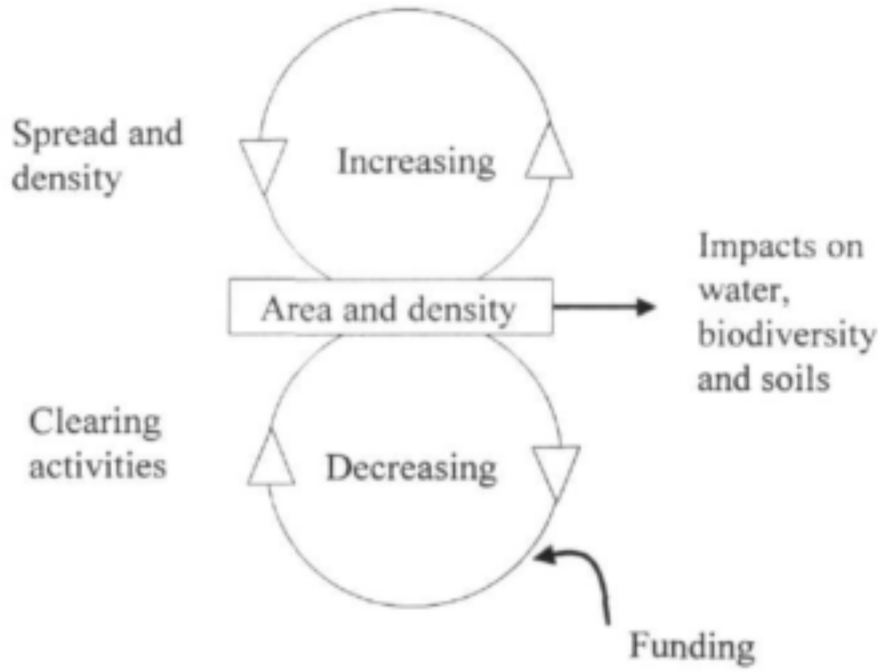

Figure 4.1: The system structure of alien invasion and its interaction with clearing activities. The two components of the system counteract one another, the spending rate is an external input which influences the whole system.

4.3 Modelling System Response to Spread and Clearing

Invasion consists of two processes, arrival of the propagules and the subsequent increase in the population of the invader organism. Usually the rate of population increase is very low immediately after the arrival of the propagules. Mortality of the newly arrived species works against population growth. The organism also may have to adapt to local conditions, so it may be several generations of the population before vigorous spread begins. Once established, however, population growth rate becomes exponential because of initially unlimited space.

At some stage, when the population size has increased sufficiently, intra-species competition begins to have a negative effect on new recruitment and the growth in the spread rate slows. After canopy closure, the invasion has reached a steady state. Future disturbances, such as fire, may occasionally clear a portion of the invaded area. However, new recruitment is usually extremely rapid after fire and closed canopies remain the status quo.

The rate of spread of aliens is one of the more difficult aspects to estimate because data are few from which to validate any simulations. We have some anecdotal evidence, for example from Versfeld (pers. comm) that river systems in the Kouga area of the Southern Cape became heavily invaded by *Acacia mearnsii* within 20 years. Richardson (1989) illustrated how a catchment area became heavily invaded with pines over 40 years.

We have considered single homogeneous populations and ignored the finer structure detail such as differences in age, genotype and sex. These populations can be described by a single state variable: population size. Their dynamics are an inherent characteristic of the population at any one time.

4.3.1 Modelling Population Growth

Invasion is a resource-limited process that is constrained by the area of land available to invasion. The process of invasion occurs approximately as follows: Small nascent populations arise but the incremental area invaded during each time step is initially small. This occurs because, assuming constant rates of expansion, the increment on a small population is small itself. The absolute change in area of each time step is dependent on the total invaded area at the time.

At some stage, the apparent rate of change in population size, or invaded area, becomes exponential, although the intrinsic growth rate, which includes the net effect of both germination and death, remains the same. In the next stage, the apparent rate of change of population size decreases exponentially to a limit. This limit is the total area available to invasion.

The process may be simulated by inhibited-growth modeling using the logistic function, which is often used in the biological sciences for population studies. The function is also known as the Verhulst-Pearl equation (Spain, 1982). We have used the logistic in this study to simulate the increase in area of invasion, the equation is described as follows:

$$n=r*n_t*(1-n_t/k)*t$$

where, n = area increment (ha)

k = area limit (ha)

n_t = area at time t (ha)

r = rate of change of area (dimensionless)

t = the time interval (1 year).

Some important modifications needs to be explained. The spread of aliens is simulated by the decrease in the *uninvaded* area. When an area has been completely invaded, the uninvaded area must therefore equal zero. The invaded area is made up of the three vegetation density classes, of which the relative proportion of each changes over time. This change, or transition, between density classes, is described in the next section. At any time the total area of the three density classes must equal the maximum invadable area minus the uninvaded area. The use of a scheme of three density classes has been adopted to allow use of the data on the cost of clearing collected by the Working for Water Programme.

4.3.2 Determining the Population Growth Rate

There have been very few studies on the rate of spread that can give meaningful data on *r*. Apart from this shortcoming, invasion occurs in such inhomogeneous environments that we can only use a range of values for *r*. Versfeld *et al.* (1998) give a range of potential values (see Table 1 in their Appendix 7, repeated here in Table 4.1), in which it would seem that the most appropriate range for *r* is 0.01 – 0.3, based on invasion to full canopy cover taking of the order 40 – 160 years over a wide range of situations.

Table 4.1: A range of spread rates from Versfeld et al. (1998)

SPECIES	SPREAD RATE *r*
Impatiens (U.K.)	0.03 - 0.013
Pinus radiata	0.20
Acacia Cyclops	0.08
Prosopis spp.	0.18
Mimosa pigra	0. 26
Mimosa pigra (North Australia)	0.64

4.3.3 Rate of Transition Between Density Classes

During each time step in the model, a fixed proportion of invaded area of the light class transits to the next more dense class. The same happens for the medium density class. The net effect is that the area of each of these two density classes changes as it is gives up an area to the next higher density class and is also incremented by a quantity of area from the lower density class. The highest density class only accumulates area.

This process is simulated by using a set rate of 0.33 of the area of each class transiting to the next more dense class. This is intended to simulate a condition where invasion takes place quickly over a large area at low densities, but the rate of conversion of invaded area to greater densities slows down as the density increases.

Versfeld *et al.* gives a Table 4 in their Appendix 7 of calculated density class transition rates calculated from Richardson and Brown (1986), summarized below in Table 4.2. See also Section 4.4

Table 4.2 : Density class transitions for pines from Versfeld et al. (1998), based on Brown and Richardson (1986)

DENSITY CLASS TRANSITION	TRANSITION RATE (FRACTION PER YEAR)
Un-invaded -> scattered	0.028
Scattered -> medium	0.040

4.3.4 Modelling The Clearing of Aliens

Every year a portion of the catchment may be cleared of alien invaders. The area cleared depends on:

- how much money is available for clearing operations,
- the density of the aliens in the area to be cleared,
- the clearing cost per unit area of the different density classes, and
- the priority for clearing (i.e. which density class is cleared first).

4.3.5 Amount of money available for clearing operations

In the model, clearing operations are differentiated from follow-up operations. A clearing operation is the first removal of alien vegetation. A follow-up is an operation in which re-growth of aliens in a previously cleared area are removed. The priority for field operations is normally to first do follow-ups in areas that have already been cleared. When alien invaders are felled or cleared or even just killed, their numerous seeds remain viable in the soil. *Acacia mearnsii* (black wattle) is a typical example of this. Physical disturbance and burning as a result of clearing operations in many cases sets off a vigorous sprouting of these seeds. An investment is wasted if re-growth is allowed to occur, therefore the follow-up is the first spending priority in an area.

Two initial follow-ups are normally conducted after initial clearing, each in consecutive years Remaining money can then be spent on clearing new areas, i.e. the initial clearing. Thus for constant spending rate, the larger the area cleared, the more money that needs to be devoted in following years to follow-up rather than clearing of new areas. The effect of this is less money to go round in the succeeding years clearing of new areas. In the model, spending is therefore allocated to the follow-up tasks, then what remains is used to reduce the current area of invasion.

4.3.6 Clearing cost per unit area of different density classes

The cost of clearing an invaded area is primarily a function of the density of the invasion. Dense invasions are much more expensive to clear than sparsely invaded areas. Costs of clearing different density classes and the follow-up operations have been developed for the Working for Water Programme and listed in Versfeld *et al*. (1998). These are repeated here in Table 4.1.

It should be appreciated that the values in Table 4.1 are averages of data that can vary widely. There is variation is a reflection on the manner in which operations against aliens are conducted. In some projects, the trees have been completely felled and left to rot on the ground, or removed where they have some commercial value. In others, they are ring-barked and also poisoned in some cases (especially Eucalypts because they re-sprout and are difficult to kill otherwise). Ring-barking is a less expensive operation and the dead trees remain standing. One of the advantages of this is where invasions are fairly heavy in sensitive ecosystems, such as in riparian forest. Felling trees into these systems over a short period of time leads to significant damage - dead trees also fall in time but without the canopy and at widely varying intervals.

4.3.7 The Priority for Clearing

Moody and Mack (1988) have shown that it is more cost effective in the long run to clear lightly invaded areas first, rather than the more densely invaded areas. In their paper, they compare the strategies for clearing the main focus of invasion versus clearing the satellite foci that arise from the main invasion. Their satellite foci are equivalent to lightly invaded areas. Moody and Mack (1988) showed that the invasion spreads much more rapidly if the satellites were ignored in a one time control effort

4.3.8 Economic Assessment Using The Unit Reference Value (URV)

The clearing of invasions usually takes place over a number of years of activity. The area to be cleared for one project differs from another, as does the spending rate. Also, an inflation, or discount rate, needs to be factored into any economic assessment where the investment takes place over a number of years. A method is required to assess different clearing options on a uniform and common basis, firstly between different rates of spending on a single clearing project, and secondly, between different projects that produce water benefits in different ways, such as a comparison between a storage dam and a clearing operation.

Table 4.3: Costs of clearing and follow-up operations for different vegetation types, from Versfeld et al. (1998).

SPECIES GROUP	TREATMENT	COSTS BY DENSITY CLASS (R/HA)		
		LIGHT (< 25% COVER)	MEDIUM (25-75% COVER)	DENSE (> 75% COVER)
Acacia	Initial (clearing)	486	1 505	2 063
	1st follow-up	310	746	1 403
	2nd follow-up	169	428	694
Eucalyptus	Initial (clearing)	525	4 518	4 786
	1st follow-up	275	429	802
	2nd follow-up	145	323	441
Pinus & Hakea	Initial (clearing)	585	1 112	3 844
	1st follow-up	249	512	818
	2nd follow-up	200	300	400
Other tall trees	Initial (clearing)	413	1 801	2 938
	1st follow-up	276	1 206	1 968
	2nd follow-up	136	594	969
Tall shrubs and other species	Initial (clearing)	350	456	582
	1st follow-up	235	305	390
	2nd follow-up	116	150	192

The Unit Reference Value (URV), which is used by the DWAF to compare the relative costs and benefits of different water schemes, is a technique that has relevance to our purpose. The results of URV analyses can be used to guide project formulation and to rank alternative projects. The URV is a ratio of the net present value of a time-based series of investment to the net present value of the time-based benefit stream. The method of calculation is given as follows:

URV = (Net Present Value of Cost of Clearing) / (Net Present Value of Water Benefit)

The formula for net present value is represented as follows:

$NPV = V1 / (1 + Rate) + ... Vn / (1 + Rate)^n$

Where,

Vn is the value during period *n*, and is either the water benefit or the cost of clearing, depending on which term of the equation is being considered. Determination of the water benefit is described in further detail in a subsequent section. The cost of clearing is the combined investment, operation and maintenance costs and any other associated costs that are needed to make the products and services of the project available for use or sale, in this case the removal of alien invading vegetation.

n is the term of the analysis (i.e. the number of years over which the calculations are performed).

Rate is the discount rate, representing the periodic interest rate (the fixed interest rate per compounding period). Usually this is equivalent to the inflation rate and this is set at a value of 0.08, or 8%, in this study.

4.3.9 The Annual Total Area Cleared of Aliens

The total annual cost of clearing is equal to the investment amount. In the model, the area cleared every year is calculated by first utilising the investment to do the necessary follow-ups, thereby changing the area of the second follow-up to zero, and the first follow-up to the second follow-up. If there are funds remaining, that amount is then invested in clearing new area at a rate according to the clearing cost per unit area of the lightly infested density class. Remaining funds are then utilised to clear new area from the medium density class at its appropriate clearing cost per unit area. The method is continued with the densely invaded class.

4.3.10 Calculation of the Water Benefit

The water benefit is estimated by taking the difference in streamflow reductions between what **would** have been the situation should invasion have been left to proceed without interference, and the situation after clearing. Thus, in the model, there are two curves, the upper bound curve which estimates the area covered by spreading aliens in a situation of non-intervention, and the lower-bound curve representing the controlled area, which estimates the remaining quantity of invaded area following clearing activities. These ideas are illustrated in Fig 4.2.

The difference between these two curves represents the change in area of alien invaders over time that came about as a result of clearing operations. In a situation of non-intervention, the increase in area of aliens that follows the top curve represents a mixture of the three density classes. The lower-bound curve contains a different mix of density classes, because of the protocol of clearing lightly invaded areas first. The water benefit is calculated by determining the streamflow reduction in a situation of non-intervention, i.e. the top curve, and subtracting from it the streamflow reduction in a situation of alien clearing activities.

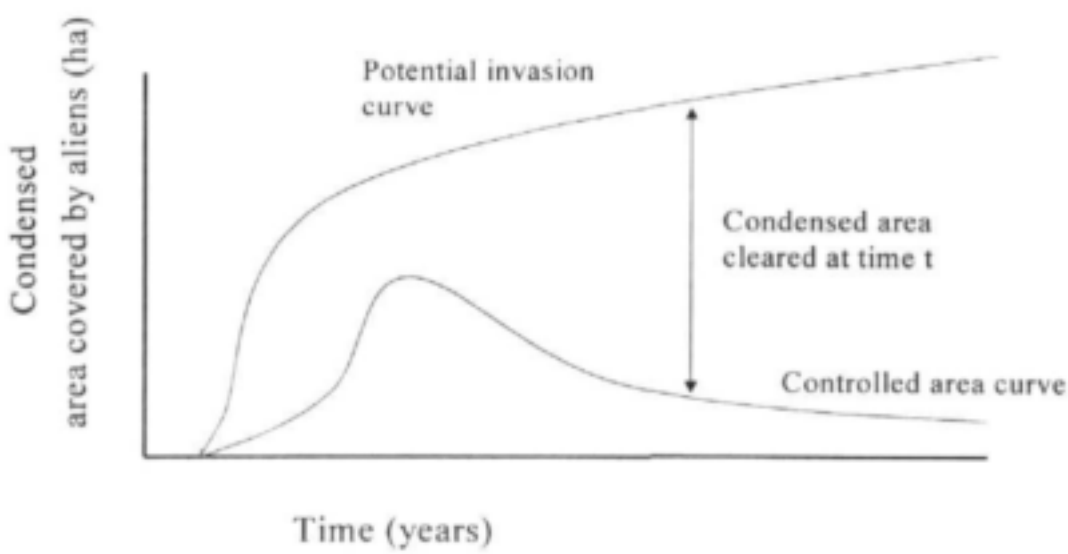

Figure 4.2 A schematic representing the method of determining the cleared area at time t, where the lower curve representing area of aliens remaining at time t after clearing activities, is subtracted from the upper curve, which represents the area of aliens where un-inhibited growth and spread takes place, to give total area cleared at time t.

Streamflow reduction is determined following the method of Le Maitre *et al.* (1996) and van Wilgen *et al.* 1997. The equation is given as follows:

Streamflow reduction (mm) = 0.0238 x biomass ($g.m^{-2}$).

This equation is based on data from mature plantations with a closed canopy, therefore the area of invasion in each density class is first adjusted to its equivalent if there had been 100% canopy cover. The scaling factors are given in Table 4.4:

Biomass is a function of vegetation type and age. In this model we have followed the method of Le Maitre *et al.* (1996) and Versfeld *et al.* (1998), in which biomass is a function of age in three biomass classes. The equations for biomass are given in Table 4.5 according to the vegetation type, or category:

Because biomass is a function of age of the vegetation, the age must be estimated. Age of vegetation in different areas differs because the frequency of fire is varies in different areas. In the Western Cape, fires occur with a frequency of once every 8 – 20 years, which we have taken as once every 15 years, giving a mean veld age of 7.5 years. In grassland, fires occur more often and have a frequency of about once in every 1 – 4 years. However, fires in the riparian zones of grasslands are much less frequent and we have given the age of alien trees in these zones as 20 years (see Versfeld *et al.* 1998) for a more detailed description.

Table 4.4 Density classes and their scaling factors as a fraction of a closed canopy

Density class	Canopy cover (%)	Scaling factor
Light	0 – 24	0.125
Medium	25 – 49	0.375
Dense	50 – 100	0.750

Table 4.5 Above-ground biomass (b) growth curves of different vegetation structures as a function of age.

Vegetation structure	Biomass ($g.m^{-2}$)
Tall alien shrubs	$b = 5\,240 \log_{10}(a) - 415$
Medium alien trees	$b = 9\,610 \log_{10}(a) - 636$
Tall alien trees	$b = 20\,000 \log_{10}(a) - 7\,060$

Age is, therefore, one of the input variables that are considered according to the landscape for which simulations are being conducted.

4.3.11 URV As A Ratio of Investment Streams

In the simulations, the net present value of the cost of clearing of that year is accumulated with the cost of clearing of the previous year. Similarly, the water benefit of clearing for that year is accumulated with the water benefit of the previous year. The accumulated clearing cost value is then divided by the accumulated water benefit, deriving a URV for the year.

4.4 Confirmation of Model Performance

Oreskes *et al.* (1994) note that in the earth sciences numeric models always represent open systems and can never be verified, or even validated. They note that to say that a model is verified is to say that its truth has been demonstrated, but that demonstrating the truth of any proposition is impossible except in a closed system. They also note that only confirmation is possible, and further, that confirmation is a matter of degree. Some predictions agree with data, and others do not Oreskes *et al.* (1994). How then do we evaluate model performance with respect to observational data?

As we have noted before, there is a paucity of spread data, especially in South Africa. Therefore we can only seek to demonstrate the degree of correspondence between the model and the real world in the broadest terms. From an internal logic point of view, we believe that the model does not contain obvious structural errors. The use of the logistic as a model of population growth in a resource limiting environment is fairly widely established and alien invasion does occur is a resource limited process. Our representation of the transition between density classes is mostly a representation of convenience, especially because field clearing-cost data is collected according to the density classifications. The use of a value of one third as a basis for transition rates between density classes is, however, highly speculative because there is no data to support one value or another. We believe the model to be internally consistent (*sensu* Oreskes *et al.* 1994) in that complexity of the different processes in the model is more or less equal.

Model results depend on the quality and quantity of the input parameters. The transition rate between density classes has been hard-coded into the model so as to reduce the number of input variables required from the modeller during simulations. The transition rate has been set such that one third of each density class transits to the next class of increased density each year. In order to understand how the model behaves some experimental simulations can be developed. Consider a hypothetical area of 100 units as the constraint or limiting area in which invasion can take place, an initial population of 10 units (i.e. already 10% invaded) and a r of 0.3 (close to the maximum rate).

The model gives a result of 10 years for the area of lightly invaded (scattered) area to reach a maximum, 13 years for the medium density class to reach a maximum area and at 20 years the dense class is at 84% of total cover (Fig. 4.3). If the initial population is brought down to one unit, the simulated invasion takes much longer, 28% of the area being still uninvaded and 34% being densely invaded after 20 years. The shape of the density class curves in Fig. 4.3 are what one would intuitively expect. However, the actual rates of invasion is one of our biggest uncertainties.

In a test of the model against data given by Richardson and Brown (1986), we simulated the invasion of 237 ha (the limiting area) over 40 years using an r of 0.2, while the density class transition remained at 0.33 for both scattered to medium and medium to dense. In this result, 10% remained uninvaded, 8% scattered, 11% medium and 71% dense, which is an acceptable comparison with the observed data (14% scattered and 83% medium and dense). From this result, we make the conclusion that the density class transition rates in Table 4.2 are not comparable to those used within this model.

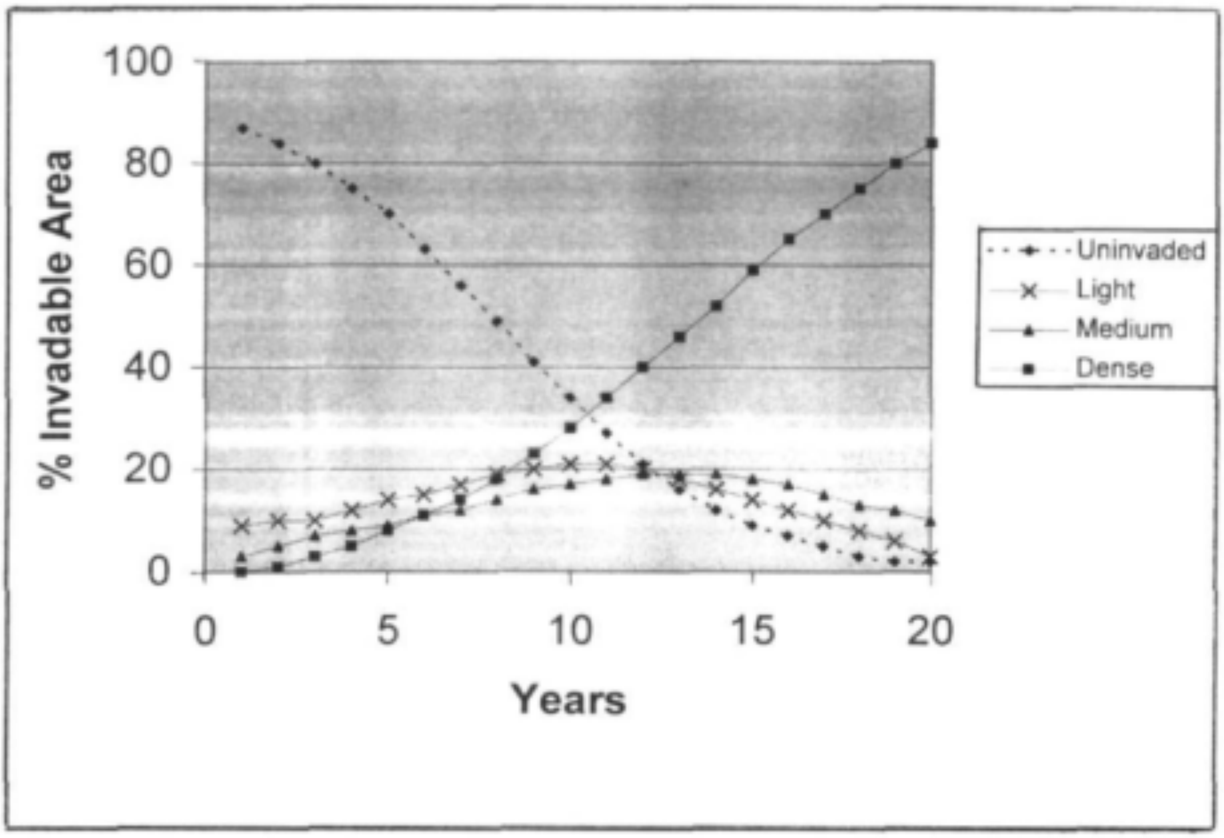

Figure 4.2: Example of spread, with the uninvaded area decreasing and the transitions to higher density classes, from light, through medium to dense.

4.5 Simulating Invasion in South African Landscapes

Table 4.6 gives estimates of how each of the scenarios developed in Chapter 3 might change the rate of invasion in different South African landscapes. The choice of values as a percentage change in *r* is based on a rough assessment of how each scenario accelerates, or retards the invasion, developed from the implications of the scenarios developed in the previous chapter. These modifications are described briefly below.

In the scenario New Mozaic the invasion base rate increases, a reflection of how the poorly performing economy restricts the ability to use funding for control measures. However, coherent laws, policies and regulations are in place and being implemented, although the lack of funding does restrict this. Control of invasions takes place but is patchy.

In the Garden of Eden scenario, the future is determined by the strong implementation of laws, policies and regulations which prevent or slow the importation of alien plants. Although the increased trade, and therefore opportunities for invasion might raise the invasion rate (including the effects of a booming economy on the internal movement of goods and therefore the possible spread of materials), there is a strong pressure against imported propagules, created by well-funded and strongly implemented laws, policies and regulations. In this scenario, funding is available for control measures, as well as research into bio-control, and it assumes some successes. Thus r is substantially reduced.

The Another Farmyard scenario, with its a strong economy, represents a high rate of importation of alien plants, as well as an extensive disturbance regime in the South African landscape. This is a result of inappropriate farming methods. The invasion rate is significantly increased, and weak laws, policies and regulations fail to have and impact on the disturbance regimes or imports of alien plants. Some clearing might take place in areas where the impacts of invasion can be easily determined and ascribed to the correct source.

Finally, in the Green Desert scenario, the poorly performing economy implies extensive use of alien plants as a resource for energy, fodder and building materials. Although its use has an extensive impact in some places, extensive plantings of small woodlots are encouraged, increasing substantially the number of loci from which spread could take place. The implementation of laws, policies and regulations is weak, or non-existent, and having no effect on the importation of foreign plants. The poorly performing economy also implies no funding resources for cleaning activities, or other counter measures, such as Biocontrol. This scenario would possibly represent the highest spread rate.

Table 4.6: Percentage changes in r according to different scenarios

Scenarios	% change in r
New Mosaic	10
Garden of Eden	-25
Another Farmyard	25
Green Desert	20

5. MODELLING METHODOLOGY AND RESULTS

5.1 Stratifying Invasions According to Landscape

Four South African environments were selected as examples where invasion by alien woody plants has important impacts on ecosystem services. These are:

a) Eastern and southern escarpment mountain catchments
b) Riparian zones
c) Open commercial farmland
d) Rural commons

5.1.1 Eastern and southern escarpment mountain catchments

Headwater catchments occur along the eastern escarpment from the far north of South Africa down the eastern seaboard and then along a thin zone in the south that comprise the Cape Fold mountains and westwards to the Western Cape. These catchments provide water to the most important agricultural regions of the country where primary productivity is also the highest (Schulze *et al.* 1997). Much of South Africa's forestry production occurs in this zone. Invasion of substantial areas of the mountain catchments will have very severe effects on the national economy. Le Maitre *et al.* (1986) show how invasion of mountain catchments could mean a loss of 34% of Cape Town's water supply.

Pines spread into these areas from plantations via winged seeds that can travel great distances (Richardson and Brown 1986). Occasional fires soon lead to the establishment of patches of trees, and within a few fire cycles, the invasion quickly becomes dense (Richardson and Cowling 1992). In the southern Cape mountains, a winter rainfall area and fynbos biome, *P. pinaster* and *P. radiata* are the dominant pine invaders. In mountain catchments in the summer rainfall, *P. patula* is known for its aggressive invasive characteristics. A limitation of pine invasion appears to be rainfall, and they do not invade rigorously in areas with less than 500-600mm (Appendix 7, p21,Versfeld *et al.* 1998).

In KwaZulu-Natal Drakensberg, most plantations are located some distance from the headwater catchments, although there are some potential seed sources in patches near buildings. In Mpumalanga and the Northern Province, plantations occur within the headwater catchments, or in very close proximity. In the summer rainfall areas, spread rates of invasions are moderated by frequent fires. Fires that occur before the invading trees have a chance to set seed results in their removal from the landscape. Riparian areas in the escarpment zone are often invaded by *A. mearnsii*, which is common along some rivers in the headwater catchments

The influence of the scenarios on the possible rates of spread and costs of control have been modeled, the results of which are given in Table 5.1a. An *r* of 0.2 was used to simulate the population growth rate, and was obtained from the work done by Richardson and Brown (1986).

5.1.2 Riparian Zones

Riparian zones all over southern Africa are at risk of invasion, except perhaps for the alpine regions of the KwaZulu-Natal Drakensberg. This includes the arid areas such as along the Orange River and in the north west of the country in general. In the eastern parts of the country, riparian zones are not usually utilized for agriculture and are not actively managed. Because of their linear nature, the ability of floods to carry seeds rapidly downstream and disturb the soil, low levels of soil water stress and frequent animal movement, riparian areas can undergo very rapid invasion. Versfeld (pers. com.) notes that in 20 years substantial riparian invasion by *A. mearnsii* has taken place along the rivers in the Kouga area. *A. mearnsii* and eucalypt species are the most common woody alien invaders of this zone. Fires which might keep surrounding lands free of woody plants burn less frequently within riparian zones, allowing the development of mature stands of alien vegetation.

In the drier western areas of South Africa, riparian zones include those of the dry river beds where there may be a significant quantity of water below the surface. These ground water areas are important sources of water for human and animal communities. Towns and farms depend on such water supplies. *Prosopis* species are the most common and successful invaders because of their ability to develop deep root systems, reaching as far as 50 m below the surface, thus out-competing other species that do not have this ability.

5.1.3 Open commercial farmland

Open commercial farmland is a term given to those areas that are farmed for commercial gain. This land tends to be sparsely populated, the farming activities largely mixed and usually mechanized. The principal area of concern is a zone defined by Net Primary Production of about 8 – 10 t.ha $^{-1}$ per season, which covers the eastern part of the Highveld, eastern Free State and much of KwaZulu Natal (Schulze, et al. 1997). This area is key to South Africa's food security.

Areas that are ploughed often are under little threat from invaders. The grasslands are however at risk where frequent fire is not utilized as a range management tool. Invasions of *A. mearnsii* often take place along riparian zones. In parts of KwaZulu Natal and Mpumalanga some parts of farms other than the riparian areas are becoming invaded with this species and therefore reducing the area of productive land. Invasions also start where farmers may have first planted trees as woodlots but gradually increase in area. Seeds also move around via farm machinery. Eucalypt species are another common woodlot tree. Because the invasion is at first slow, often little is done about it, but once the area becomes significant, the cost of control increases beyond the scope for the farmers concerned.

Rates of invasion are generally low, except along the riparian areas, which are dealt with in the previous section. In our analysis we have used an r of 0.12.

5.1.4 Rural commons

Substantial parts of South Africa are utilized as zones of free access over which local authorities such as the chief hold jurisdiction for purposes of land and resource allocation. Typically the areas are poor, without electricity and rely on firewood as a source of energy. These commons have not changed status since the landmark elections of 1994 and remain in this form of land use.

The manner in which the communal tenure system operates has a bearing on resource use and hence possible invasion:

1. A person has functional ownership of the homestead
2. Functional ownership of fields during the rainy season for grain production,
3. Fields are part of the commonage during winter.

On the true commonages, there is a complex system of ownership (von Maltitz, pers. com.). Aliens are viewed as an indigenous and useful species for fuel, building materials and shelter. Electrification of rural villages is unlikely to happen quickly, reticulation over such wide areas will be very costly and there will be little likelihood of cost recovery. These rural areas are mostly subsistence farmers and ability to pay is small. Where electrification has taken place, there may or may not be an impact on the resource (alien trees). Wood for bulk heating might still be required, electricity would be used for providing light and use of certain household goods such as television, but costs in power consumed would be saved because there the local cash economies are small and there is very little money to be expended.

Therefore there is a high demand on the wood resource in these communal tenure areas. Alien plants are an important part of the livelihoods of people living there. However, in parts of the eastern Cape, such as Stutterheim, the invasion has gone beyond with what people can cope and black wattle (*A. mearnsii*) continues to spread. In contrast, there is very significant alien wood use in the Umkomaas valley and aliens are mostly kept under control there.

Substantial invasion by aliens would have a big impact on natural resources. This would lead to a breakdown of traditional values and control structures governing the resource use within these rural areas. A probable result would be a breakdown in traditional social structures and all resources would shift to open access. This in turn may lead to overuse and degradation of the natural resources.

Table 5.1: **Clearing costs of invasions in different South African landscapes, and modified under different scenarios. The unit area is 100 000 ha and the starting population is 1000ha at scattered density. The tables are as follows:**

Scenario	Area (ha) after 20 years uncontrolled invasion	Rate of spending to maintain invasion at current level (R million/yr)	URV (R/m^3)	Investment rate to clear alien plants in 20 years (R million/yr)	URV (R/m^3)	Delay 5 years. Investment rate to clear alien plants in 20 years (R million/yr)	URV (R/m^3)
Escarpment							
New Mozaic r=0.22	36 926	0.21	0.03	0.25	0.03	0.57	0.03
Garden of Eeden r=0.15	14 421	0.18	0.04	0.20	0.05	0.41	0.06
Another Farmyard r=0.25	50 228	0.23	0.02	0.27	0.02	0.69	0.03
Green Desert r=0.24	45 661	0.22	0.02	0.26	0.03	0.65	0.03
Riparian Zones							
New Mozaic r=0.33	82 482	0.30	0.02	0.32	0.02	1.00	0.02
Garden of Eeden r=0.23	41 208	0.23	0.03	0.25	0.03	0.62	0.03
Another Farmyard r=0.38	93 585	0.33	0.01	0.35	0.01	1.23	0.02
Green Desert r=0.36	90 243	0.32	0.01	0.34	0.01	1.15	0.02

Table 5.1 Continued ...

Scenario	Area (ha) after 20 years uncontrolled invasion	Rate of spending to maintain invasion at current level (R million/yr)	URV (R/m^3)	Investment rate to clear alien plants in 20 years (R million/yr)	URV (R/m^3)	Delay 5 years. Investment rate to clear alien plants in 20 years (R million/yr)	URV (R/m^3)
Open Commercial Farmland							
New Mozaic r=0.13	10 536	0.13	0.04	0.19	0.05	0.35	0.06
Garden of Eeden r=0.09	5 377	0.10	0.06	0.17	0.07	0.30	0.08
Another Farmyard r=0.15	14 421	0.15	0.04	0.20	0.05	0.40	0.05
Green Desert r=0.14	12 352	0.14	0.04	0.20	0.05	0.39	0.05
Rural Commons							
New Mozaic r=0.055	2 866	0.06	0.07	0.15	0.09	0.25	0.11
Garden of Eeden r=0.037	2 047	0.04	0.07	0.14	0.10	0.22	0.13
Another Farmyard r=0.063	3 319	0.06	0.06	0.16	0.08	0.26	0.10
Green Desert r=0.060	3 142	0.06	0.06	0.16	0.09	0.26	0.11

5.2 Discussion of Model Results

5.2.1 Impacts of delaying clearing activities

Riparian zones have the highest intrinsic population growth rate of the four categories listed. The most important effect of this elevated growth rate is the difference in clearing costs if a delay is imposed before clearing can take place. Costs can increase by three times if clearing takes place after an imposed delay of five years. Using the riparian invasion as an example, with an initial population of 1000 ha within a possible range of 100 000 ha, and beginning clearing immediately, it takes R 0.32 million per year for 20 years to clear out the invasion . After a delay of five years however, (a difference of five years delay), R1 million per year would have to be spent for the next 20 years to clear out that invasion. Thus five years of delay in clearing can result in the eventual clearing cost being three times greater every year. This multiple is however not sustained for invasions in the more slowly spreading environments such as the Rural Commons, where the cost of clearing the invasion only doubles in area after a clearing delay of five years.

The clear implication of this modeling is that clearing activities should not be delayed. The costs that result from delays increase rapidly. The other implication is that if delays are necessary, for reasons such as a lack of funding for example, then control activities should be prioritized to the areas where the spread rates are the highest. While this may be a self-evident result, it would be pointless to spend scarce financial resources clearing aliens that are spreading slowly when there are areas threatened by a much greater rate of spread.

5.2.2 Spread rates

Spread rates are critical to our understanding of the future environmental impact of aliens. The reason is that the amount of money that has to be spent on controlling the situation is sensitive to spread rate variation. Organisms with high spread rates require a more money for control purposes than do those with slower spread rates. This may seem self evident, but it suggests that the control efforts should be prioritised, *inter alia*, by spread rate, as well as the economic impact of the alien plants.. This again may be self evident, but the point is that so little is known about the spread rates of the different invaders.

Table 5.2 shows that for an already established invasion, the difference in clearing costs over a 20 year investment period more than doubles for a spread rate that changes from $r = 0.04$ to $r = 0.38$, *all other factors being equal!* Therefore economic efficiency increases with rate of clearingrapid clearing is economically more efficient than.

Table 5.2 Investment rates and Unit Reference Values (URV) for different alien plant spread rates

Spread rate *r*	Investment rate for clearing alien plants over 20 years (R million / yr)	URV (R / m^3)
0.38	0.35	0.01
0.33	0.32	0.02
0.25	0.27	0.02
0.15	0.20	0.05
0.09	0.17	0.07
0.04	0.14	0.10

5.2.3 *The Impact of Follow-up on Initial Clearing Rate*

As alien plants are cleared, that area becomes prioritised for follow-up in the next few years. Follow-ups are a priority for spending because, as was pointed out in Chapter 4, the cleared area reverts to its invaded state as seeds from the alien plants germinate in the cut over and disturbed areas.

Conceptually, as the area of initial clearing increases, so must increased funding be held back in the following years for the necessary follow-ups. If a constant amount of money was made available every year, what would be the amount of money that could be spent on initial clearing in contrast to the amount that would be spent on subsequent follow-ups? Simulations show that the amount spent on follow-ups fluctuates from year to year initially, but then tends towards a constant rate after about 7 to 10 years.

5.2.4 *Simulating the Impact of Biological Control on Clearing Costs*

Biocontrol has the effect of reducing the spread rate, this can be simulated by reducing r. By reducing the spread rate by half, the investment rate is reduced by more than a third over 20 years (See Table 5.2). If clearing is delayed by 5 years and then clearing takes place in 20 years, the cost is reduced by nearly one half. With a delay of 10 years, the costs of clearing are reduced by 60%.

Reducing the spread rate by a half is a reduction which could be achieved by a relatively inefficient biocontrol agent. Even so, many millions of Rands could be saved each year in clearing costs. Efficient biocontrol agents that substantially reduce not only the spread rate, but the total size of the infestation therefore have very large cost/benefit ratios in favour of the benefits to be obtained.

5.2.5 The Unit Reference Value as a project evaluation tool

Table 5.2 shows that the URV increases as spread rates decrease. Over the range $r = 0.38$ to $r=0.04$, the URV increases by 10 times. This counter-intuitive result occurs because the water benefit released by clearing a fast spreading population of alien plants is much greater than that of slowly spreading alien plants. As a project evaluation tool, the URV shows clearly that the efficiency of investment is much greater in clearing the fastest spreading species than when invested in more slowly growing species.

6. DISCUSSION

6.1 Scenarios as a Planning Tool

The scenario development process described in the previous section is useful in an environment where there is a paucity of data, and because of the very considerable complexity of the biological process of invasion. The scenario development process makes clear the driving forces of invasion.

Schwartz (1991) noted however that no scenarios, or futures, are more likely than others, only that they represent distinct possibilities. Usually, the future turns out to accommodate a number of outcomes from each of the scenarios. In our presentation of scenarios one should not fall into the trap of preferring one scenario over the other. The point of scenarios is to suspend our disbelief in all possible futures, in other words, to face the possibility that previously unconsidered things might happen. Scenarios explore for facts but they aim at perceptions. We hope that these lead to a change in some deeply held perceptions.

The interplay of political and social systems with technology are important. While certain things may be possible technologically, political systems may prevent these things from happening. Technologically, the country has the resources to combat alien invaders and preserve or enhance environmental sustainability, through, for example the application of biocontrol technology. However, if political awareness of the problem is lacking and funding for research on issues such as the rate at which invasions are taking place in South Africa, the outlook for environmental sustainability in the country is poor. The minimum prize of this study as such, would be a recognition that biocontrol research and coherent and vigorously implemented laws, policies and regulations should be a priority.

The scenarios developed in this study have attempted to show that there are plausible futures for the state of invasion by alien woody species. Two of these scenarios, *Another Farmyard* and *Green Desert*, imply very significant environmental degradation, including diminished water resources , damage to soils and reduced biodiversity. The significance of these two scenarios is that although they diverge along the Strength of Economy logic, they are both characterized by a logic of weak implementation of laws, policies and regulations.

There are two very important differences between the two scenario logics. The Strength of Economy logic is one that is much influenced by the state of the global economy. A significant proportion of the South African economy is outside the country's local influence because of its exposure to the global economy. A strongly performing local economy will not be possible in a poorly performing global economy.

However, the regulatory environment is entirely within the scope of influence of South African regulatory efforts. The scenarios have shown that this is a key area where an impact could be made on the rate of invasion.

One important conclusion arising out of the scenario development is that laws, policies and regulations governing alien invaders and their implementation should be revisited. The scenarios have shown that this is a key area where control of invaders could be vulnerable. The point is that, because of the nature of invasions and their spreading characteristics, failure to address the situation now could result in severe environmental stress in the next two to three decades, including the benefits of ecosystem services such as water production. A case could be made that alien invasion - all over the world - is part of global change. This view is very relevant to us in South Africa and is addressed briefly in a later section.

A shortcoming of this study however has been the lack of a wider audience for the development of these scenarios. Ideally, and in retrospect, the development of these scenarios should have included a number of key people in government agencies, such as the Department of Water Affairs and Forestry, and especially those concerned with the implementation of the new Catchment Management structures.

6.2 The Need for Effective Legislation

Invasion by alien plants threaten not only southern African water resources, but also its ecological integrity. Ecological systems which function well and are diverse are not only resilient to challenges such as disease, drought and human disturbance, but are also much more productive (Meffe and Caroll, 1994).

The need for effective legislation can be illustrated by a simple example. Trees that are cultivated for the timber industry are also the prime invading species (*Pinus* species, Australian acacias and eucalypts). Where these trees are farmed for commercial purposes, regulations control their distribution, size of plantation and proximity to riparian zones because of their impact on water resources. When these same trees invade the landscape, there is little, if any, regulatory control. This dichotomy of responses is a conundrum in the management of South Africa's natural resources.

Further, some Government departments actively encourage the spread and use of invasive species as a source of wood fiber and forage. The Department of Water Affairs and Forestry, for example, both encourages the planting of *Leucaena leucocephala*, an invasive species, and manages Working for Water, a programme dedicated to ameliorating the problem.

South African legislation governing alien invaders is spread over several Acts (Le Maitre, 1996). These are the Conservation of Agricultural Resources Act (43 of 1983), the National Water Act (36 of 1998), the Mountain Catchment Areas Act (63 of 1970) , the Environment Conservation Act (73 of 1989) and the National Forest Act. The Conservation of Agricultural Resources Act is the most important in terms of controlling alien invasive plants, including exotic species (Le Maitre, 1996). There is no Act however that specifically addresses the problem of invasive plants, except to serve other interests such as the conservation of agricultural resources, or that of water.

The multitude of Acts is divisive, in that there is no focus on alien invaders *per se*. This leads to a diluted intervention, or, as described above, organisations at cross purposes with themselves. An effective legislation is required, one that considers the impacts and control of alien invaders in their entirety.

6.3 Extending the Scenarios through Simulation Modelling

The simulation modelling extends the scenario development. While scenario development is qualitative, and implications of each scenario are described in qualitative terms, the simulation modelling attempts to put numbers to the scenario outcomes. Other scenario developers, for example Schwartz (1991) and Wilkinson (1995) explicitly do not follow this method, we however believe it is a valuable addition in this context.

Each scenario was therefore used to aid model simulations of invasion in specific environments found in South Africa. There could be much debate about the spread rates used as input into the simulations. The uncertainty that exists around spread rates is acknowledged and accuracy of the simulations is not claimed. However, the trends of the simulation results show that interventions which retard the rate of invasions could be very beneficial in terms of preventing future expenditure of clearing costs.

6.4 Lessons for the Future

Others also have a vision of the future, and this study echoes their findings:

"*If we look far enough ahead , the eventual state of the biological world will become not more complex but simpler – and poorer*" (Elton, 1958).

The world's ecosystems will become homogenized. This future has been called *The Homogocene* or *The Feral Future* (Low, 1999). Homogenization of our ecology is a very negative development for several reasons. These include:

1. Diverse systems are more productive (Meffe and Carol, 1994).
2. In a world dominated by relatively few species, the world becomes very vulnerable to some pathogen that may attack some of the dominant species. Loss of productivity will have profound social consequences.

The areas that will be primarily affected by this homogenization will be in the more humid eastern parts of the country where growth rates are more rapid than elsewhere because of moisture availability. Exceptions to this rule are the arid parts where *Prosopis* has been able to establish in the sandy river channels. The Karoo and western arid and desert areas of the country are otherwise much less vulnerable to invasion because of climatic extremes.

6.5 The Value of Biocontrol

Biocontrol is often seen as the panacea to the control of invasion, but the truth is that it does not always work, or it does not work very well (Low, 1999). There have been some spectacular successes in South Africa, as in Australia on invasive species such as the *Opuntia* species, which is controlled by the cactoblastis moth (Low 1999, Olckers and Hill 1999). In the Kruger National Park, however, baboons eat the cactoblastis larvae and is thus itself controlled. In some cases, species introduced for biocontrol purposes become invaders in their own right and thus become a new problem (Simberloff and Stiling, 1996a, 1996b).

However, if biocontrol can be introduced against some of our major weeds in terms of water resources, this could have a significant effect with a financial return. Simulations show that if the intrinsic spread rate r can be reduced by 25% or even 10%, this can have a dramatic influence on the costs required for other control measures (see Section 5.2.4).

6.6 Invasion as a Form of Global Change

While this work has restricted itself to the impacts of woody alien invaders that have an impact on the water resources of South Africa, the problem of alien invading organisms is a global one. Ecosystems all over the world are being modified through the intervention of man (Bright, 1998). The invasion process can therefore also be described as one of *global change*. It is also as a driver of global change.

A wide variety of organisms have wide ranging impacts that include natural terrestrial ecosystems, agricultural lands, aquatic and marine ecosystems, industrial processes, human and livestock health. The continuous mixing of species across the continents is an aspect of global change that is analogous to climate change, in that the causative factors are very largely anthropogenic. Table 6.1 provides a small sample from around the world of invading alien organisms. In these particular examples, the invasion is, however, practically irreversible, especially where the organisms are small and very numerous.

A list of problematic alien invaders at global scale could be extended into a very long list indeed. Australia has 2700 species of weeds alone, this number does not include all the other types of organism that are declared there as alien invasive species (Low 1999). The United States, which has more lax regulations than Australia regarding importation of foreign species, has approximately 50 000 alien species. This results in an economic loss of US$138 billion every year, with weeds costing the economy US$ 35.5 billion per year Pimental *et al.* (1999). This situation is repeated in many countries across the world.

There are severe global consequences that include the wholesale loss of ecological processes as well as agricultural, forestry and fishery resources if biotic invasions remain unchecked (Mack *et al.* 2000). Together with human-driven atmospheric and oceanic changes, biotic invasions are a major agent of global change, especially of earth's biota. Evolutionary processes are disrupted, abundances of indigenous species altered and extinctions caused (Mack *et al.* 2000).

Table 6.1 Examples of mostly irreversible invasions by alien organisms into a variety of habitats worldwide.

Alien Invader	Target organism / ecosystem	Type of Impact	Origin of Organism and Date of introduction	Pathway	Reference
Eurasian cheatgrass (*Bromus tectorum*)	Western USA grasslands	Alters fire regime of whole ecosystems, reduces diversity	Europe/Asia	Unknown	Enserink 1999
Western corn rootworm (*Diabratica vigifera* – actually a beetle)	Agricultural fields (Yusgoslavia, Bulgaria, Italy)	Loss of corn production – disruption of food security	Americas (1995)	Military transport	Enserink 1999
Varroa mite	South African honeybee parasite	Potential loss of native flora resulting from pollination failure	Europe / North America (1990's)	Unknown	Enserink 1999
Zebra Mussel (*Dreissena polymorpha*)	Global	Loss of habitat, fouling of pipes, boats, beaches	Europe/Asia	Ballast water	Meffe and Caroll 1994
Brown tree snake Boiga irregularis	Pacific Islands	Total loss of native avifauna (Guam, threatening Hawaii)	Australia / New Guinea (1945)	Military transport, aircraft,	Meffe and Caroll 1994
Paperbark (*Melaleuca quinquenervia*)	Florida Everglades	Alters fire regime of whole ecosystems, causes health problems	Australia (1906)	Planted as a swamp tolerant ornamental	Low 1999
Cane Toad (*Bufo marinus*)	Tropical Australian ecosystems	Eats small mammals, frogs, snakes, toads, poisons predators	South America	Introduced to control sugar cane pests	Low 1999

There is no current evidence to show that the invasions will naturally reverse themselves, intervention is therefore a necessity.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

Several requirements for further research have become evident from this work. They can be broadly described as a need for a greater insight into the ecology, environmental impact, and the economics and management of invasions:

7.1 Invasion Ecology

The invasion process requires greater understanding. The acquisition of data on the following is therefore required:

a. The key drivers of invasions. These can be assigned to two broad categories, the *human dimensions* as a driver of alien invasion (Jeff McNeely, IUCN, pers.com.), and the biophysical drivers of invasion. The preparation of the scenarios touched on both cases, especially the human dimensions, for example population growth, international trade links, global economic trends, the forestry and horticultural industries, land redistribution policies of government and laws, policies and regulations. The analysis attempted to understand their strengths and interactions, but by no means could this analysis be considered to be exhaustive.

b. Spread rates of the different species. Rate of spread varies according to landscape, the main causes of environmental disturbance, including floods, fires and anthropological and faunal activities and limiting factors such as nutrients. The simulations of the costs of control, funding needs and predictions of spread are very sensitive to the rate of spread variable, yet there is very little data from which to develop better models.

7.2 Environmental Impacts

c. The hydrological impacts of different alien plants. In this study we used a simple streamflow reduction model based on the runoff data observed from catchments containing commercial plantation forestry. For other alien plants we have made assumptions regarding their relative biomass (to plantation forestry) and assumed proportional streamflow reductions.

An important requirement is the water use of other alien plants, especially within their prime sites of invasion, for example *Acacia mearnsii* within the riparian zones of a large proportion of the eastern escarpment rivers in South Africa. This lack of data is all the more important as the issues of water licences and water pricing are being debated with increasing frequency in the country.

7.3 Economics and Management of Invasions

d. The costs of clearing the different species. The cost of clearing varies according to the characteristics of the vegetation, densities of canopy cover, type of terrain and the technologies used for clearing and management practise. Few data exists that will enable cost-effective and practical strategies for management and control to be developed.

e. Different management options. The extent of the alien invasion problem in South Africa is so large that current primary mechanical and chemical methods of control will prove to be too expensive. Given this reality, biological controls are sometimes considered as a panacea for the control of invasions because these methods, once established, are self-sustaining. However, there are many invasive species for which no biological controls yet exist and it may take a long time for suitable agents to be found and tested for implementation.

   Other control methods are therefore necessary for some species. For example, *Chromolaena odorata* is apparently susceptible to a particular fire regime, and the use of fire in parts of the landscape could be an effective management option. But this approach would need further research regarding the practical applications of fire. Fire is also a driver of invasion by fire-adapted species. *C. odorata* is a very extensive weed in KwaZulu-Natal.

f. The effectiveness of biological control in altering spread rates. It was shown through the simulation modelling that even a moderate impact on spread rates could have a significant financial benefit. In order to justify biological controls, especially ones that are not spectacularly successful in rapid removal of the targeted organism, some means is needed in determining whether there is a return on investment. This need also requires that uncontrolled spread rates are known.

g. Further model development. The model developed in this study simulates the key aspects of invasion and control in a robust way. Further refinement is necessary, this could take place in an iterative manner by:

- Use in practical applications, where its advantages and shortcomings could be noted,
- Refinement in the relevant issues that are raised.

At present the model is executed in a DOS environment and the output is reported to the screen via a sequence of numbers. Users might prefer a graphical environment for model input and simulation results.

8. CONCLUSIONS

Woody alien invading species already pose a significant threat to the water resources and ecological integrity of South Africa. At even slow growth rates, over the next 20 years the invaded range can double, while at high growth rates their range can increase by factor of five if there is a sufficient area to be invaded. Although we could not establish how much of the country could be invaded, or what clearing activities for the whole country calculated for the future, the driving forces for invasion were established.

Four key conclusions and recommendations arise from this study:

1) A coherent set of laws, policies and regulations that control the import and distribution of invasive species needs to be rigorously and comprehensively implemented;
2) Biological countermeasures can offer a very cost-effective solution to continuing invasion, but other methods of control also need to be investigated,
3) Control measures should not be delayed because of the cost implications,
4) Projects for clearing alien plant invaders should use rate of spread as a means of prioritization, and
5) The ecology and economics of invasions are not well understood and the subjects need investment.

By influencing the key driving force of laws, policies and regulations, the country can influence which future trajectory of invasion is followed. Through rigorous implementation of regulations, the country can put itself on a trajectory or path towards the *New Mozaic* or *Garden of Eden* scenarios. This will reduce the number of propagules entering the country. The future is then influenced only by the way the economic future plays out. Laws, policies and regulations should be researched, formulated and implemented in a coherent matter. Coherency of these regulations implies the need for a national weed strategy – this might include a national Weed Act. Policies should not be separated according to the different sectors that are affected by invasions.

Although there is some uncertainty regarding spread-rates, the general trend of the simulation results indicate the possibility of very significant cost advantages of biological countermeasures. A key conclusion therefore is that biological countermeasures should be a high research priority for government as a means of protecting ecosystems and ecosystem services. While it will take several years of research before biocontrol agents could be found for some of the most problematic invader species, the payoffs, or benefits, that could be obtained from successful biocontrol agents could be very large.

Simulations have also shown that the failure to prioritise the most rapidly spreading species results ultimately in far higher control costs. A corollary to this is that postponing control measures also results in significantly higher costs. While there may be cogent reasons for postponing expenditure because of competition for scarce funds, these arguments rarely consider the greatly increased costs that are implied for control measures at a later stage. Because large populations of alien plants have already become established in South Africa, implementing control measures will be difficult and costly.

There is a high risk in relying on the later development of biological countermeasures to avoid expenditure of funds on clearing costs now. The development of biological countermeasures is not a straightforward science and the process takes a few years to be proved a viable method.

The ecology of biological invasions, and their economic impacts, is not well understood. It is fairly easy to see the macro effects of these invasions, but their economic impacts have never been quantified in terms of the lost opportunity costs of water consumed by invaders, or lost productivity as a result of erosion of soils and loss of biodiversity, or the costs incurred in maintaining land in a productive state. Investment is required in both developing the science and economics of invasions.

Finally, the scenario development process has been useful in showing that there can be significantly different future outcomes for the country, depending on which choices we choose to follow today. By building a scenario tool, we are able to consider alternative future environments that may result from today's decisions.

Furthermore, a modelling tool has enabled us to see how the human/invader system behaves with respect to the removal of the invaders and the benefits that the removal activities bring. Through modelling, this project has developed an easy to use but powerful model for evaluating project options, through the use of the URV.

We have shown that the country is in a *stage* of invasion, which represents a lost/not lost opportunity for intervention. The key to future sustainability of South Africa's ecosystems and the services they provide it to act now.

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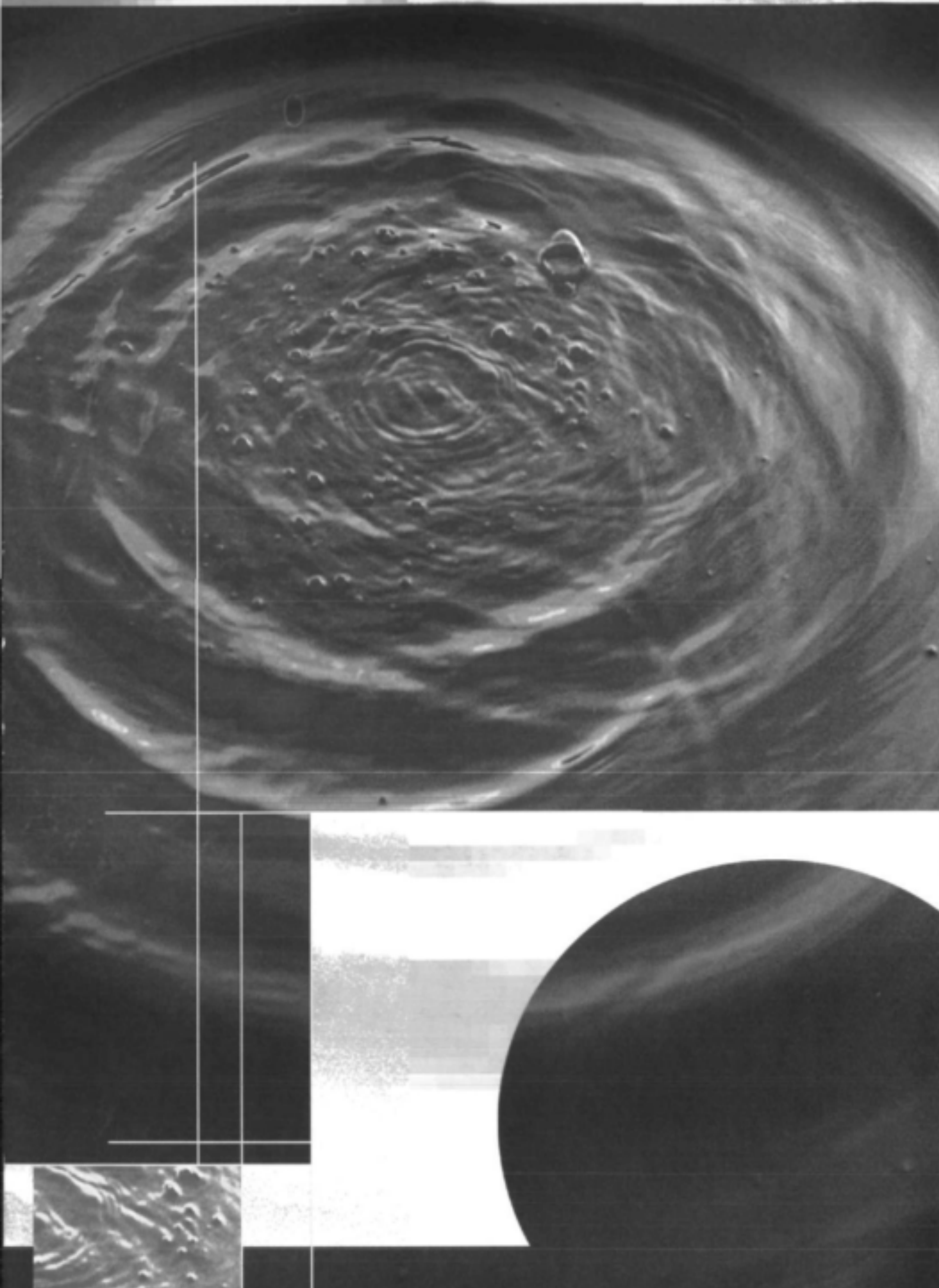

Water Research Commission

PO Box 824, Pretoria, 0001, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www.wrc.org.za

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