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Economics of invasive alien species: pre-emptive versus reactive control

Licentiate Thesis

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ECONOMICS OF INVASIVE ALIEN SPECIES: PRE-EMPTIVE VERSUS REACTIVE CONTROL

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PREFACE

This thesis builds on five pieces of earlier work. My dissertation for the degree of Bachelor of Science from the University of York, United Kingdom (Heikkilä 1999) provided a good starting point. In addition, one refereed book chapter, two refereed research articles and one poster written in collaboration with Dr. Jukka Peltola (Heikkilä and Peltola forthcoming; 2004; 2003; 2002) provided the basis for the theoretical and empirical analysis conducted in this thesis. The analysis presented in these papers provides the core of this thesis, but this forum allows me to extend the discussion in two important ways. First, it is possible to elaborate on the results and discuss the relevant factors in greater detail than is possible in research articles. Second, it is possible to relate the discussion to the wider background – the global challenge of dealing with invasive alien species.

Parts of this thesis provide a component for the work done in a collaborative research project of the University of Jyväskylä, University of Helsinki and MTT Agrifood Research Finland. The three-year research project, funded by the Ministry of Agriculture and Forestry, was finished in 2006. Its main economic objective was to determine the economically most sensible control policy for the Colorado potato beetle and to participate in producing a pest risk analysis for the plant protection authorities. Thanks are due to Professor Johanna Mappes at the University of Jyväskylä for directing that project. With gratitude I would also like to acknowledge funding for my studies from Emil Aaltonen Foundation and Aino and August Johannes Tiura Foundation.

This thesis has been in preparation for about four years. To my satisfaction, I can note that it has been outdated in two respects. First, the new Finnish Food Safety Authority Evira started its work on 1 May 2006. It is a merger of the National Veterinary and Food Research Institute, the National Food Agency, the Plant Production Inspection Centre and certain sections of the Ministry of Agriculture and Forestry. The new authority may – hopefully – be able to look at the issue of biosecurity in a more holistic fashion than earlier separate institutions. Second, a national strategy for invasive alien species is under preparation. This is also likely to help in approaching the issue in a comprehensive manner. These two recent changes are not accounted for in the discussion and analysis within this thesis.

A thesis nominally introduces the work of one person. In reality, many others have contributed to its making in various ways. When I first started working on the Colorado potato beetle in York back in 1998, I had little idea that the small bug would a few years later get me a job and another degree. In 2002 I began to work on the topic again. I would like to express my sincere gratitude to Dr. Jyrki Aakkula and Dr. Jukka Peltola who had enough trust in me to employ me at MTT Economic Research. I would like to thank the Director of Economic Research, Docent Kyösti Pietola for encouragement, support and flexibility in letting me work on this thesis. I would also like to extend my thanks to other staff at MTT Economic Research for making it such a cosy place – both at worktime and at sparetime. Very special thanks naturally go to my collaborator Dr. Jukka Peltola (currently at the Prime Minister's Office). His enthusiasm, insight, (plentiful!) ideas, comments, humour and support have done much good to understanding and dealing with the issues discussed in this thesis, as well as to understanding how research and work is conducted in general.

At the University of Helsinki, Department of Economics and Management, I would like to thank my supervisor Professor Markku Ollikainen for his valuable insight and comments. Thanks are also due to participants at the environmental economics research seminars, and especially to Dr. Marko Lindroos, Dr. Chiara Lombardini-Riipinen, M.Sc. Piia Aatola, M.Sc. Antti Iho, M.Sc. Anna-Kaisa Kosenius, M.Sc. Antti Miettinen, M.Sc. Kimmo Ollikka and M.Sc. Jarno Virtanen who read through and commented on parts of the thesis. Thanks are extended also to participants at the FRONTIS workshop on economics of plant health in Wageningen, the Netherlands, who provided comments on the research conducted for this thesis. I would also like to thank the examiners for their constructive comments. Finally, I would like to thank my parents as well as my friends and relatives, without whom many things, including this thesis, would have little meaning.

Helsinki, 7 December 2006
Jaakko Heikkilä

ABSTRACT

The expanding global economy presents various challenges to production and environmental systems worldwide. Biosecurity provides a framework for managing the risks presented by different types of diseases and species spread by globalisation. One element of biosecurity is protection against invasive alien species (IAS). These are species spread by human actions outside their natural zones of dispersal. IAS present a threat to biological diversity at all levels and may have a negative impact on the goods and services provided by ecosystems. IAS may result in non-production and production costs. The first category includes physical impacts materialising as environmental, health and cultural costs, whereas the second category includes the subsequent economic impacts, such as production losses, domestic market effects and trade effects. In addition, IAS may impose control costs either on the society or a specific sector, depending on the type of species and the chosen policy. Management of IAS is a public good and remains under-provided by the free market, which partly explains the involvement of the state in IAS control.

A broad division of IAS management is between what is here called pre-emptive and reactive control. Pre-emptive control refers to actions taken to totally eradicate the IAS when found. Such actions reduce the probability of entry and/or establishment of IAS. Reactive control refers to letting a possible invasion to take place and be followed by application of reactive control measures, reducing the extent and magnitude of damages in the event of an invasion. Preventative actions are generally advocated as the preferred strategy to deal with IAS, but it is possible that the costs incurred due to an invasion are less than the costs incurred in continued preventative actions. In such a case, continued efforts to prevent the species from invading consume the limited resources and may lead to other, more dangerous, species not being targeted with sufficient resources. These two policies are in this study considered in the context of the Colorado potato beetle (CPB). The CPB is a destructive plant pest, whose main host plant in Finland is the cultivated potato. The potential for the beetle's range expansion to Finland has been shown by both genetic and climatologic studies, and it provides a convenient case for studying the effects of invasions, uncertainty and local change. Given the life history characteristics of the CPB, there are five important factors from an economic point of view. First, the beetle has spread very rapidly across the continent, although its spread has slowed down as it has approached its ecological limits. Second, in propitious environmental conditions its population size can increase extremely rapidly. Third, it is capable of causing significant damage to potato plants. Fourth, cold summers and winters hinder its establishment, but it is most likely capable of establishing in at least some parts of Finland. Finally, lack of natural predators and ability to develop resistance to chemical control substances make the beetle difficult and expensive to control.

This thesis seeks answers to four specific issues: i) review and evaluate the scale, type and magnitude of impacts IAS are capable of causing; ii) specify the policy problem in IAS management and review how the institutional framework in Finland addresses the issue; iii) review existing cost-benefit studies on agricultural IAS and determine the components that such studies should include; and iv) undertake an economic risk assessment of the CPB in Finland and evaluate the conditions under which it is optimal to prevent the species from establishing. On basis of a literature review undertaken, we suggest ten points to be taken into account when conducting economic policy evaluations of IAS: i) choose at least two realistic policy options to evaluate; ii) consider all possible direct and indirect impacts, monetise the ones you can and take the others into account qualitatively; iii) describe which costs and whose costs are included in the analysis and how they are derived; iv) formalise the basis of the analysis; v) undertake an ex-ante analysis to supplement an optional ex-post analysis; vi) carry out sensitivity and uncertainty analysis; vii) consider how the impacts excluded from the quantitative analysis affect the results; viii) discuss to whom the costs and benefits accrue; ix) make a (conditional) policy recommendation; and x) relate the findings to the wider framework of biosecurity measures.

The empirical analysis uses a cost-benefit framework to assess the policy response, comparing the costs of prevention with the costs that would ensue if the species is allowed into the country. The primary focus is on ex-ante analysis, although an ex-post assessment of past seven years is also conducted. The framework presented estimates expected aggregate costs over time, using Monte Carlo simulation and allowing stochastic variation in the key variables. In addition, linear temporal change in certain key variables is included in the analysis. The main lesson from the ex-post cost-benefit analysis carried out in this study is that it is not sufficient to look at the costs over only a short period of time. Protection against IAS is to a large extent an investment that may produce potentially very high revenues in terms of avoided costs in the future. The results of the ex-ante cost-benefit analysis indicate that the current policy based on a protection system is economically viable, provided that there will be some future change and a non-insignificant level of pest winter survival. Considered the other way round, we can give up protection if we are certain that there is no future change, pest winter survival stays permanently below about 20%, or potato crop losses will not exceed 5% of the yield. If we cannot be certain that one of these three conditions materialises, we should be cautious regarding the possibility of abandoning protection because the risk associated with giving up protection is at the extreme nearly thirty times greater than that associated with protection. Results also indicate that the fact that invasions come very seldom is not a valid argument for abandoning protection, and that it is the variable costs of the protection system rather than the fixed costs that are important in determining policy profitability. The sensitivity analysis suggests that winter survival, logistic spread rate and variable cost of protection are the most important variables in determining economic profitability. The aggregate results suggest that the current policy of CPB exclusion should be continued.

The future challenge lies in considering the issue of IAS and diseases in a holistic biosecurity framework. Within this framework, the issue would be managed in an integrated fashion from the point of view of multiple threats, multiple pathways, multiple parties involved and multiple methods and stages of control. Many challenges lie ahead in planning a functioning framework to deal with the issue of biosecurity.

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LIST OF ACRONYMS

ADI	Acceptable daily intake
AIDS	Acquired Immune Deficiency Syndrome
BCR	Benefit-cost ratio
BSE	Bovine spongiform encephalopathy
Bt	*Bacillus thuringiensis*
C	Celsius (Centigrade)
CAD	Canadian dollar
CBD	Convention on Biological Diversity
CDF	Cumulative density function
CITES	Convention on International Trade in Endangered Species of Wild Flora and Fauna
CPB	Colorado potato beetle
CS	Consumer surplus
DDT	Dichloro-diphenyl-trichloroethane
DEFRA	Department for Environment, Food and Rural Affairs (UK)
DEM	Deutschmark
e	Euro
EC	European Community
EPPO	European and Mediterranean Plant Protection Organisation
EU	The European Union
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic information system
HIV	Human immunodeficiency virus
IAS	Invasive alien species
KTTK	Kasvintuotannon tarkastuskeskus, Plant Production Inspection Centre (Finland)
LHS	Left hand side
MAF	Maa- ja metsätalousministeriö, Ministry of Agriculture and Forestry (Finland)
MC	Marginal cost
MR	Marginal revenue
MTT	Maa- ja elintarviketalouden tutkimuskeskus, Agrifood Research Finland
NPV	Net present value
NTB	Non-tariff barrier
PDF	Probability density function
PS	Producer surplus.
PV	Present value
RHS	Right hand side
SBSTTA	Subsidiary Body on Scientific, Technical and Technological Advice
SPS	Agreement on the Application of Sanitary and Phytosanitary Measures
TBT	Agreement on Technical Barriers to Trade
TSWT	Tomato spotted wilt tospovirus
UK	United Kingdom
UN	United Nations
US(A)	United States (of America)
WHO	World Health Organization
WTO	World Trade Organisation
ZP	Zone protégée, protected zone

LIST OF SPECIES

Latin name	**Common name (if available)**
Acacia dealbata	[wattle]
Acacia mearnsii	[wattle]
Aedes albopictus	Asian tiger mosquito
Anoplophora glabripennis	Asian longhorn beetle
Aphanomyces astaci	[fungus]
Arion lusitanicus	Spanish slug
Astacus astacus	Crayfish
Avena fatua	Common wild oat
Avena sativa	Oat
Bacillus thuringiensis	[bacterium]
Bemisia tabaci	Tobacco whitefly
Berberis vulgaris	Barberry
Boiga irregularis	Brown tree snake
Branta canadensis	Canada goose
Brassica napus	Oilseed rape
Bursaphelenchus xylophilus	Pinewood nematode
Castor canadensis	Canadian beaver
Castor fiber	European beaver
Centaurea solstitialis	Yellow starthistle
Cercopagis pengoi	Spiny water flea
Chrysomya bezziana	Screwworm fly
Clavibacter michiganensis sepedonicus	[bacterium]
Clupea harengus membras	Baltic herring
Coleomegilla maculate	Pink spotted lady beetle
Convolvulus arvensis	Field bindweed
Cygnus cygnus	Whooper swan
Cygnus olor	Mute swan
Dama dama	Fallow deer
Diabrotica virgifera virgifera	Western corn rootworm
Doryphorophaga doryphorae	[parasitic fly]
Dreissena polymorpha	Zebra mussel
Engraulis encrasicolus	Anchovy
Erwinia amylovora	[bacterium]
Eucalyptus	[tree]
Euphorbia esula	Leafy spurge
Edovum puttleri	[parasitic wasp]
Frankliniella occidentalis	Western flower thrips
Galium album	Upright bedstraw
Galium verum	Lady's bedstraw
Gleditsia triacanthos	Honeylocust
Globodera pallida	Pale cyst nematode
Haliaeetus albicilla	White-tailed sea eagle
Halicoerus grypus	Grey seal
Heracleum spp.	Hogweeds
Homo sapiens	Human
Hordeum vulgare	Barley
Hystrix brachyura	Himalayan porcupine
Impatiens glandulifera	Himalayan balsam
Lates nilotica	Nile perch
Lebia grandis	[ground beetle]
Leptinotarsa decemlineata	Colorado potato beetle
Loxodonta africana	African elephant

LIST OF SPECIES CONTINUED…

Latin name	Common name (if available)
Lupinus spp.	Lupin
Lythrum salicaria	European purple loosestrife
Matsucoccus feytaudi	Maritime pine bast scale
Meligethes aeneus	Pollen beetle
Mnemiopsis leidyi	Leidy's comb jelly
Morella faya, previously *Myrica faya*	Fire tree
Mustela lutreola	European mink
Mustela vison	Mink
Nyctereutes procyonoides	Raccoon dog
Odocoileus virginianus	White-tailed deer
Ondatra zibethicus	Muskrat
Oryctolagus cuniculus	European rabbit
Ostrinia nubilalis	European corn borer
Pacifastacus leniusculus	Signal crayfish
Panthera leo	Lion
Phalangium opilio	Daddy longlegs
Phasianus colchicus	Pheasant
Plasmodium spp.	[parasitic protozoa]
Podisus maculiventris	Spined soldier bug
Pomacea canaliculata	Golden apple snail
Populus spp.	[tree]
Puccinia graminis	Black rust
Pusa hispida	Ringed seal
Ralstonia solanacearum	[bacterial pathogen]
Rastrococcus invadens	Mango mealybug
Rattus exulans	Pacific rat
Rosa rugosa	Rugosa rose
Schistocerca gregaria	Desert locust
Sciurus carolinensis	Grey squirrel
Sciurus vulgaris	Red squirrel
Secale cereale	Rye
Solanum tuberosum	Potato, cultivated
Solenopsis invicta	Red imported fire ant
Tamarisk spp.	Saltcedar
Thrips palmi	Melon thrips
Tilletia indica	[fungus]
Trichosurus vulpecula	Possum
Triticum aestivum	Wheat
Xylella fastidiosa	[bacterium]

LIST OF DISEASES

Avian influenza
Beet necrotic yellow vein furovirus
Bovine spongiform encephalopathy
Citrus canker
Classical swine fever
Dengue fever
Eastern equine encephalitis
Fireblight
Pierce's disease
Tomato spotted wilt tospovirus

LIST OF SYMBOLS

A_{INITt}	Invasion magnitude (from outside) (ha)
$A_{INITtrend}$	Trend variable in invasion magnitude (slow/rapid)
A_t	Annual area controlled (ha)
a_t	Spread area in linear spread (ha)
A_{TOT}	Total production area (ha)
C	Total costs of pre-emptive control (e)
C_F	Fixed costs of pre-emptive control (e)
C_{Vt}	Variable costs of pre-emptive control (e)
D_t	Crop damage caused by the pest (%), $0 \leq D_t \leq 1$
F	Fixed costs, bought services and miscellaneous costs (e)
g	Inspection area multiplier
h	Production area of representative producer (ha)
I_t	Annual variable inspection visits (visits)
K	Carrying capacity of the system
loc	Location
N_{0i}	Number of pest individuals invading the i^{th} hectare
N_t	(Post-control) population size at time t
p_B	Pre-invasion (base) producer price (e)
p_S	State-dependent producer price (e)
p_t	Modified potato producer price (e)
p_x	The per unit price of non-control inputs (e)
p_z	The per unit price of control (e)
$p_z z_{trend}$	Trend variable in z_t (slow/rapid)
q	Base production quantity per hectare (kg)
R	Reproductive rate
r	Discount rate (%)
s_{INITt}	Spread multiplier in first year
s_t	Spread multiplier in nonlinear spread
T	Terminal time period
t	Time period
v	Reduction in pest numbers due to control
V_1	Variable costs, bought services per visit (e)
V_2	Variable costs, control substances per ha (e)
V_{2trend}	Trend variable in V_2 (slow/rapid)
V_3	Variable costs, eradication and compensation per ha (e)
w_t	Failure area of pre-emptive control (%), $0 \leq w_t \leq 1$
w_{trend}	Trend variable in failure area of pre-emptive control
x_t	Quantity of non-control inputs
z_t	Quantity of control inputs per hectare (reactive control)
γ_t	Invasion probability (%), $0 \leq \gamma_t \leq 1$
γ_{trend}	Trend variable in invasion probability (slow/rapid)
Δ	Change
Δp_t	Invasion induced price change (e)
ε	Yield effect on price
η	Effectiveness of control inputs
ξ	Size of the invasion
π_i	Producer profit (e)
Π_t	Aggregate producer profit (e)
θ_t	Proportion of population that survives winter (%), $0 \leq \theta_t \leq 1$
θ_{trend}	Trend variable in winter survival (slow/rapid)
φ	Number of pest individuals eradicated by the producer
ω_t	Failure probability of pre-emptive control (%), $0 \leq \omega_t \leq 1$
ω_{trend}	Trend variable in failure probability
*	Optimum value

1. INTRODUCTION

1.1 The challenge of invasive alien species

The expanding global economy presents various challenges to both production and environmental systems worldwide. Biosecurity provides a framework for managing the risks presented by different types of diseases and species spread by globalisation. One element of biosecurity is protection against invasive alien species (IAS). These are species that are spread by human actions outside their natural zones of dispersal. The increasing scale of international commerce and travel together with the expansion of free trade areas, intensifying production practices and climatic changes increase the risk of IAS spreading also to more distant geographic locations, including Finland. For the purposes of this study, IAS are defined as follows (after Clinton 1999).

DEFINITION 1 – INVASIVE ALIEN SPECIES
Invasive alien species is with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem and whose introduction does or is likely to cause economic or environmental harm or harm to human health.

IAS can be introduced outside their natural habitats either intentionally or unintentionally. In the new habitats they can establish, outcompete native species and take over the new environments. IAS are found in most geographic locations, in most categories of living organisms and in most ecosystem types. They thus present a threat to biological diversity at all levels and may have a negative impact on the goods and services provided by ecosystems (Vitousek et al. 1996).

IAS may result in either non-production or production costs, or both. The first category includes physical impacts materialising as environmental, health and cultural costs, whereas the second category includes the subsequent economic impacts, such as production losses, domestic market effects and trade effects. In addition, species in both categories may impose control costs either on the society or a specific sector, depending on the type of species and the chosen policy. In the United States about a quarter of all agricultural gross national product is lost annually due to damages imposed by invasive pests or costs of their control (Schmitz and Simberloff 1997; U.S. Congress, Office of Technology Assessment 1993). Globally, agricultural losses to introduced species could be between US$ 55-248 billion annually (Bright 1999).

Invasions take place on a global scale and will continue rapid increase in this century due to interplay with other global changes such as increasing globalisation of markets and rapid increases in global trade, travel and tourism (Di Castri 1989). Especially in the northern regions, climatic changes and global warming are predicted to increase invasion attempts of alien species, including invertebrate pests, fungi, bacteria and viral diseases (Jeffree and Jeffree 1996; MAF 2005; Walker and Steffen 1997). Threats to animal and plant health by invading organisms are thus on the increase. This means that also the environment, natural resources and resource-based production in Finland are prone to attacks by invasive species. Examples of such species in Finland are provided by pinewood nematode (*Bursaphelenchus xylophilus*), Colorado potato beetle (*Leptinotarsa decemlineata*) and hogweeds (*Heracleum* spp.).

Changes in local climatic conditions and agricultural policies as well as uncertainty related to stochastic environmental fluctuations make invasive species policy relatively challenging to design and implement. These changes are often exacerbated by dynamic changes in the species characteristics. Management of IAS is nonetheless a public good – a good that is non-excludable in production (anybody can enjoy the benefits) and non-rival in consumption (usage does not diminish the good). Due to these characteristics consumption exceeds supply, and invasive species control remains under-provided by the free market. This partly explains the involvement of the state in IAS control measures.

The European Community has recognised IAS as an emerging issue, but so far relatively little work has been done on economic evaluation of IAS impacts. At ministerial level, the Council of the European

Union "stresses the importance of capacity building in relation to invasive alien species" (Council of the European Union 2002a). In Finland very little economic policy analysis of IAS has been carried out. Different pests and pathogens have naturally been studied, but it is only recently that the issue has been viewed in the larger framework of IAS. In a recent publication regarding the future development of the Finnish agrifood sector to year 2030 (MAF 2002a) IAS are indirectly mentioned in several parts. For instance, climatic changes and free movement within the expanding European Union are seen to promote establishment of new weeds, diseases and pests. The issue, therefore, is beginning to attract wider recognition.

1.2 Pre-emptive and reactive control

The broadest division of IAS management is between what is here called pre-emptive and reactive control. In other words, whether there should be a system (institution or instrument) that ex-ante aims to reduce the likelihood of entry and/or establishment of IAS, or whether resources should be devoted to ex-post reactive control if and when the IAS invades in order to reduce the impact of the entry and/or establishment (Perrings 2005).

DEFINITION 2 – PRE-EMPTIVE CONTROL
Pre-emptive control refers to actions taken to provide the appropriate infrastructure and to maintain vigilance regarding possible invasion events and, if and when found, totally eradicate the invasive species using the available resources. Pre-emptive control reduces the probability of entry and/or establishment of an invasive alien species.

DEFINITION 3 – REACTIVE CONTROL
Reactive control refers to letting a possible invasion to take place and be followed by application of reactive control measures such as chemical control, in order to control the damages that the invasive species may impose. Reactive control reduces the extent and magnitude of damages in the event of an invasion by an invasive alien species.

The division made here is just one of many possible categorisations. For instance, Filbey et al. (2002) divide the United States state-level legislative tools to five categories: i) prevention; ii) regulation; iii) control and management; iv) enforcement and implementation; and v) co-ordination. For the purposes of this study, the two-fold division above is, however, sufficient.

Preventative actions are generally advocated as the preferred strategy to deal with IAS (e.g. Perrault and Carroll Muffett 2001), but it is nonetheless possible – at least for certain species – that the costs incurred due to an invasion are less than the costs incurred in continued preventative actions. In such a case, continued efforts to prevent the species from invading consume the limited resources and may possibly lead to other, more dangerous, species not being targeted with sufficient resources. Furthermore, many species are imported for use in recreation (e.g. pheasant) or production (e.g. mink) or for other beneficial purposes (e.g. canaries and parrots). The optimal policy should allow imports of species that result in greater aggregate benefits than costs, but prohibit species that cause more costs than benefits. In other words, the policy should allow actions that produce positive net benefits for the society.

An example of the pre-emptive approach is the European Union system of protected zones (ZP, zone protégée) which aims to prevent the introduction and spread of organisms harmful to agricultural production.[1] Protected zones are a regional tool that can be used to account for differences in ecological conditions. They are defined as follows (after EC 2000).

DEFINITION 4 - PROTECTED ZONE
Protected zones are zones "in which one or more harmful organisms referred to in [the] Directive, which are established in one or more parts of the Community, are not endemic or established despite favourable conditions for them to establish themselves there [or] in which there is a danger that certain harmful organisms will establish, given propitious ecological conditions, for particular crops, despite the fact that these organisms are not endemic or established in the Community."

[1] For a brief review of the European plant health framework, see Pfeilstetter (2005) or Unger (2005).

Under the protected zone system it is permissible to import agricultural products associated with the harmful organism into a protected zone only from another protected zone or from a designated buffer zone. The system also requires eradication of quarantine pests if they are found within the protected zone. Pre-emptive control in this paper deals mainly with reducing the likelihood of establishment through eradication.

The EU legislation is incorporated into Finnish national legislation through the Act on the Protection of Plant Health of 2003. It aims at eradicating quarantine organisms if encountered in Finland by obligating individual farmers within Finland to inform the authorities of any quarantine pest observations and to follow any orders from the plant protection authorities regarding eradication of those species. It also specifies penalties for not following orders and obligations and sets out the rights of producers to compensation (Government of Finland 2003).

The six quarantine organisms for which Finland has a European Union protected zone – and which thus have to be eradicated if encountered – are presented in Table 1 (after KTTK 1998; MAF website; MAF 2003d; MAF 2004a,b).

Invasive species	***Type and status***	***Economic analysis***
Beet necrotic yellow vein furovirus	Disease of the goosefoot family, in Finland mainly sugar beet is at risk. Spreads easily and is difficult to eradicate from soil. Has not been encountered in Finland.	None to our knowledge
Colorado potato beetle *(Leptinotarsa decemlineata)*	Important insect defoliator of potato. Has not established permanently in Finland.	Current study
Fireblight (caused by *Erwinia amylovora)*	Bacterial disease of ornamental shrubs and fruit trees. Has not been encountered in Finland. Control is very difficult.	None to our knowledge
Pale cyst nematode *(Globodera pallida)*	Worldwide one of the worst pests of potato. Control is difficult. Has not established permanently in Finland.	Qualitative (MAF 2004a)
Tobacco whitefly *(Bemisia tabaci)*	Pest that has multiple hosts, transmits viruses and is resistant to several pesticides. In Finland can only live in greenhouses and has not established permanently.	None to our knowledge
Tomato spotted wilt tospovirus	Important disease of vegetable and ornamental plants. Encountered sporadically in Finland.	MAF (2003d)

Table 1. Quarantine plant pests with a protected zone in Finland.

In addition to giving protection against invasive organisms, protection systems may also act as technical barriers to trade and as such potentially give the areas concerned an artificial trade advantage. Concern regarding this issue has been voiced by for instance Australia in the COP-6 meeting of the parties to the Biodiversity Convention (ICTSD 2002). The issue is indeed problematic due to the difficulties present in differentiating legitimate sanitary and phytosanitary measures from disguised protectionism (Margolis et al. 2005).

Actions involved in preventing a pest from invading and establishing are costly, comprising for example surveillance, labelling, import restrictions, eradication, compensation payments and post-monitoring. Often the benefits of not having the pest around outweigh these costs, but this is by no means inevitable (Mumford 2002). Several countries have voluntarily renounced their EU protected zone, including the UK (except for Northern Ireland) for beet necrotic yellow vein virus, France for maritime pine bast scale (*Matsucoccus feytaudi*) and Denmark for tomato spotted wilt tospovirus and tobacco whitefly (*Bemisia tabaci*) (European Commission 2000, EC 2000). Economic factors are likely to have influenced these decisions. Furthermore, on at least one occasion cost-benefit analysis has been in favour of denouncing the protection system (MacLeod et al. 2005).

In pre-emptive control the economic cost can be divided into fixed and variable costs of the protection system. The fixed costs consist of maintaining the appropriate infrastructure and undertaking regular checks to monitor the pest status.[2] The variable costs depend on the invasion frequency and magnitude and consist of authority driven eradication of the pest and financial compensation for the producers. The protection system may also impose costs through trade effects, as the exports of infected countries

[2] It is perhaps worth clarifying that by fixed costs we mean costs that are independent of the presence or the absence of the pest. The exact amount of fixed costs can still vary over time, for instance depending on technology. In the empirical analysis carried out in this study, the level of fixed costs is assumed to remain unaltered.

are restricted or banned. In the case of reactive control two types of costs materialise. First, there are changes in producer surplus due to price changes, pest control costs and the value of the lost production, caused by imperfect control or interim damage occurring before control application.[3] Second, there may be changes in consumer surplus if product prices increase due to reduced supply. Also possible environmental, health or cultural impacts may reflect on consumer welfare.

Even in this simple pre-emptive versus reactive control framework there are various outcomes that may occur. Our framework consists of two pure strategies. The first is to invest resources to prevent the pest from invading and establishing in the first place. The second strategy alternative is to ignore pre-emptive actions, let the pest invade if it so happens and let the producers adapt to the pest's presence. In principle also a spatially or temporally combined case is possible. In the spatially combined strategy pre-emptive actions would be carried out in certain areas, whereas reactive control would be applied in other areas. In temporal combination pre-emptive control would be carried out first, followed by reactive control. However, neither of these combinations is analysed in this study.

It should be noted that the two strategies as defined here cannot be taking place at the same time in the same place.[4] Pre-emptive control consists of (authority driven) eradication in the case of an invasion and of maintaining the appropriate organisation in the non-invasion times. Hence it is either the plant protection authority eradicating any outbreaks, or the management is left entirely to producers thus giving up the goal of eradication. The same conclusion in the case of the Colorado potato beetle in the United Kingdom is reached by Mumford et al. (2000), who note that "there are few alternatives to the two policy options of: i) exclusion (with eradication of outbreaks) [and] ii) abandoning exclusion and relying on grower routine management and control".

In addition to aggregate costs of the policies, the policy choice also affects the distribution of costs and income. This effect takes place through funding of the policy as well as through the price of the affected (agricultural) product. The prices may be affected by the demand side factors (which in this study are assumed to remain unchanged), the production costs, the total quantity produced and the effect of the total amount produced on price. Production costs may increase due to additional inputs being required to control the invasive pest. The total quantity on the other hand may be affected by crop damage done by the pest. Depending on the market structure, these translate into changes in the consumer price.

Such domestic price changes are likely if the aggregate output changes sufficiently and international price transfers are imperfect (i.e. imports are not a perfect substitute for domestic production or world price with transportation is above the domestic price). Hence, aggregate producer profit after an invasion may turn out to be higher than before the invasion, if the price increase is sufficient to compensate for the increased costs of production and any crop losses. Basically two types of changes in the division of income can be considered. First, some producers may be affected by the invasion more than others, resulting in a redistributed division of profits among the producers. Second, the price increases may increase producer profits, but at the same time reduce consumers' surplus.

To whom the policy costs and benefits accrue depends largely on which policy is chosen and how it is financed. It is naturally possible to construct different types of transfer mechanisms, and hence the costs and benefits can in theory be targeted at any desired group within the society. Because in this study an equal weight is given to both producers and consumers, to whom the costs and benefits accrue does not impact on the aggregate economic performance of the two policies. Hence the equity discussion can be to a large extent separated from the efficiency discussion. Issues dealing with to whom the costs and benefits accrue are discussed in more detail at the end of this study.

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[3] In addition there may be demand-side factors that affect producer surplus, for instance through potentially unfounded fears people have regarding diseases related to the product in question. These impacts are beyond the scope of this study, but it should be noted that in some cases such impacts may be sizable.

[4] Note, however, that what is termed pre-emptive and what reactive depends on what is chosen as the decision point, for instance whether preventing invasion or establishment is the primary target (see for instance Perrings 2005).

Throughout this study it is assumed that the producers will only have to encounter the costs of lost production and the costs of control in the case of reactive control, whereas the consumers[5] end up paying the costs of the protection system as well as suffer possible invasion induced changes in consumer surplus. This is consistent with reality in that Community and national legislation allow the producers to get compensation for the lost production and eradication costs associated with the protection system. The policy choice thus has economic and distributional implications. These costs and their effects on different parties (as assumed in this study) are summarised in Table 2.

Policy Choice		Expected costs	Who bears the costs
Pre-emptive control	INVASION	Variable costs of the protection system, fixed costs of the protection system	Consumers/taxpayers
	NO INVASION	Fixed costs of the protection system	Consumers/taxpayers
Reactive control	INVASION	Consumer surplus changes, producer surplus changes	Consumers/taxpayers, (affected) producers
	NO INVASION	None	None

Table 2. The costs associated with the two policies.

1.3 The case study: Colorado potato beetle

The Colorado potato beetle (*Leptinotarsa decemlineata*) (CPB) is a destructive plant pest, whose main host plant in Finland is the cultivated potato (*Solanum tuberosum*). The CPB is established in North America, some Central American countries, many Asian countries and most European countries (EPPO 2005; EC 2000). It was introduced from the United States to France in 1922, from where it rapidly spread throughout Europe (EPPO 2005). In addition to Finland, other areas in Europe that remain free of the beetle include Ireland, United Kingdom, Sweden and certain Spanish and Portuguese islands.

The beetle's primary mode of transport to Finland seems to be wind-borne long-distance migration. The first invasion by the CPB in Finland took place in 1983, but was localised and short-lived. The two main recent invasions were in 1998 and 2002, with the first confirmed case of winter survival observed in 2004. Most of the plots affected in both 1998 and 2002 were situated in the south-eastern Finland, suggesting that the beetles had spread from either Russia or Estonia. The potential for the beetle's range expansion to Finland has been shown by both genetic (Boman et al. 2006a) and climatologic (Baker et al. 1998; Jeffree and Jeffree 1996) studies.

About 30-40% of the total potato production in Finland is in the CPB protected zone, which covers the regions of Satakunta, Turku, Pirkanmaa, Uusimaa, Häme, Kymi and the Åland Islands. The actions and eradication measures within the protected zone are determined by national and Community legislation (EC 2000; KTTK 1998; MAF 2004b). Although the protected zone is only for the given areas, national actions are applied in the entire country and hence the beetle is to be eradicated wherever encountered.

The protected zones are a voluntary black-list instrument that member countries may use to protect their production environment against specified invasive plant pests. This protection comes at a cost, which should be compared to costs that would ensue given alternative policy strategies. The studies carried out on policy effectiveness in the case of the CPB have indicated that the costs of exclusion measures have been less than the costs that would ensue would it be introduced (Mumford et al. 2000; Aitkenhead 1981 cited in EPPO 2005). The specific aim of this study is to evaluate the desirability of continuing this policy of exclusion in Finland in relation to Colorado potato beetle.

However, invasions are not a stagnant and certain process. Hence uncertainty and change are important to account for when choosing to design and implement various policies. In the case of the CPB in Finland these are integral to the problem. Existing uncertainty can be divided into three categories

[5] Consumers are in this study equated with taxpayers, as potato is such a widely used product in Finland that it is consumed by practically everyone.

according to Heal and Kriström (2002). First, we are uncertain of the CPB invasion process and its pre-determinants in the points of origin in Russia. This can be seen as scientific uncertainty, which arises when a certain physical relationship is not known. Secondly, it is unknown how the continued invasions would affect the production patterns in Finland. This can be seen as impact uncertainty, where the impacts of natural phenomena on the various components of human societies are uncertain, even if the physical science behind them is known. Finally, there is a third type of uncertainty, which can be categorised as policy uncertainty. For instance, there is uncertainty related to which policies are needed to address the problems, how those policies impact on the issue in question and what are the costs of undertaking the policy.

Further, local changes are likely. First, Finland's membership in the European Union has opened borders and increased trade and movement of goods and people. Secondly, potential warming of temperatures may be changing environmental conditions in Finland. With the changing weather, the threat from both increasing invasion pressure and permanent establishment of the CPB in Finland increase. Finally, agricultural practices and modifications in those practices in surrounding countries as well as in Finland may also increase the invasion pressure. Resulting from all this, the CPB invasion pressure is increasing in Finland.

These factors prompt interest in finding efficient protection policies that would also function under uncertain and changing conditions. This study deals with ex-ante assessment of possible costs of an invasion by the CPB into the Finnish agricultural system. To account for uncertainty, invasions are modelled as temporally random events and stochasticity in key variables is built into the analysis. In addition, an extensive sensitivity analysis is carried out. To account for change, the analysis includes three trends that represent changes in climatic conditions and pest traits. In other words, uncertainty and local change are integral factors in the analysis.

1.4 The aims, methods and structure of the study

As the discussion above suggests, economic analyses of IAS are important because of the significant economic impacts they may impose and the public good properties involved in their management. This thesis considers the economic impact of IAS and assesses two alternative policies available for controlling their dispersal.

The general aim of this thesis is to discuss under which conditions it would be economically sensible from the society's point of view to prevent an invasive plant pest from invading Finland, and what would be the likely consequences if preventative actions were not taken. The specific aim is to evaluate the economic desirability of continuing the CPB protected zone policy in Finland, explicitly accounting for uncertainty and local change in the policy analysis.

The thesis provides grounds for policy assessment and produces practical information to aid decision-making related to CPB in specific and IAS in general. Four specific issues to which answers are sought are to:

i) review and evaluate the scale, type and magnitude of impacts IAS are capable of causing;
ii) specify the policy problem in IAS management and review how the institutional framework in Finland addresses the issue;
iii) review existing cost-benefit studies on agricultural IAS and determine the components that such studies should include;
iv) undertake an economic risk assessment of the Colorado potato beetle in Finland and evaluate the conditions under which it is optimal to prevent a species from establishing in this particular case.

The study uses a basic cost-benefit framework to assess the policy response. The framework used in this study compares the costs of prevention with the costs that would ensue in an alternative policy strategy in which the species is allowed into the country. The primary focus is on ex-ante analysis, although an ex-post assessment of past seven years is also conducted. The framework presented estimates expected aggregate costs over time, using Monte Carlo simulation and allowing stochastic variation in the key variables. In addition, linear temporal change in certain key variables is included in the analysis.

The issue can be approached from several points of view. In this thesis, the approach is multi-dimensional: to highlight the pervasive nature of IAS, several dimensions and approaches to the issue are presented. The thesis is a combination of three basic methods: i) prescriptive discussion of economic damages and the institutional framework; ii) theoretical analysis of the cost structure of pre-emptive and reactive policies; and iii) empirical cost-benefit analysis of the two policies using Monte Carlo simulation.

The discussion on IAS is divided into two sections. The first section provides basic physical information on IAS and the second section introduces economics to the discussion. The thesis addresses in part a multidisciplinary audience involved in plant health research and in governmental policy-making process. The aim in terms of this audience is to review the challenge presented by IAS and to conceptualise an economic response to the challenge, i.e. how to protect – in general terms – the environment, production systems and human health from the associated risks. The other half of the thesis narrows down the problem considerably, dealing in a temporal framework with one type of a pest – one that causes damage to agricultural production.

Zoonotic and animal diseases as well as environmentally harmful species are discussed whenever relevant, but the emphasis of the discussion is on plant health. The three main omissions from the scope of this study are that a thorough and complete discussion on ecology and management of IAS is left out, discussion of IAS impacts on foreign commerce is limited to certain basic observations, and genetically modified organisms are not accounted for. The chapters following the present one are organised as follows.

Chapter 2 provides a brief history of IAS and a literature review of their physical impacts. It also discusses the institutional context in which IAS are considered both internationally and in the European Union. The section reviews the situation in Finland and concludes by presenting the species discussed in the empirical section of the thesis – Colorado potato beetle.

Chapter 3 discusses the economic dimension of the IAS. The discussion begins with the type of economic benefits and costs that IAS may impose, including production losses, control costs, secondary market impacts and environmental, health and cultural effects. The chapter proceeds by presenting the IAS management problem and its public good properties, followed by a discussion of economic studies on IAS, concentrating on three themes: i) prediction and screening; ii) vulnerability of the ecological-economic system; and iii) optimal control. The chapter concludes by presenting several case studies where pre-emptive and reactive control are assessed in terms of economics.

Chapter 4 begins by discussing the preliminaries of the analytical model. It then constructs the equations used in the empirical section to evaluate the effects of the CPB under the two policies (pre-emptive control and reactive control). The appropriate comparative statics of the models are also discussed. The chapter provides the analytical structure of the thesis. However, it is noteworthy that also the theory here is driven to an extent by the setup of the empirical case.

Chapter 5 applies the model of Chapter 4 to a specific case study. A numerical application is made to empirically assess the threat posed by the Colorado potato beetle in Finland. This ex-ante cost-benefit analysis provides the main contribution of the study to scientific literature and to decision making. The basic results and the results of an extensive sensitivity analysis are presented and discussed.

Chapter 6 discusses the overall implications of the literature review and the case study analysis. It concludes by discussing certain further issues and possible extensions to the analysis.

2. INVASIVE ALIEN SPECIES – ECOLOGY AND INSTITUTIONS

2.1 Definition and a brief history

The terms alien species and invasive species have been defined in a United States Executive Order 13112 signed by President Clinton. The definition that was already given in the introduction can be broken down as follows.

DEFINITION 5 – NATIVE SPECIES
'Native species' means, with respect to a particular ecosystem, a species that, other than as a result of an introduction, historically occurred or currently occurs in that ecosystem. (Clinton 1999)

DEFINITION 6 – ALIEN SPECIES
'Alien species' means, with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem. (Clinton 1999)

DEFINITION 7 – INVASIVE SPECIES
'Invasive species' means an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health. (Clinton 1999)

The definition of an invasive species is analogous to the definition of an externality by economists: someone has to be affected by the action (introduction) before it can be defined as an externality (invasive species). A species that invades an empty niche in an ecosystem and causes no harm to anything is thus an alien species, but not an invasive species. Despite the distinction made in the Executive Order and elsewhere, the terms alien, exotic, foreign, introduced, invasive, non-indigenous and non-native species have often been used interchangeably in the literature (see e.g. Colautti and MacIsaac 2004). We prefer to promote the convention of calling those species that are not native to the ecosystem concerned and cause harm to some process invasive alien species (IAS)[6].

The biological diversity of the world results in part from geographical barriers that have restricted natural movement of organisms. For instance, there are gorillas in Africa, orangutans in Indonesia, monkeys but no apes in South America and no primates in Australia (McNeely 2001). When it comes to species that rapidly invade large areas, our own species, *Homo sapiens*, is probably one of the best examples. Furthermore, humans have always carried other species with them.

In some sense one could argue that all species are alien species in a place such as Finland that was covered by ice in the last glacial period. Standard ecological succession involves changes in species interactions and some early-succession species are negatively affected by the late-succession species. It is important to note that succession and range expansion are natural phenomena. Dealing with historical invasions thus presents some difficulties in terms of definitions. However, there is no need to go into a philosophical debate here. For the purposes of the present study it is sufficient to note that human-related factors have greatly increased the rate of invasions in recent times, and it is these modern invasions that are the focus of this study.

Di Castri (1989) suggests that there have been three phases in the history of species introductions. The first phase involves "fixing the pattern of 'man-invader' –relationship". This took place in the early Neolithic times – some 10,000 years ago – when man abandoned hunter-gathering and began agricultural production with domesticated species. In Di Castri's (1989) second phase the biogeographic enclosures were unlocked, beginning at the time of the great discoveries in around 1500s. Trade routes to other continents opened up whole new opportunities for both accidental and intentional introductions. This is when many classical and pervasive introductions – for instance goats, pigs, cats

[6] The definition is similar to the definition given in the Convention on Biological Diversity and differs from the purely biological definition which does not account for the impacts of the species (Born et al. 2005). Some authors (e.g. Richardson et al. 2000), suggest that the term invasive should have nothing to do with economic or environmental impact. In addition, Carlton (1996) discusses what he calls cryptogenic species, referring to species that are demonstratively neither native nor introduced. We abstract from such complexities and adopt the definition provided in the Executive Order.

and rats – took place. In addition to discoverers and traders, armies have for a long time been (and still are) an important pathway for species to move around. One of the notorious examples is the spread of the cattle disease rinderpest to Africa by the Italian army in the late 1880s (McNeely 2001). Finally in Di Castri's (1989) third phase the "rules and rhythm of natural evolutionary game" have been changed. This is the situation we are at this moment, having modified nearly all available habitats and genetically altered many species. Due to the ever growing globalisation there are nowadays many pathways for species to be transported quickly from one place to another, including tourists, aeroplanes, ship ballast and cargo containers.

For instance, in Finland alone there were 66,583 landings on Finnish airports by non-domestic civil aircraft in 2004. These aircraft carried 8,925,510 passengers and 120,819 tonnes of cargo and mail (Finnish Civil Aviation Administration website). International trains between Russia and Finland carried 252,000 passengers and 15,300,000 tonnes of cargo (VR-Group website). Harbours received directly from abroad 33,181 vessels carrying 53,169,635 tonnes of imported international cargo and 8,120,825 passengers (Finnish Maritime Administration website). Add to these figures for instance the North American nursery catalogues that offer about 60,000 plant species and varieties to a global market through the internet (McNeely 2001). It does not require much to see the huge potential for species to be spread rapidly around the globe.

Despite the potential, it is worth noting that only a tiny fraction of invasions are successful. The so-called Williamson's Tens Rule[7] states that only about 10% of species imported escape to the wild, only about 10% of those species that invade become established and only about 10% of those that get established become pests (Williamson and Fitter 1996). The main point is that not all species can establish in all habitats, and even if they can, they may not be able to reach a viable population size to become pests. If they do, they are likely to impact on the receiving system.

2.2 Physical effects

This section discusses in general terms the direct impacts that invasive alien species may impose. The discussion of economic impacts that these physical impacts may lead to is postponed until Chapter 3. The biological methods available for studying the invasion events include for instance GIS-based gap analysis or pathway analysis (Andersen et al. 2004a). The establishment phase can be studied using for instance population viability analysis, in which case establishment is seen as the opposite of extinction, which has been studied extensively (Andersen et al. 2004a; Drake 2004). The likelihood, nature and extent of physical impacts of IAS are generally affected by three factors: the characteristics of the invading species, the characteristics of the receiving ecosystem and the external conditions present at the time of the invasion.

Kolar and Lodge (2001) undertake a meta-analysis of eight published studies and discuss the characteristics that determine establishment and spread of plant and bird species. They find that the region of origin of the species is in all studies significant in determining whether establishment takes place or not. The authors conclude that the strongest result of their analysis is that successful establishment is positively related to propagule pressure. Cannas et al. (2003), using a general cellular automaton model to predict and control invasions of honeylocust (*Gleditsia triacanthos*), find that the invasion speed is mainly influenced by mean seed dispersal distance and minimum reproductive age, whereas seed production had only a minor impact on the invasion speed.

In all plant studies analysed by Kolar and Lodge (2001) the transition from establishment to invasiveness was seen to be significantly influenced by history of invasions, vegetative reproduction, low variability in seed crops and uneven phylogenetic distribution. No characteristic has been found that is consistently *unrelated* to bird invasiveness. Plant invasiveness on the other hand is not related to length of flowering period and whether the plant is annual or perennial.

[7] Note that this is only a rule of thumb applying in some situations but not in others. For instance, in deliberate game introductions in the Nordic countries a success rate of about 80% has been encountered (Nummi 2000).

The issue is difficult to assess in general terms, since species characteristics that favour invasiveness may hinder establishment, and vice versa (Kolar and Lodge 2001). Furthermore, it seems that generally it is very difficult to find species characteristics that consistently make them good invaders. For instance species with rapid population growth (so-called r-selected species) are often said to be good invaders, but significant counter-examples have been found, because the success depends on the interaction with the receiving system (Newman 1993).

The effects of the invasion depend also on the type of ecosystem and the type of niche the species occupies. For instance, introductions are more likely to have significant impacts when there are no competitors or predators of the invading species, and it is hence able to reach large population levels (Pimm 1991). Persistence, resistance and resilience of the receiving ecosystem are important factors in determining whether the invasion succeeds and to what extent it affects the particular ecosystem. *Persistence* measures how long the system can last until it is changed by the invasion (Pimm 1991). *Resistance* measures the impacts of one variable on other variables. For instance, if an invasion takes place, the level of resistance of the system determines how large the consequences elsewhere in the ecosystem are (Pimm 1991). Finally, *resilience* measures how well the system can return to equilibrium after it has been disturbed (Pimm 1991) or alternatively how large a change the system can withstand and still return to equilibrium (Holling 1996).

Considering the issue from the point of view of agriculture (or any other simplified ecosystem), it is easy to see the problem. Biological diversity of the system is generally seen to contribute towards better ability to withstand invasions. Agricultural systems are often simplified versions of natural ecosystems, and due to reduced genetic variability their ability to withstand invasions by pests and diseases is often lower than that of natural systems.

In theory alien species can also increase biological diversity – addition of a species after all increases diversity (at least when measured by species richness). However, invasive alien species usually have the opposite effect, because of the various biotic or abiotic interactions with native species. There are four types of direct effects on native flora and fauna (Nummi 2000). These are predation and herbivory, competition, parasites and diseases, and interbreeding. Each will be shortly reviewed below. The discussion is fairly general, and can be applied to any species, not just invasive ones. However, the links to invasions are explained.

2.2.1 Predation and herbivory

Invasion may impact on the target system through predation or herbivory. The first point to note is that biological interactions almost always function in both directions.[8] It is thus important to account for the interactions between the species. This interaction is positive if one species enhances the survival of the other (symbiosis, commensalism) and negative if one species is weakened by the interaction (competition, predation, amensalism). This is the case also with predation. It is not only the prey population that is affected: the abundance of prey can effectively regulate the invasive predator population. It is thus more convenient to consider predator-prey interactions than simply predation, using for instance the Lotka-Volterra equations (Begon et al. 1996b).

The impact of an invasive predator depends on the strength of interaction between the species, which is in part caused by whether the predator is polyphagous or not (Pimm 1991). At the extreme, predation, parasitism and herbivory may result in a removal of a native species from the ecosystem (local or global extinction). Such effects are demonstrated in the context of simple food-chains below (all figures after Pimm 1991). The boxes represent species at three trophic levels (primary producer, herbivore and predator). The shaded box represents the species that is removed from the food-chain due to presence of the invasive species and the arrow shows how the system changes as a result. Note

[8] At theoretical level, the exceptions to this are commensalism (one species benefits from the presence of the other, while the other is not affected in any way) and amensalism (one species suffers from the presence of the other, while the other is not affected in any way) (Begon et al. 1996b).

that the invasive species itself is not illustrated in the food-chains, only the impact that it imposes on the system.

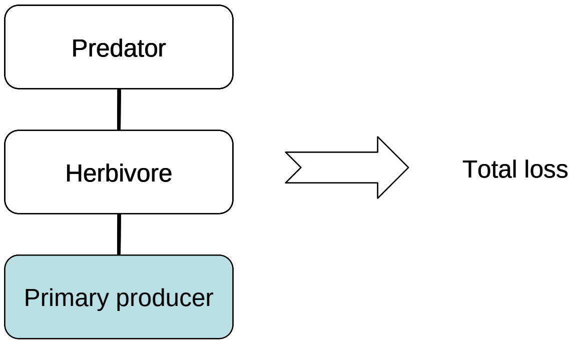

Figure 1. Potential impact of a removal of an organism at the bottom of the food chain

As illustrated in Figure 1, if the organism that is removed as the consequence of an invasion is at the bottom of the food chain (i.e. a primary producer) the result may have important consequences for the entire food chain, if the extinct species is the only supply of food for an upper organism. It could occur when for example an introduced herbivore species ends up consuming all the plants of a certain type □□ being able to do so as it consumes a variety of species itself (i.e. it is polyphagous). On the other hand, if there are several primary producers in the food-chain in question, a removal of any one of them may not have as drastic impacts on the entire chain as illustrated in Figure 2.

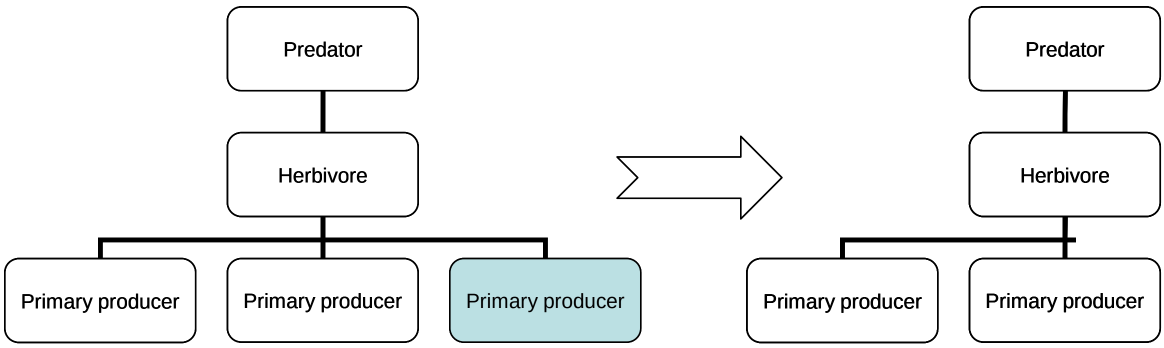

Figure 2. Potential impact of a removal of an organism at the bottom of the food chain

If the removed species is at the top of the food chain, the results could be as illustrated below. If a predator of a monophagous herbivore is removed, it is likely to reduce the density of the primary producer, but the primary producer is unlikely to go extinct provided that the herbivore relies solely on it as its food source. This is illustrated in Figure 3.

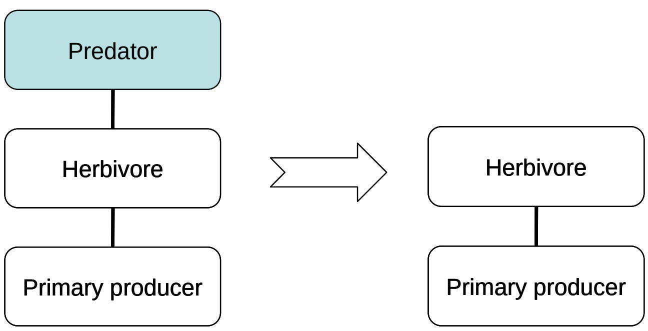

Figure 3. Potential impact of a removal of an organism at the top of the food chain

However, if the herbivore has more than one food source, as illustrated in Figure 4, the removal of the predator may result in the herbivore increasing in numbers and exterminating all but the most resistant plant species. This species then becomes the factor limiting the abundance of the herbivore. It is also possible that a previous invasion by an exotic herbivore aids future invasions of exotic plants that are better evolved to withstand the herbivore than native plants in the new regions. Further discussion on this topic of invasional meltdown can be found in for instance Parker et al. (2006).

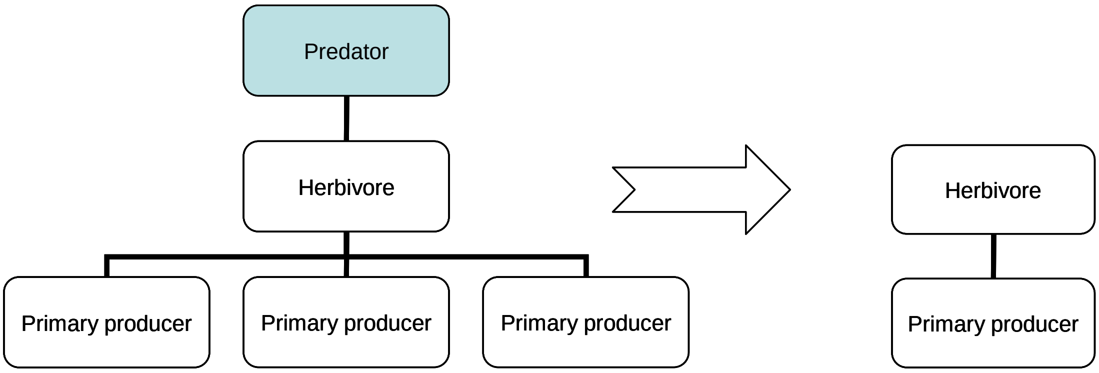

Figure 4. Potential impact of a removal of an organism at the top of the food chain

A similar effect may occur also higher in the food chain. Good examples of this are provided by the brown tree snake (*Boiga irregularis*) in Guam, where it reduced the number of native bird species (Pimm 1991), or the Nile perch (*Lates nilotica*) in Lake Victoria, where it reduced the number of native fish (Primack 1993). The result of such interactions is, of course, an overall reduction in the biodiversity of the ecosystem. However, unless the impacts are substantial, it may not be easy to show what the effects of predation are (Nummi 2000). The main point nonetheless is that the characteristics of the system and of the species involved determine the outcome of the invasion by a predator or an herbivore.

2.2.2 Competition

IAS may compete with native species for biotic (e.g. nutrients) or abiotic (e.g. space, light, minerals) resources. Again, the strength of the interaction is likely to be case-specific, depending on characteristics of both species as well as on the external environment. Competition may be divided into exploitation and interference competition (Begon et al.1996a,b). In exploitation competition an individual is prevented from consuming a resource, because another individual has already consumed it. There does not have to be direct contact between the two individuals, it is enough that they are in approximately same area in space and time. Note that for there to be competition, the resource in question has to be in limited supply. Interference competition on the other hand involves one individual actively defending a resource from exploitation by the others. In this case the resource may be, for example, shelter, mate or territory. The resource does not have to be in limited supply, as it effectively becomes scarce because of the defensive actions.

Interspecific competition (competition between species) mostly takes the form of exploitation competition: an invasive species for instance consumes a food item before the native species encounters it. Usually the species specialise in such a way that they are not dependent on exactly similar resources – in other words no two species occupy the same niche in the ecosystem. The Competitive Exclusion Principle (also known as Gause's principle) states that if two competing species coexist in a stable environment they do so by differentiation of their realised niches. If there is no such differentiation, then one species will outcompete the other (Begon et al.1996a,b).

An invasion can result in competition between species, as they have not coevolved to differentiate their niches. In the longer term, either niche separation or extinction of one of the species takes place. Finally, it is worth emphasising that competition as such is not harmful to the growth of any population. It is the resulting decrease in fecundity that is important. A species that is not successful in competing will have less resources available because i) someone else has already consumed most of them (exploitation) or ii) someone stronger is preventing access to the resource (interference). If for instance less food is available, the individuals may not be as resistant to diseases and natural enemies or may be killed due to malnutrition.

An example of an invasive alien species that competes with other species is the common wild oat (*Avena fatua*). Common wild oat is a weed that was introduced to Finland in 1920s in imported grain seed and feed grain. It competes with oat (*A. sativa*), wheat (*Triticum aestivum*), rye (*Secale cereale*) and barley (*Hordeum vulgare*) – all ancient alien species. It competes with them by occupying the same space and consuming a share of nutrients, water and sunlight (Jalli and Paju 2002). Thus the impacts of IAS are not limited to native species, but also (beneficial) alien species may be affected. For further examples of competition between IAS and other species in Finland, see Nummi (2000).

2.2.3 Diseases and parasites

IAS may act as vectors for either human, plant or animal diseases, or the diseases themselves may be classified as invasive.[9] Given a sufficiently large viable population, it is unlikely that the entire population can be exterminated even by a very fatal disease. There is always a compromise between how virulent a disease is and to what extent it can spread. The faster it kills the less time there is for infected individuals to spread the disease to others (Newman 1993). Thus there are some natural checks to disease spread, but that does not mean that diseases would not impact on the receiving systems.

Spread of diseases that may infect humans (zoonoses) can be exemplified by the Asian tiger mosquito (*Aedes albopictus*) in the United States (Vitousek et al. 1996). The larvae of the species spread to the US in used car tires. In its native areas the species spreads for instance the dengue fever, whereas in the US it is a vector of eastern equine encephalitis – a viral infection which is often fatal to people. In addition, many pathogens themselves can be categorised as invaders, one of the most devastating ones being the human immunodeficiency virus (HIV). Another topical and potentially devastating example is the recent spread of the avian influenza in Asia and Europe.

In addition to zoonotic diseases, IAS may also transmit plant and animal diseases. Native animals are often not adapted to diseases carried by IAS. These diseases may be completely harmless to the invasive species who carry them, but devastating for the native species. This is especially the case in island populations that have been very much isolated from any other population (Primack 1993).

In Finland spreading of diseases can be exemplified by the invasive signal crayfish (*Pacifastacus leniusculus*) that spreads crayfish plague caused by fungus *Aphanomyces astaci* – another invasive species. Through the disease signal crayfish thus has a negative impact on the population of native crayfish (*Astacus astacus*). As the plague is not fatal to the signal crayfish, there is a constant threat to native crayfish wherever the two coexist (Nummi 2000).

As for parasites, they are estimated to present over 50% of all the species, and can be divided into macroparasites (e.g fleas or ticks) and microparasites (e.g. *Plasmodium* species that causes malaria). A parasite is defined as "an organism that obtains its nutrients from one or a very few host individuals causing harm but not causing death immediately" (Begon et al. 1996a). Parasite-host interactions have been extensively modelled. Such interactions often result in a lower reproductive contribution to the next generation by the individual that is being parasitised. This can be due to increased likelihood to be killed by predators when weakened by parasites, or to not being able to acquire a mate. In some species elaborate traits are produced which, according to one theory, signal that the individual is free of disease and thus has enough energy to produce those traits (Petrie et al. 1991). Parasites thus facilitate responses at both intraspecific (e.g. competition for mates) and interspecific (e.g. increased likelihood to be predated upon) levels. Notice also that unless they actually kill the host, they merely *facilitate* the regulation process by enhancing already existing regulatory factors.

Furthermore, there may be more organisms than just the parasite and the host present. One of the hosts may be merely a vector that transmits the parasite (or a disease) to another organism without being significantly affected itself in the process. Such additional species naturally complicate the

[9] It is at this point worth pointing out that although the term invasive alien *species* is used throughout this study, many diseases fit perfectly in the definition of IAS. Hence they are included in the discussion whenever convenient.

interactions further. An example of such a case in Finland is the barberry (*Berberis vulgaris*), which is an ancient alien species used as an ornamental plant. The species acts as an alternate host to black rust (*Puccinia graminis*), which is a parasite of grasses including cereal crops (Nummi 2000). Hence the role of the barberry as an alternate host enhances the chances of survival by the black rust.

2.2.4 Interbreeding

If the invading species is genetically close enough to the native one, interbreeding may occur. One of the difficulties here is that interbreeding (or hybridisation) can be very difficult to detect (Nummi 2000). When two closely related species interbreed, the result is generally a loss of diversity at the genetic level (and possibly ultimately at the species level).

An example of interbreeding is provided by hatchery-bred salmon in the western coast of North America. In addition to spreading diseases, the hatchery-bred salmon can interbreed with wild salmon of the same or closely related species, often leading to fitness reductions or sterility of offspring (Naylor et al. 2005). In Finland, hybridisation can be exemplified by the native lady's bedstraw (*Galium verum*) interbreeding with the invasive upright bedstraw (*G. album*). Pure stands of *G. verum* exist nowadays only in some islands (Nummi 2000).

Factors that limit interbreeding include for instance spatial separation, incompatibilities in crossing and reduced fitness of the hybrids (Barbour et al. 2006). In addition, in plants interbreeding may be prevented by temporal separation in flowering. For instance, if flowering by the two species is in asynchrony (i.e. at different times), interbreeding may not be physically possible. This has been found to be an important factor in limiting interbreeding between native and exotic *Eucalyptus* species in Australia (Barbour et al. 2006).

2.2.5 Structural effects

In addition to the above direct biological interactions, IAS may impose structural impacts on either human systems or on ecosystems. They may impact on various kinds of manmade structures by, for instance, physical blocking of power plant water intake pipes. Such impacts will be returned to when the economic consequences of IAS are discussed. Structural impacts that function through biotic processes include habitat transformation and alteration.

Habitat transformation involves a change in the type of habitat. An example is provided by the introduction of European rabbit (*Oryctolagus cuniculus*) to central Chile where it became a major pest due to lack of predation and lack of control by the myxomatosis disease. The ecological consequences were sizable. Following the invasion, the presence of rabbits restricts the native perennial herbs to areas under the canopy of sheltering shrubs. Rabbits are also more lethal and destructive than local rodents in their forage, which may lead to regeneration not being able to take place and the already sparse matorral being further opened up. Although there does not seem to be much competition between rabbits and native fauna due to the way they are spatially distributed, the species dependent on dense scrub may find it harder to find such habitat in future as rabbits keep on opening up the habitat (Jaksic and Fuentes 1991).

Habitat alteration involves change in the characteristics of the habitat, but not of the habitat type itself. Alteration may occur if, for example, the invading species impacts on mutualistic interactions between the native species (Traveset and Richardson 2006) or if it is a nitrogen-fixer that increases the level of nitrogen in the soil altering the balance of populations. Fire tree (*Morella faya*, previously *Myrica faya*) in Hawaii exemplifies such an impact through interactions with the abiotic environment (Vitousek et al. 1996). The tree is able to fix its own nitrogen, which is often a limiting factor for the growth of many species, especially in young volcanic sites such as Hawaii. Nitrogen availability in the soil may affect the species composition substantially. Through nitrogen fixing the fire tree increases also availability of nitrogen to other species, and often the species benefiting from such a change in the conditions are other invasive species. Thus one species may succeed in changing the dynamics of the entire system.

Another example – this time in an aquatic setting – is provided by the deliberate introduction of the Nile perch (*Lates nilotica*) to Lake Victoria (Primack 1993). The case exemplifies the complex interactions and impacts through the biotic environment. The perch was introduced for fishing, but ended up causing the extinction of several hundred endemic fish species. The case was more complex than the perch just predating or outcompeting the other species. There are high nutrient inputs into the lake from the surrounding agricultural land. Populations of algae and other flora and fauna increase due to this, but were previously controlled by the endemic fish. As overfishing and predation by the perch ran down the numbers of native fish, the algae were able to thrive and bloom, depriving the deeper water of oxygen. As a result, the native fish living in the depths were forced to the shallower waters, where they in turn were predated. The result was a vicious circle leading to more eutrophication and more loss of biodiversity.

The impacts involving habitat alteration or transformation may be more subtle than the basic biological interactions. They may function by, for instance, changing the patchiness of the system, the fire regime, hydrology or nutrient and energy flows (Andersen et al. 2004b). The physical impacts of IAS often involve a great deal of uncertainty and complexity. De Poorter and Clout (2005) list the following complexities: i) dual personality species (species that may be commercially important but cause damage elsewhere); ii) time lags between the establishment and range expansion; iii) interactions between two alien species may cause damages, although neither species on their own is damaging; iv) invasion by one species may facilitate invasion by others (invasion meltdown); v) there may be evolutionary adaptations over time; and vi) IAS impacts may be compounded by global change.

Many of these types of impacts are difficult to predict prior to the introduction. In fact, a fundamental feature of IAS impacts is that it is not possible to predict all the impacts with certainty (Newman 1993). Furthermore, often the impacts in a new area cannot be predicted on basis of the impacts that the species imposes in its native range or under confined conditions (for instance in field trials or in zoos). Finally, ability for habitat modification may increase the invasion success of the species as well as allow for a faster growth rate in sub-optimal habitats compared to species that are not capable of transforming the habitat (Cuddington and Hastings 2004). Further discussion on ecological impacts and their evaluation can be found in Parker et al. (1999). The main points to note here are that the impacts may be wide-ranging and uncertainty is inherent to the issue.

2.3 Institutional basis for controlling invasive alien species

2.3.1 Invasive alien species and the policy environment

The challenge presented by IAS has been noted by scientists the world over and national or regional studies have been made in for instance Australia (Martin 2003), Austria (Rabitsch and Essl 2006), Canada (Colautti et al. 2006), China (Yan et al. 2001), European Union (Schrader and Unger 2003), Germany (Gebhardt 1996; Reinhardt et al. 2003), New Zealand (Jay et al. 2003; Parkes and Murphy 2003), South Africa (van Wilgren et al. 2001; Le Maitre et al. 2002) and the United States (Pimentel et al. 1999; 2005) – as well as some attempts to look at the issue globally (Lowe et al. 2000; Shine et al. 2000).

In addition to scientists, also politicians are increasingly finding the issue important. It has been brought to the political arena in for instance Australia (Nairn et al. 1996), the European Union (EC 2002; Council of the European Union 2002a,b; Council of Europe 2003; Scalera and Zaghi 2004), New Zealand (Biosecurity Council 2003), the United Kingdom (DEFRA 2003; Fasham and Trumper 2001) and the United States (GAO 2002; U.S. Congress, Office of Technology Assessment 1993).

The European Community has recognised IAS as an emerging issue, but does not have a specific research programme on alien species, and so far little work has been done on economic evaluation of IAS impacts (EC 2002). At ministerial level in the 2413rd Council Meeting (Environment) in Brussels in March 2002 it was established that in implementing Sustainable Development Strategy, the Council (Council of the European Union 2002a):

> "recognises the importance of scientific research … to provide the knowledge on which recommendations may be based … in particular with respect to genetic resources, invasive alien species and forest biological resources; … [and] stresses the importance of capacity building in relation to invasive alien species …"

There have been assessments in sectoral contexts, for instance in relation to forests (Cock 2003) and biological diversity. In relation to biodiversity, the European Platform for Biodiversity Research Strategy emphasises the need for interdisciplinary research and international collaboration, and suggests three priority issues for research: i) development of techniques to predict invasiveness; ii) improvement of monitoring, detection, prevention and control techniques; and iii) multidisciplinary scientific support for appropriate policy on prevention, management for control and legislation, public awareness and information (EC 2002).

The Community Biodiversity Strategy includes four sectoral biodiversity action plans, which refer to IAS in sectoral contexts. The action plan of agriculture (EC 2001) identifies "uncontrolled spread of alien and wild species" as a possible result of agricultural practices on biodiversity, but it does not set out any specific IAS-related measures. It also recognises as a primary aim implementation of practices which prevent the spread of non-native species associated with agriculture. Also the Sixth Environmental Action Programme (2001−2010) acknowledges concern regarding the potential risks to biodiversity from undesired and unforeseen consequences of the introduction of IAS (EC 2002).

Also in Finland the importance of IAS is beginning to get recognised. They feature for instance in recent reports on national plant protection strategy 2004−2013 (MAF 2003b), biological diversity in matters handled by the Ministry of Agriculture and Forestry (MAF 2003a) and national strategy for adaptation to climate change (MAF 2005). In addition, a report on future conditions of the Finnish agrifood industry to year 2030 (MAF 2002a) mentions IAS indirectly in several parts. First, it is pointed out that a possible reduction in genetic basis makes production more vulnerable to pest risks. Second, climatic changes are seen to enable establishment of new weeds, diseases and pests in new areas. Finally, free movement within the expanding European Union is seen to spread diseases and animals to previously unoccupied areas.

The IAS issue is thus pervasive and beginning to get attention in the political arena. Such attention naturally raises also critical viewpoints. There has recently been some discussion within the academia whether the current attention given to IAS is just another form of xenophobia. We leave the answer to this question for the reader to figure out and refer the interested reader to the opposite arguments of Simberloff (2003a) and Sagoff (2005; 1999).

Having briefly looked at the issue from historical, ecological and political perspectives, let us complete our overview by reviewing the current international, supranational and national legislation regarding IAS. The legal texts are presented in more detail in Appendix 1.

2.3.2 International legislation

There are several international agreements that touch upon the issue of IAS in their own sectors – some examples of these are provided in Appendix 1. Despite all the international agreements, the importance of domestic policies is substantial, because international agreements need to be incorporated into national law before they enter into force (Bell and McGillivray 2000).

Sometimes the mere fact that agreements are multilateral and have many parties makes them weak compromises. Barrett (1999) has analytically shown that global agreements with many parties can sustain co-operation only when gains to co-operation are small – in other words, when the agreement is not very much needed in the first place. Trade agreements are perhaps an exception to this, as they allow effective sanctions to be used against those who breach them. In fact, in another paper Barrett (1997) shows that the threat of trade sanctions may sustain even global environmental agreements. Naturally, international agreements may also impose moral obligations on individual agents (or countries) and hence influence behaviour over time even without effective sanctions. Two important IAS-related international agreements are introduced below.

The World Trade Organization (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS) was signed in Marrakesh, Morocco in 1994. The agreement is similar to the Agreement on Technical Barriers to Trade (TBT), but whereas TBT deals with general standards, SPS is exclusively for standards related to food safety and animal and plant health.

The definition of sanitary and phytosanitary measures corresponds to preventative measures in this thesis. The basic idea behind the SPS agreement is that these preventative measures are acceptable tools and can also restrict international trade flows, provided that i) the need for them can be scientifically proven; ii) the measures are not discriminating between similar member countries; and iii) the measures are not more trade-restricting than necessary. This basic idea is stated in the preamble to the SPS agreement as follows (WTO 1994):

> "no Member should be prevented from adopting or enforcing measures necessary to protect human, animal or plant life or health, subject to the requirement that these measures are not applied in a manner which would constitute a means of arbitrary or unjustifiable discrimination between Members where the same conditions prevail or a disguised restriction on international trade."

Thus the SPS agreement adopts the same basic principles that the WTO itself is built on: market liberalisation, reciprocity, non-discrimination and transparency (Dunkley 2000). Any measure applied should not unjustifiably or excessively restrict trade, should not discriminate between similar trading partners, has to be scientifically proven and should be undertaken in a transparent fashion.

An important point to note is that risk assessment should be based on scientific evidence and the cost-effectiveness of alternative strategies to limiting risk should be taken into account. Moreover, the agreement urges to take into account the objective of minimising negative trade effects when decisions regarding the level of protection are made. If there is a measure that achieves the appropriate level of protection but is less trade-restricting than the current measure, then the current measure is more trade-restricting than is necessary.

Further, adopting a precautionary approach seems to be unacceptable under the SPS, unless adequate scientific evidence is available or research into the issue is initiated. However, what exactly constitutes sufficient scientific evidence for different member countries is likely to vary, as is the understanding of what is meant by "a reasonable period of time" within which the precautionary measure should be reviewed (WTO 1994).

One of the main disputes under the SPS agreement has been the so-called beef hormone case between the United States and the European Communities, which was ruled in favour of the US. The ruling was based on lack of scientific evidence from the European Union on showing the dangers of using hormones in beef production. Some studies quoted in this thesis, for instance Kelly et al. (2002) and EC (2006), are constituents of this process of providing the necessary scientific evidence to justify specific trade-restricting phytosanitary policies.

The second important international agreement relevant to IAS is the United Nations Convention on Biological Diversity (CBD). The CBD was the outcome of the United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil in 1992. Thailand became the 188th party to the agreement when it ratified the text on January 29, 2004.

The agreement aims at conserving biodiversity, promoting sustainable use of its components and sharing fairly and equitably the benefits from genetic resources (CBD 1992). It also recognises that environmental issues cannot be separated from the larger economic framework at which individuals operate (Bragdon 1996). The relevant part for IAS (Article 8) states that (CBD 1992):

> "Each Contracting Party shall, as far as possible and as appropriate: … (h) Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species."

The principle is stated fairly simply and imprecisely, leaving an impression that the issue has been recognised but then watered down for some reason. In fact, the initial draft of the Convention included a much stronger clause, which would have established a CITES style authority and a priority-based IAS listing process (Jenkins 1996). As it stands, the Convention can be criticised for requiring action only "as far as possible and as appropriate" (CBD 1992), as well as for pointing explicitly to national sovereignty over natural resources (Bell and McGillivray 2000). Furthermore, many countries – including the United States – have yet to ratify it.

Despite these shortcomings, it is so far the only widely adopted international instrument we have for dealing with IAS and as such it is a valuable institution. The Convention also established an intergovernmental scientific advisory body, the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), whose functions include, among others, assessing the measures taken in accordance of the Convention. The SBSTTA guiding principles emphasise that primary attention should be given to preventing IAS introductions (Perrault and Carroll Muffett 2001).

2.3.3 Community legislation

On 21 December 1976 entered into force a directive that deals specifically with harmful organisms and introduces the concept of protected zones in what was then European Economic Community. This is Council Directive 77/93/EEC on protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community. It has subsequently been replaced by Council Directive 2000/29/EC of 8 May 2000, which is the directive discussed below.

The preamble of the directive notes the danger presented by harmful invasive organisms. Harmful organisms are defined as "pests of plants or of plant products, which belong to the animal or plant kingdoms, or which are viruses, mycoplasmas or other pathogens" (EC 2000). However, the directive, despite its name, only considers the risk to productive plants, not to plants in natural ecosystems. It thus seems to be entirely based on protecting agriculture and forestry.

The directive emphasises the necessity of actions at the place of production or on first point of introduction to the Community, as well as basically prohibits the use of separate national legislation, unless established at the Community level. Protected zones – defined earlier in Definition 4 – are presented as the regional tool to account for differences in ecological conditions. The trade restrictions included in the protected zone system can be justified on basis of Article 6 of the SPS agreement.

The directive also presents the idea of a Community level fund to deal with the risks as well as to enforce control at the external frontiers of the Community. For instance Portugal received funding through the fund for over a third of its expenses incurred in eradication of the pinewood nematode (*Bursaphelenchus xylophilus*). However, the usage of the fund is limited to pests that arrive with traded goods, since only in such cases are the member countries eligible to receive compensation through the fund.

The approach of the directive[10] is based on 'blacklists' of organisms, i.e. it permissible to import and trade in plants or plant products unless otherwise specified. The opposite approach would be the so-called 'whitelist' system, under which the burden of proof lies with the importer to show that a specific organism does not present a threat. A system based on a whitelist would probably be more effective at preventing invasions, but could in some cases breach the SPS agreement, where the imposer of a trade restriction has to scientifically prove the need for the protection measures. The blacklist system is thus more acceptable from the free trade point of view, but it has to be noted that such systems may be slow

[10] The directive has subsequently been amended (2002/89/EC) such that it may in certain conditions be applied also to species outside the annexes.

to react to new information regarding certain species being harmful. Some countries have adopted a so-called 'greylist' system, where different species can be assigned to different categories, depending on the estimated risk they impose. More on the advantages and disadvantages of different lists can be found in Schmitz and Simberloff (1997) and in Filbey et al. (2002).

Whereas Council Directive 2000/29/EC deals with pests threatening primarily productive plants, the threat presented by IAS to natural ecosystems is covered in Council Directive 92/43/EEC of 21 May 1992, on the conservation of natural habitats and of wild fauna and flora (EC 1992). The IAS relevant part is similar to the relevant part in the Bern Convention (see Appendix 1), but this time the requirements are specified to a greater extent. However, it is notable that the entire directive deals mainly with protected natural areas (it lays the foundation for the Natura 2000 network). Hence IAS are only included as 'supplementary provisions' (EC 1992).

Further, preventing an introduction is available as an option for the members "if they consider it necessary". In other words, preventative actions are not in any way required by the directive. Hence the power of the directive for protecting the environment from the IAS is much weaker than the power of Directive 2000/29/EC for protecting plant health in production sectors.

Finally, trade aspects of IAS are dealt with in Council Regulation[11] 338/97 of 9 December 1996, on the protection of species of wild fauna and flora by regulating trade therein (EC 1996). IAS are to be included in Annex B which shall contain:

> "(d) species in relation to which it has been established that the introduction of live specimens into the natural habitat of the Community would constitute an ecological threat to wild species of fauna and flora indigenous to the Community."

Thus, whereas Council Directive 2000/29/EC allows trade restrictions in relation to species that threaten plant production, Council Regulation 338/97 does the same for species that threaten natural environment. Again, the approach is based on a blacklist (Annex B of the regulation).

2.3.4 Finnish national legislation

The supranational EU legislation discussed above is incorporated in the Finnish national legislation. Basically, Council Directive 2000/29/EC is included in the Act on the Protection of Plant Health of 2003, Council Directive 92/43/EEC in the Nature Conservation Act of 1996 and Council Regulation 338/97 stands by itself.

Perhaps the most important piece of national legislation in relation to IAS is the Act on the Protection of Plant Health (18.7.2003/702), which replaced the old Plant Protection Act of 1994 (Government of Finland 2003). The new Act is essentially similar to the old one, but it identifies in greater detail the responsibilities of the authorities. The authority responsible – the Plant Production Inspection Centre KTTK – is specifically named in the Act. In addition, the plant protection authorities are now entitled to assistance from the customs, border control, police and rescue officials, indicating that the issue is being given appropriate attention.

As is quite evident by comparing the Act with Council Directive 2000/29/EC, the Directive is executed by means of this Act. Its main points are that it obligates individual farmers to inform the authorities of quarantine pest observations, as well as to follow any orders regarding eradication. It also sets out the punishments for not following the instructions. On the other hand, it also sets out the right of the producer to get compensation for the control and eradication costs as well as for the value of the lost crop. However, there are conditions under which denial of compensation can be carried out. First, quality defects seem to be ruled out of the compensation mechanism, and second, failure to follow good production practices (undefined in the Act) may also result in denial of compensation. The penal

[11] The difference between directives and regulations is that directives need to be included in national legislation before they enter into force, whereas regulations stand by themselves. However, also directives do stand alone after a few years (specified in the directive) if they by that time have not been included in national legislation.

provisions and the compensation procedure state that compensation is primarily paid for pests that are to be eradicated, as opposed to those that are merely to be controlled or contained.

A certain kind of more flexible and precautionary approach is more evident in the new Act. First of all, the definition of a plant pest now allows the Act to be applied to those pests that may cause direct or indirect damage to natural plants or plant products. In other words, the Act can in principle be applied to species threatening natural ecosystems. Further, the Act explicitly states that in addition to the species in the blacklist, it can be applied to species outside that list if they pose a threat to plant health. The Ministry of Agriculture and Forestry may permit actions regarding pests that have not (yet) been included in the appropriate annex of Directive 2000/29/EC. Further, the Plant Production Inspection Centre KTTK (i.e. the relevant authority) may take such action even when not ordered by the Ministry, if they see that the threat is imminent. This is a remarkable improvement on the normal, rather rigid, functioning of blacklists. On another side, the reference to essentiality of procedures is new to this Act as compared to the previous one. It remains to be seen how the Act is executed in practice in relation to these points.

Altogether, the new Act is a stronger tool than the previous Act for plant protection authorities to ensure protection against some IAS, but it also seems to make provisions for the State to escape compensation payments in many cases – for instance with species that cause mainly quality defects.

Another piece of national legislation dealing with IAS is the Nature Conservation Act (1096/1996) and especially Section 43 on 'Preventing the spread of non-native species' (Government of Finland 1996). Whereas the Act on the Protection of Plant Health deals primarily with species harmful to production processes, the Nature Conservation Act accounts for the impacts of invasive species on ecosystems.

However, it is worth noting two points. First, plant introductions are still allowed in gardens and fields, hindering any real attempt to control the spread of IAS. Second, even outside these areas, introductions are allowed for silvicultural purposes. Thus the implication seems to be that nature can be protected, provided that doing so does not compromise economic production possibilities. Also the powers of the officials are much weaker than in the case of IAS that threaten health of productive plants. Hence the Nature Conservation Act seems to be much weaker than the Act on the Protection of Plant Health – just as was the case with the associated directives.

Finally, three other pieces of national legislation that deal with IAS from their own perspectives are the Animal Diseases Act (e.g. Article 13), Fishing Act (Article 94) and Hunting Act (Article 42) (Government of Finland 1980; 1982; 1993; Nummi 2000). These in principle dictate that species of foreign origin cannot be imported to Finland or released in the wild without permission from the appropriate Ministry. Both the Fishing Act and the Hunting Act dictate that the permission has to be denied if the importation is likely to result in 'significant' damage to native species or environment. How 'significant' is interpreted by the legal system in this context remains unknown to me. It is also interesting to note that fish and crab species that can be imported without permission can be set out in a separate decree. Thus the Fishing Act – in contrast to other legislation discussed above – makes use of whitelists rather than blacklists as a policy tool.

2.4 Invasive alien species in Finland

There is one general report on IAS in Finland, titled 'Alien species in Finland' (Nummi 2000). The paper was submitted as a national report to the Secretariat of the United Nations Convention on Biological Diversity. On a regional scale a report titled 'Introduced species in the Nordic countries' was released in 2000, produced by a working group established under the Nordic Council of Ministers. In addition to these two reports, the internet resources available include the 'Finnish Clearing-House Mechanism', 'North European and Baltic Network on Invasive Alien Species (NOBANIS)', 'Baltic Sea Alien Species Database' and 'Regional Biological Invasions Center' (in St. Petersburg). See the reference section for the internet addresses.

There are approximately 1,380 known alien species in the Nordic countries. Of the approximately 640 alien species in Finland, a vast majority – about 93% - are terrestrial, and most of them plants (SYKE 2001). Of the estimated 42,000 species living in Finland about 1.5 % are thus non-native (Wahlström et al. 1992). Studies have been made on only a few separate species[12], perhaps the most comprehensive one being the national preparedness strategy for the threat presented by pinewood nematode (*Bursaphelenchus xylophilus*) (MAF 2002b; 2006). It, however, lacks detailed economic analysis and merely points out that costs are dependent on so many variables that they cannot be reliably estimated ex-ante. Nummi (2000) also includes four case studies: pinewood nematode, Himalayan balsam (*Impatiens glandulifera*), spiny water flea (*Cercopagis pengoi*) and Canadian beaver (*Castor canadensis*). In addition there are studies by the Ministry of Agriculture and Forestry on tomato spotted wilt tospovirus (TSWT) (MAF 2003d) and cyst nematodes (MAF 2004a). Apart from the studies on pinewood nematode and TSWT the studies do not explicitly consider socio-economic factors.

There are two properties of Finland to note in relation to IAS. On one hand, the harsh climate and the relatively isolated geographical location present an obstacle to the invasion of many species, but on the other hand the relatively low number of native species allows easier establishment of suitable new species (Nummi 2000).

Nummi (2000) divides the Finnish IAS into three main categories:

i) Ancient unintentional introductions – including many plants, house mouse and rats. This category includes many of the plants that have spread with agriculture.

ii) Historical intentional introductions – including fish, game and garden plants. This category includes the species that have been introduced in the last hundred years or so, mainly for economic purposes.

iii) Modern mainly unintentional introductions – including many pests and marine organisms. This is the category we should be particularly concerned about for the purposes of the present study. It corresponds to Di Castri's (1989) third phase in the history of introductions.

Some historical invasions in Finland (Nummi's category 2) are listed in Table 3 (after Jalli and Paju 2002; Kauhala 1996; Leinonen 2000; Leivo 2004; Nordström et al. 2003; Nummi 2000; Timgren 2001; Tomppo and Joensuu 2003; Westman et al. 2002).

Invasive species	***When and how?***	***Impacts***
Canada goose *(Branta canadensis)*	1964 intentionally for game hunting	Crop damages, minor on ecosystems
Canadian beaver *(Castor canadensis)*	1933-37 to restore the European beaver (wrong species!)	(Restored) European beaver (*Castor fiber*), forestry
Common wild oat *(Avena fatua)*	At least since 1920s in imported grain seed and feed grain	Competes strongly with agricultural crops
Fallow deer *(Dama dama)*	1930/50s	Minor
Mink *(Mustela vison)*	1920s-1930s escaped from fur farms	Birds, possibly European mink (*Mustela lutreola*)
Muskrat *(Ondatra zibethicus)*	1920s intentionally for game hunting	Changes aquatic species relations (locally)
Mute swan *(Cygnus olor)*	1934 intentionally for parks	Minor, may compete with native *Cygnus cygnus*
Pheasant *(Phasianus colchicus)*	1901 intentionally for game hunting	Minor, possible agricultural crop losses
Raccoon dog *(Nyctereutes procyonoides)*	1930s spread from introductions in former USSR	Minor
Signal crayfish *(Pacifastacus leniusculus)*	1967 intentionally for crayfishing (still ongoing)	Competes and spreads disease of native crayfish (*Astacus astacus*)
White-tailed deer *(Odocoileus virginianus)*	1934, 1948 intentionally to enrich wildlife and for game hunting	Minor (crop damage, road accidents, spreads a parasite that is fatal to elks)

Table 3. Historical invasions in Finland.

As for more recent invasions in Finland (Nummi's category 3), some examples are provided in Table 4 (after Kauppila and Bäck 2001; Kivipelto 2000; KTTK 2002; Leppäkoski 2000; MAF 2004a; Ministry of the Environment 2005; Nummi 2000; Rautapää 2002; SYKE 2001; SYKE 2002; Timgren 2001).

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[12] There is much work in Åbo Akademi University on aquatic invasive species. We have chosen to limit the discussion in this thesis primarily to terrestrial species.

Invasive species	*When and how?*	*Impacts*
Colorado potato beetle *(Leptinotarsa decemlineata)*	1983, 1998, 2002 spread from the south-east aided by winds	Potato crop reduction
Spiny water flea *(Cercopagis pengoi)*	1992 in ship ballast	Ecosystem effects unknown, clogs up nets, waterways and beaches
Hogweed(s) *(Heracleum* spp.)	Intentionally as a garden plant	Competition with native species, contact causes severe skin burns
Pale cyst nematode *(Globodera pallida)*	2000, unknown	Potato crop reduction
European rabbit *(Oryctolagus cuniculus)*	Unknown, possibly pet escapes	Status in Finland fairly unknown
Rugosa rose *(Rosa rugosa)*	Early 1900s but rapid spread since about 1990	Modifies ecosystems unfavourable to native species, hinders recreational use of beaches
Spanish slug (*Arion lusitanicus)*	1990 in imported soil	Garden plants, cosmetic aspects
Zebra mussel *(Dreissena polymorpha)*	1995 (Gulf of Finland) in ship ballast	Minor so far, big impacts in e.g. North America

Table 4. Recent invasions in Finland.

The list is only a sample of species that have recently invaded Finland, but it represents the variability of the species concerned. Let us now introduce in more detail the species that is the target of the empirical analysis in this study – Colorado potato beetle.

2.5 Colorado potato beetle

2.5.1 Ecology of the Colorado potato beetle

The Colorado potato beetle *Leptinotarsa decemlineata* Say (Coleoptera: Chrysomelidae) is an oligophagous insect, feeding exclusively on Solanaceae family and primarily on *Solanum* genus. It is one of the most important pests, and the most destructive insect defoliator, of cultivated potato (*Solanum tuberosum*) (Hare 1990; Raman and Radcliffe 1992). Other species targeted by the beetle include tomato, egg plant, pepper and tobacco (EPPO 2005; Hare 1990; O'Neil et al. 2005). Despite these other targets, potato is the main host plant in Finland, both in quantitative and in economic terms.

Figure 5. An adult Colorado potato beetle.

An adult beetle is pictured in Figure 5. The beetle usually has two to three generations a year, although in the northern latitudes it generally has one generation and in the south can have as many as four generations (EPPO 2005). If the mean daily air temperature does not exceed 11−14ºC and humidity is high, the beetle population may not be able to spread and the population size may actually decrease. On the other hand, mean daily air temperature of 17−20ºC results in mass spread and development (EPPO 2005). The mean summer temperature in Finland in 1971−2000 is 14.1-16.0ºC in most parts of the country (FMI 2006).

The life cycle of the beetle includes the spring adults that emerge from the soil where they have over-wintered in around middle of June (in eastern Ontario), which is about the same time as the potato crop begins to break through the ground (Harcourt 1971). Although the actual time of emergence depends on the local climatic conditions, it is usually in synchrony with the potato crop emergence. The beetle then lays eggs, with a single female laying as many as 2,000 eggs over the summer (EPPO 2005). Given a temperature above +12ºC, the eggs hatch in 4-12 days, and turn into larvae, of which there are four instars. The fourth instar buries itself in the soil and pupates. After about 10-12 days, the summer adults emerge (EPPO 2005; Harcourt 1971; Raman and Radcliffe 1992).

The reproductive potential of the beetle is massive. It has been calculated that in favourable environmental circumstances, but with 90% egg mortality and varying degrees of larval mortality, a single pair can produce an offspring population that in five years, if not controlled, measures 1,100,000,000,000 (1.1×10^{12}) individuals (EPPO 2005).

Crop damages

All the CPB life stages feed on potato, with the fourth instar causing about 75% of the total larval defoliation (EPPO 2005; Harcourt 1971; Raman and Radcliffe 1992). The CPB reduces tuber yield of potatoes indirectly by reducing the leaf area, hence decreasing the area available for photosynthesis. Although the relationship between photosynthetic leaf area reduction and yield loss is not straightforward, in general reduced leaf area leads to a decreased yield. The relationship is affected by for instance how much the leaf area is reduced, and at what stage of plant development that is done (Hare 1980; Hare 1990; Nault and Kennedy 1998).

The magnitude of damages is also affected by the outside temperature. The feeding rate of the CPB, and hence also the defoliation rate, is dependent on temperature, as is the development rate of the beetle. In general, as the temperature increases, so do the feeding and development rates (Lactin et al. 1995). At 10ºC food intake by the beetle is zero, reaching the maximum at 25ºC (EPPO 2005). In addition to temperature, the CPB shows feeding and egg-laying preferences regarding different potato cultivars, but the differences in cultivar tolerance and resistance seem to be minor (Kivioja 2005).

If left uncontrolled, the beetle is able to totally defoliate the potato plant, causing a total crop loss (Hare 1990). There are no density dependent mechanisms to help it conserve its food resource (Harcourt 1971). Detailed quantitative descriptions of the beetle's destructiveness in Europe are lacking. EPPO (2005) states that in some EPPO countries the yield losses are up to 50% of the yield. Baker et al. (1998) cite a study in which yield losses in Poland were 5% with control and 40% without control. Newspaper reports from Russia suggest a figure of 20%, but this is probably only a rough estimate (Parkkonen 2002).

In North America there have been several scientific attempts to determine the level of yield losses. The state-wide yield losses in Michigan, USA were on average 12% of the yield, although they could be up to 21% in seriously affected areas (Grafius 1997). In the case of tomato, yield losses up to 67% have been observed in a field test in Maryland (EPPO 2005). These figures may be slightly higher in Europe because most of the beetle's predators, parasites and diseases have remained in America (Sandhall and Lindroth 1976; Raman and Radcliffe 1992). This is a phenomenon that is fairly commonly encountered with invasive alien species.[13]

Cold tolerance

The CPB avoids winter colds by digging into the soil – to a depth of about 25-40cm – to overwinter and by entering a period of diapause, which both increase its chances of surviving through the winter (Boiteau and Coleman 1996; EPPO 2005; Nault et al. 1997). The low temperature exotherm determines the lowest temperature that can be survived by a freeze intolerant insect species. For CPB adults in diapause it is about -12ºC, although generally exposure to -7.5ºC for 48 hours or more is lethal to most beetles (Boiteau and Coleman 1996). If the soil in which the beetles overwinter is wet, temperatures below zero may be reached. This is true especially when there is no protective snow cover.

[13] Consider for instance the already mentioned case of the European rabbit escaping myxomatosis when invading Chile.

In Finland the mean winter temperature in 1971−2000 is between -4ºC and -10ºC in most parts of the country (FMI 2006). However, it is the extreme temperatures and especially the consecutive cold days that ultimately determine whether the beetle can overwinter in Finland. In the Ukraine mortality during hibernation has averaged 30%, but could be up to 83% (EPPO 2005).

In addition to the winter temperature, also the summer temperature has been found to be important for determining whether the beetle can establish in a particular area. If the summer is too cold, there is no opportunity for proper development, and thus even a mild winter can exterminate the population. Studies in Finland show that normal Finnish summers or frosty nights do not limit dispersal of the beetle, whereas a very cold summer (10-15ºC) does limit the dispersal. On the other hand, there has been some indication that the northern populations (in Russia) have adapted to the colder climate through faster development (Boman et al. 2006a,b).

In Russia it has been estimated that the requirement for a full generation developing (needed for establishment) is at least 60 days of temperature being over +15ºC, and the winter temperature not falling below -8ºC (Vlasova ca. 1980, cited in EPPO 2005). However, the summer of 2004 saw the first confirmed case of winter survival in Finland (Dr. Leena Lindström, verbal communication; KTTK 2004). Finnish winter presents challenges to the beetle dispersal, but does not prevent it (Boman et al. 2006a). Hence the beetle has the ability to establish in at least southern Finland. Having said that, there are uncertainties related to the particular conditions that determine whether overwintering and survival of the beetle is successful or not in northern latitudes (Lyytinen et al. 2006).

<u>Pesticide resistance</u>

In 1937 only seven species of pests were known to be resistant to one or more pesticides. By 1984 this number had increased to 447 species (Schepel 1996), and by 1991 there were over 500 insects and mites resistant to at least one insecticide or acaricide (Georghiou and Lagunes-Tejeda, cited in Grafius 1997). This trend is also exemplified by the CPB, which is renowned not only for its powers of destruction, but also for its ability to rapidly develop resistance to insecticides.

In the Long Island, USA, the CPB has been targeted with insecticides for more than 100 years. The beetle's resistance to DDT was first observed in 1952, seven seasons after the introduction of the pesticide. This indicates that the beetle was able to evolve resistance to DDT in 14 generations. After the failure of the DDT, each new insecticide introduced failed, with the useful life of each successive introduction becoming progressively shorter (Hare 1990; Raman and Radcliffe 1992). The CPB is resistant to at least 25 insecticides (Georghiou and Lagunes-Tejeda, cited in Grafius 1997), and many CPB populations have developed resistance to almost all registered insecticides (Hare 1990). Hence, the economic problem is that pesticide effectiveness decreases and costs increase over time due to application of larger quantities or more expensive pesticides (Lichtenberg and Zilberman 1986).

EPPO (2005) argued that about 15 years ago the beetle was no longer considered as important a pest as before in EPPO countries, due to use of effective plant protection products and routine control. The situation may have somewhat changed since, due to development of pesticide resistance in the beetle population. For instance, in Poland 100% of the individuals tested were found to be resistant to permethrins, whereas in Estonia the figure was about 20%. As for organophosphates, in Poland the prevalence was again 100%, whereas it was about 50% in Estonia and about 60% in Russia (Lindström et al. 2006).

In Europe natural predators have not established to control the beetle. In the US a lady beetle (*Coleomegilla maculata*) feeds on CPB eggs and young larvae (Coll et al. 1994). Also ground beetle (*Lebia grandis*), daddy longlegs (*Phalangium opilio*) and spined soldier bug (*Podisus maculiventris*) feed on the CPB but not on the potato plants. In addition, *Doryphorophaga doryphorae* fly parasitises the CPB larvae (Hare 1990; Stetter Neel 1992). For other predators and parasites of the beetle, see EPPO (2005) and O'Neil et al. (2005). However, native enemies have not provided enough protection against the CPB in the US (Cañas et al. 2002; Hare 1990; O'Neil et al. 2005).

Also alien species have been tried in biological control. An egg parasitoid *Edovum puttleri* was imported to the US from Colombia to control the beetle (Ruberson et al. 1989). However, it does not tolerate temperatures below about 13ºC, hence decreasing its effectiveness in many areas (Lashomb et al. 1987). Also bacterium *Bacillus thuringiensis* has been applied, but it works only on the first larval stages and works better in warmer climates. Having said that, its use has been found in some studies to be more cost effective than traditional insecticides (Stetter Neel 1992).

Altogether, no natural enemy (native or alien) has been found that would be able to keep the beetle population below a damage threshold (Cañas et al. 2002; O'Neil et al. 2005). The CPB can also be controlled through means other than insecticides or biological control. The most important alternative method is crop rotation (Grafius 1997; Stetter Neel 1992). Other methods include early planting, hand picking, removing plant vines, mulching, floating row covers and using flame throwers (Hare 1990; Stetter Neel 1992). These alternative control methods are beyond the scope of this study.

2.5.2 Spread and distribution

The beetle originates from Mexico (Hare 1990) and is currently established in North America, some Central American countries (Costa Rica, Guatemala, Cuba), many Asian countries (including Turkey, Iran, several countries of former USSR and Russian Far-East), and most European countries (except for Britain, Ireland, Norway, Sweden, Finland and some Spanish and Portuguese islands) (EPPO 2005; EC 2000). The current distribution of the species is shown in Figure 6 (source for the map is EPPO (2005)).

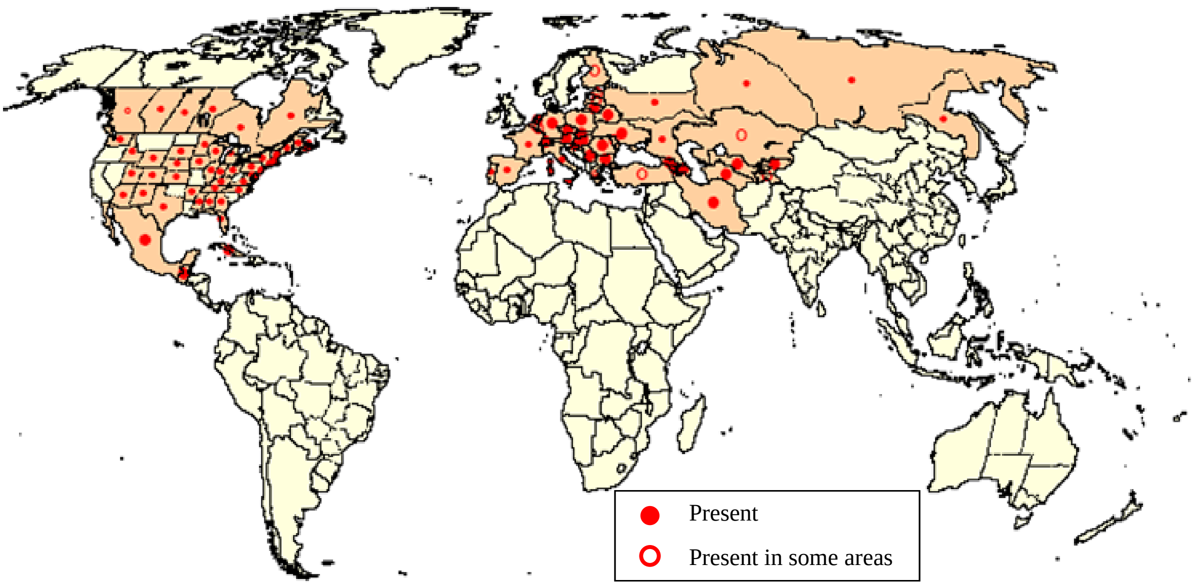

Figure 6. Global distribution of the Colorado potato beetle in 2003.

The presence of the beetle in Europe dates back some 80 years, as demonstrated in Figure 7 (KTTK n.d.). It was introduced from the USA to Bordeaux in France in 1922, from where it rapidly spread throughout Europe, reaching Spain and Germany in 1930s, Portugal and Poland in 1940s, Bulgaria and Lithuania in 1950s and Greece and Estonia in 1960s (EPPO 2005; KTTK n.d.).

The spread in Europe has in recent years been slowed down by international co-operation, for instance between France and the Channel Islands. The aim of the co-operation has been to prevent any further spread (EPPO 2005). However, for instance in Austria its population size is again on the increase (Rabitsch and Essl 2006). The European and Mediterranean Plant Protection Organisation (EPPO) lists the species in its Appendix 2, indicating that it is present in the EPPO region, but is not widely distributed and is officially being controlled (EPPO 2004; 2005).

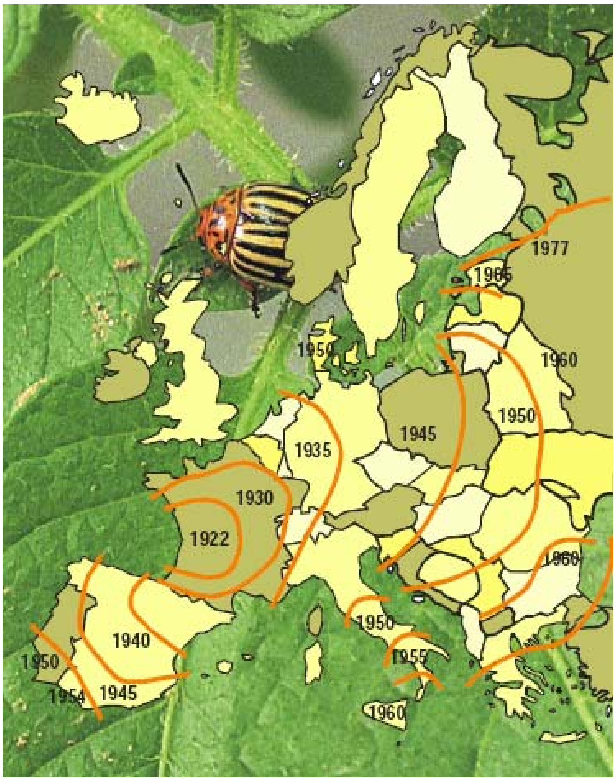

Figure 7. Spread of the Colorado potato beetle in Europe.

The beetle can disperse by means of wind-borne long-distance migration. This seems to be its primary mode of transport to Finland, although it can also be carried over large distances in sea water. In addition, transportation of its host plants in, for instance, trucks and trains provides a third method of long-distance dispersal. Near-range dispersal can take place through walking or flying (EPPO 2005; Johnson 1967; Weisz et al. 1996).

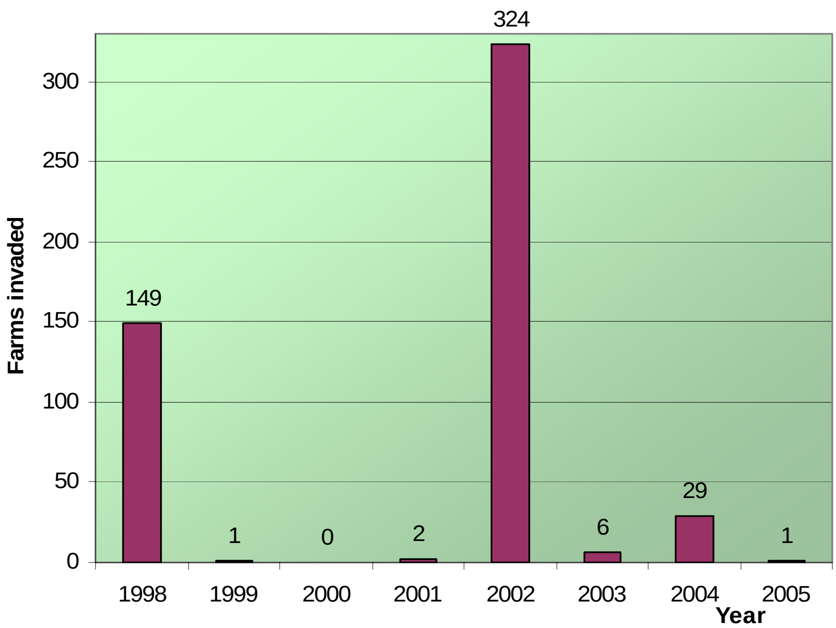

Figure 8. The number of farms invaded by the Colorado potato beetle in Finland 1998–2005.

Figure 8 depicts the number of invaded farms in 1998–2005.[14] The first recent invasion by the CPB in Finland took place in 1983, but was very localised and short-lived (Rautapää 2002). The major invasions which also initiated interest in this study took place in the summers of 1998 and 2002. In 1998, there were 149 potato farms affected, of which 26 were professional farms and two professional organic

[14] The number of invaded farms is obtained from KTTK:

farms.[15] In 2002, the biggest invasion so far, there were 324 farms affected, 55 being professional farms. The interim years 1999–2001 as well as 2003–2005 saw no large scale beetle invasions, although some observations were made each year. The time-span of the data is not very long, but within this dataset, it seems that the invasion magnitude is increasing in both the invasion years (2002 vs. 1998) as well as in the interim years (2003–2005 vs. 1999–2001).

Most of the plots affected in both 1998 and 2002 were situated in south-eastern Finland, suggesting that the beetles had spread from either Russia or Estonia. This suggestion is supported by genetic studies conducted at the University of Jyväskylä, confirming Russia as the origin of the beetles that have invaded Finland (Grapputo et al. 2005). The density of observations by municipality in years 1998 and 2002 is shown in Figure 9.

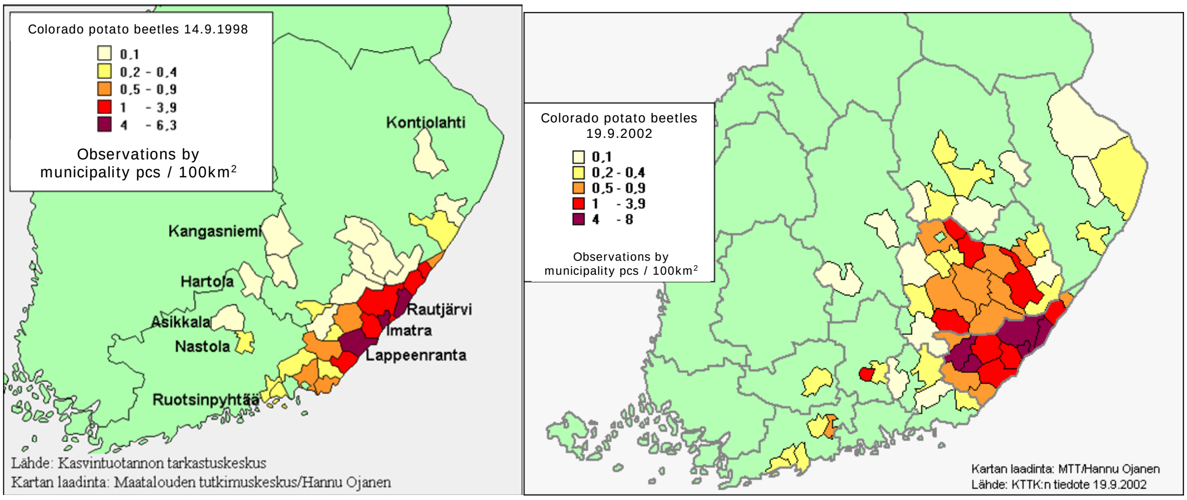

Figure 9. Colorado potato beetle observations in Finland in 1998 and 2002.

Finland has a protection system in force against the CPB. Certain areas in Finland have the European Union protected zone (ZP) status for the beetle (EC 2000; KTTK 1998; MAF 2004b). These areas include Satakunta, Turku, Pirkanmaa, Uusimaa, Häme, Kymi and the Åland Islands and they represent roughly 30-40% of the total potato production in Finland. The protected zone area is depicted in Figure 10.

Figure 10. The protected zone area in Finland.

[15] Under the current practice, the same chemical treatment is carried out on organic farms as on other farms. Thus, if subjected to an invasion, these farms lose the organic status (KTTK, verbal communication).

The actions within the protected zone and the eradication measures to be undertaken are specified in Council Directive 2000/29/EC and in the Regulation of the Ministry of Agriculture and Forestry 38/04. Although the protected zone is only for the given areas, national actions are applied in the entire country. Hence the beetle is eradicated regardless of whether it is found within the protected zone or outside the zone. Our understanding of why the entire country was not given the protected zone status is that, according to the Community legislation, the species has to be theoretically able to establish in the area. In determining the protected zone, areas north of the current zone were probably thought to be climatically unsuitable for the CPB to establish.

In relation to Finland, two points can be made. First, even though the CPB has left its parasites and predators behind, thus increasing its destructiveness in Europe, there is also an opposite effect. Since the feeding and development rates are temperature dependent, the beetle finds it harder to feed and survive in the colder parts of Europe. It may not thus cause as much defoliation as it does in southern environments. However, compared to many other European countries, the potato yields in Finland are already fairly low due to poor climatic conditions. For instance, in 2004 the yields were 22.7 t/ha in Finland, whereas the figures elsewhere were 45.7 t/ha in the Netherlands, 44.2 t/ha in Germany, 42.4 t/ha in the United Kingdom and 30.9 in Sweden (FAOSTAT). Under such circumstances, any further crop losses can be seen as fairly harmful for the domestic producers. Furthermore, as the summer temperatures also vary significantly the implications remain ambiguous.

Second, even if the beetle is able to establish in Finland it is likely to have just one full generation a year. This affects the time it takes from the beetle to acquire pesticide resistance. Thus the impacts of pesticide resistance, although still important, may not be as dramatic in the northern conditions as they are further south. However, if the invading population is already resistant due to application of pesticides elsewhere, and if there are no or little fitness costs associated with resistance, the implications of this argument are also ambiguous and require further research.

To conclude, in light of the characteristics discussed above, there seem to be five important ecological factors to take into account in the analysis: i) the beetle has spread very rapidly across the continent in the past, although its spread has slowed down as it has approached the ecological limits of its survival range; ii) in propitious environmental conditions, its population size can increase extremely rapidly; iii) it is capable of causing significant damage to potato plants; iv) cold summers and winters present an obstacle to its establishment, but the areas in Finland where it can permanently establish are difficult to predict; v) lack of natural predators and ability to develop resistance to chemical control substances make the beetle difficult and expensive to control.

For the interested reader, further discussion on the CPB and Finland can be found in Koukkunen (1999), Pirvola and Nedeström (1984), Rautiainen (2004) and Tomminen (1999). Genetic analysis of the CPB population in Finland can be found in Boman et al. (2006a,b), Grapputo et al. (2005) and Lyytinen et al. (2006). A more thorough discussion of the CPB ecology can be found in Hare (1990). Having discussed the basic ecological and institutional factors related to IAS in general and the CPB in specific, we now turn our attention to economic aspects of the issue.

3. INVASIVE ALIEN SPECIES – ECONOMICS

We now move on to discuss the economic damages, the management framework and how IAS issues can be modelled. Section 3.1 discusses the potential economic benefits and costs of IAS as well as some models that can be used in estimating those benefits and costs. Section 3.2 moves on to presenting the IAS management problem and showing in a very simple model the presence of externality and public good aspects. Section 3.3 reviews economic papers on IAS, concentrating on three specific themes: prediction, vulnerability and control. This is followed in Section 3.4 by a review of studies that discuss the fundamental concepts of pre-emptive versus reactive control, including cost-benefit analyses similar to the present study.

3.1 Potential benefits and costs

Intentionally introduced IAS may provide several potential benefits. For instance, introduced species produce about 98% of global food supply, valued at more than $5 trillion annually (Pimentel et al. 2001). They also produce positive benefits for the society in the form of, for example, various products, medicine, visual pleasure (garden plants), biological control and human accompaniment (pets). A recent – controversial to say the least – proposal suggests introducing species such as the African elephant (*Loxodonta africana*) and lion (*Panthera leo*) to North American Great Plains to restore biodiversity and aid conservation of the species (Donlan et al. 2005).

If we strictly adopt the definition of the Executive Order 13112 (recall Definition 6), an alien species with only beneficial impacts is not considered to be an invasive species. The problem is that species can be both: they may provide the desired benefits, but also result in unforeseen detrimental effects.

As an illustrative example, consider the case study done by de Neergaard et al. (2005) on two wattle species (*Acacia mearnsii* and *Acacia dealbata*) in South Africa. On one hand the species consume large quantities of water in an already dry environment, provide cover for criminals and present a threat to indigenous biodiversity. On the other hand, they provide heating and building material to the local communities, are used for medicine extraction and act as a source of income for local households selling them for firewood. Hence care needs to be taken when considering the impacts of IAS, and also the potential benefits be taken into account when discussing the damages caused.

Despite the universal scope of the issue, the United States is effectively the only country where a fairly thorough economic study on IAS damages has been conducted at the national level (Pimentel et al. 1999; 2005). The study includes control costs, production losses to animal and plant diseases and pests, and costs of certain human diseases (AIDS, influenza and syphilis). The updated version of the study estimates the annual costs as about US$120 billion. In addition, Pimentel et al. (2001) estimate the annual costs for a group of six countries (United States, United Kingdom, Australia, South Africa, India and Brazil) as US$314 billion.

In certain other countries cost estimates exist for particular sectors or species types. In New Zealand exotic pests, weeds and diseases cause annual damage equivalent to a minimum of one percent of gross domestic product (Bertram, in Jay et al. 2003). In Germany, twenty species cause an estimated annual damage of 100-265 million euro (Reinhardt et al. 2003). In Australia, weeds cause annual damage to agriculture worth about A$4 billion[16] (Martin 2003). In Canada the projected annual costs of sixteen species were estimated to be CAD$13-34 billion[17] (Colautti et al. 2006). Such aggregate figures do not provide much guidance on individual management questions, but they do point out the scale of the issue and as such are valuable in highlighting its importance.

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[16] A$ 1 ≈ 0.65 euro (Nordea Bank exchange rate, 08.03.2006).

[17] CAD$ 1 ≈ 0.75 euro (Nordea Bank exchange rate, 08.03.2006).

Concentrating on species that impact on a particular type of production process – agricultural production – Table 5 lists some examples from the literature on damages caused by IAS in agricultural environments. Note that the cost estimate is often for one area and one type of damage only and as such represents the minimum damage inflicted.

Another word of caution goes the other way: as discussed earlier, most species that are potentially invasive do not invade, and of those that do only a small proportion becomes established, let alone a pest. Thus the review is merely a biased sample of some invasions that exemplify the problem. It is worth bearing in mind that economic studies are usually not made of species that cause little or no damage at all. Further, if the invasive species was not there, it is possible that a native species could cause the same negative impacts. Having said all that, the small proportion of IAS that do establish as pests are capable of causing significant damage.

Invasive species and location		***Impacts***	***Estimated cost***	***Reference***
Canada goose (*Branta canadensis*) in Germany		Agricultural damages (grazing and field trampling)	DEM 1-3M annually (damage by both Canada goose and native geese)	Gebhardt 1996
Citrus canker disease in California		Crop damages	Ex-ante: $1.8-2.4B (NPV), including changes in consumer and producer surplus	Jetter et al. 2003
Colorado potato beetle (*Leptinotarsa decemlineata*)	England	Potato crop damages through reduced photosynthesis	Ex-ante: control costs of £3.87M present value over 30 years	Mumford et al. 2000
	England and Wales		Ex-ante: £0.4-2.7M (1979 prices) annually in costs of control and crop damage	Bartlett 1980 cited in Baker et al. 1998
Desert locust (*Schistocerca gregaria*) in the Sahel, Middle East and North Africa		Crop damages	$500M in 1987–96 on control	Hardeweg 2001
European purple loosestrife (*Lythrum salicaria*) in 48 US states		Reduction in biomass of native species, changes in wetland structure	$45M annually on control and forage loss	Pimentel et al. 1999; Aulio 2002
European rabbit (*Oryctolagus cuniculus*)	Great Britain	Crop loss of winter wheat	£6.50/rabbit (experimental conditions)	McKillop et al. 1996
	Germany	Damage to agriculture and forestry. Burrows damage parks and runways	DEM 10M annually in 1970s, today higher	Gebhardt 1996
Field bindweed (*Convolvulus arvensis*) in Kansas		Crop damages	$40M annually	Cited in Settle et al. 2002
Golden apple snail (*Pomacea canaliculata*) in the Philippines		Damage to rice seedlings	$28-45M annually (1990)	Naylor 1996
Leafy spurge (*Euphorbia esula*) in Montana, N. and S. Dakota and Wyoming		Rangeland, wildland and idled cropland weed	$130M annually	Bangsund et al. 1999
Mango mealybug (*Rastrococcus invadens*) in Benin		Mango crop damages through reduced photosynthesis	Avoided annual cost $50M in biological control programme, $531M present value over 20 years.	Bokonon-Ganta et al. 2002
Pheasant (*Phasianus colchicus*) in Germany		Damage to vegetable fields, vineyards and seeds and seedlings in corn fields	Ca. DEM 2.5M annually	Gebhardt 1996
Red imported fire ant (*Solenopsis invicta*) in California		Damage to irrigation and mechanical equipment, health, biodiversity, etc.	$387-989M annually	Jetter et al. n.d.
Tilletia indica in NW Mexico and Europe		Causes Karnal bunt of wheat, quality impact on wheat, impacts foreign trade	$7M annually in NW Mexico, €1.5-34M in the EU during the first year.	Kelly et al. 2002; EC (2006)
Tobacco whitefly (*Bemisia tabaci*) in England and Wales		Transmits plant viruses, causing tomato crop loss	£11.5M decrease in national gross margin	Morgan and MacLeod 1996

Table 5. Invasive alien species damage costs from case studies in an agricultural setting.

As indicated in Table 5, even a close subset of invasions – those affecting agricultural production – imply a diverse range of areas, effects and cost estimates. The potential costs caused by IAS are wide-ranging, but can be roughly divided into four categories: control costs, production losses, secondary market effects, and health, environmental, and cultural effects. These are discussed below in turn, also introducing some basic models that can be used to estimate those costs.

In addition to the damage categories discussed below, a recent concern is that IAS may be used deliberately to upset food production or otherwise disrupt the functioning of the society. This is not a separate category in that the effects are likely to take place through the same damage categories. However, the quiddity of this type of damage is its distinct nature of intentional malevolence. The World Health Organization has already paid attention to the issue (WHO 2002) and for instance the US Department of Agriculture has received additional funding of hundreds of millions of dollars for agri-security (USDA 2003). For further discussion, see for instance Gewin (2003).

3.1.1 Control costs

IAS often cause damages to such an extent that they need to be controlled in one way or another. Basic control methods include for instance chemical treatment with control substances, biological control, immunisation, host management (e.g. crop rotation) or genetic alteration of hosts by either traditional methods or through genetic engineering (Newman 1993).

The objective of the control measures varies – a common division of available actions deals with eradication, containment and control (CBD 1992; Council of Europe 2003; Shine et al. 2000). The most extensive measure is to eradicate the entire population. If eradication is found not to be feasible or economical, it is possible to try and contain the population to a given area and thus prevent any further spread. If also this is not possible, the final measure is to control the species in order to keep its population size and density below some minimum threshold level. Finally, restoration of the ecosystem to the pre-invasion state may in some cases be seen as a viable policy. There are various important aspects related to control measures undertaken and the costs that ensue. There is no space to go into the issue in detail or to provide extensive examples, but some main points are raised below.

Although for instance the guiding principles of the CBD advocate eradication as the next best thing if prevention fails, very few eradication programmes have been carried out in Europe (Genovesi 2005). The reasons for this include inadequate national laws, unclear responsibilities among authorities and opposition by animal rights groups. In addition, invasions that are not targeted immediately when a species is first encountered and thus become widespread can be extremely costly to control. Total eradication can in such circumstances be very difficult or impossible to achieve and eradication costs are likely to increase the fewer individuals there are left. The case of Kapiti Island in New Zealand exemplifies the problem. It cost NZ$ 50,000 to eradicate the first 11,500 individuals of the invasive possum (*Trichosurus vulpecula*) population and NZ$ 220,000 to eradicate the last 80 (Cowan 1992).[18] And all this took place on a relatively small island with no immigration and with large pests that are relatively slow to reproduce. Similarly, the eradication of the twelve individuals of Himalayan porcupine (*Hystrix brachyura*) in Devon, Great Britain cost about 230,000 euro (Genovesi 2005). Hence eradication is often feasible only when the size of the invading population is relatively small and it is geographically restricted (Council of Europe 2003). For examples of eradication successes and failures, see Genovesi (2005) and Simberloff (2003b).

Containment and control also involve challenges. If chemical control substances are used, the target species may develop resistance to the substance. Hence, as time goes by, the costs of control are likely to increase and the effectiveness of control likely to decrease (Lichtenberg and Zilberman 1986). The magnitude of this problem naturally depends on the control method used as well as the properties of the species itself. For example, Colorado potato beetle is notorious for its capability of developing resistance to most insecticides in a very short time, and hence this factor is integral in problems related to the beetle. If, on the other hand, biological control is used, a different set of management challenges that may impact on the costs and feasibility of control is likely to emerge.

In containment, the objective is to protect the nearby areas, either inside the country in question or in neighbouring countries (Council of Europe 2003). Natural geographic formations in the habitat may either help or hinder any containment efforts, and hence need to be accounted for. For instance, Sharov and Liebhold (1998) show that once a pest is present, stopping it from spreading is not an economically viable strategy unless there are sufficient natural barriers that can be used. On the other hand, in their specification slowing the spread is optimal even when only a small area remains non-invaded (Sharov and Liebhold 1998, see also Sharov 2004). Also continued new invasions may affect the success of control measures and their economic profitability, especially if eradication is the chosen objective.

[18] NZ$ 1 ≈ 0.58 euro (Nordea Bank exchange rate, 08.03.2006).

Finally, the incentives of stakeholders are important in determining whether authorities receive help in control or not. For instance, in the case of species that threaten agricultural production, help from farmers may be readily available. Large-scale help is much less likely in the case of species that threaten natural ecosystems in perhaps distant locations. Thus, support from the public and political commitment are integral factors to account for in the control strategy (Council of Europe 2003). As an example, see Parkes and Murphy (2003) for a discussion on how exotic mammals are managed in New Zealand.

We briefly discuss below how control costs can be taken into account in economic cost-benefit analyses. The two aspects discussed deal with the geographical extent to which the pest is present (pest dispersal models) and the local extent to which the pest is present (decision models).

Pest dispersal models

The spread of an (invasive) organism can be modelled to analyse the pest population pressure. There is a wide range of literature on dispersal of a population in biological sciences, and several different models can be applied (Andersen et al. 2004a; Hastings 1996). Dispersal may be for instance unidirectional, random, seasonal, metapopulation-related, only related to certain age groups, and so forth. In general terms dispersal can be seen as a result of three separate but interrelated processes. These are i) population growth; ii) immigration and emigration; and iii) movement of the population. The ultimate drivers of dispersal are population growth, evolutionary factors and in some cases environmental change (Johnson 1967). In the case of IAS the role of long-range (as opposed to short-range) dispersal is an important issue to account for.

As noted, several types of biological spread models are available (see for instance Crawley 1986; Hastings 1996; Levin 1981; Levin 1986; Liebhold et al. 1995; Newman 1993), and the type adopted should naturally be appropriate to the problem in hand. For instance, any barriers to random spread need to be taken into account, and for instance the ability for habitat transformation may increase the growth rate and hence dispersal of IAS (Cuddington and Hastings 2004). For pests carried by the prevailing winds the assumption of random spread may not be realistic for long-range dispersal, but it may work fairly well for short-range dispersal. As noted earlier, any barriers that are present may also be important for the choice of management strategy. Also environmental fluctuations may affect dispersal. In an IAS context, for instance Neubert et al. (2000) model the spread of an invasive species when there are seasonal or stochastic fluctuations in the growth rate of the population and in the probability density function of propagule dispersal. If the primary mode of movement of the IAS is transport through traded goods, gravity models and traffic flow models may be used (Andersen et al. 2004a).

Models involving pest dynamics may become very complex if the life-history of the pest is accurately accounted for. Pest individuals are added by birth, for instance logistic or exponential, and removed by death of individuals. In addition there may be immigration and emigration. This is yet relatively straightforward, but when different life stages (e.g. pupa, larva) and different age-groups with life-stage or age-group specific birth, death, immigration and emigration rates are taken into account the model may get quite complex (Kropff et al. 1995).

In IAS related analysis, the objective of pest dispersal model is to estimate how the invading population might disperse in given conditions. Despite the extensive work done on dispersal models in biological sciences in relation to some species, the economic cost-benefit assessments often deal with simple linear or logistic spread of the invading population over a number of years until some maximum carrying capacity is reached. Lacking suitable data on CPB dispersal, also we adopt this straightforward method of estimating dispersal.

Decision models

Impacts of pest control may be modelled using economic decision models. The earliest use of microeconomic theory in assessing the economic impact of pests was by Hillebrandt in 1960 (Azzam et al. 1995). He determined the optimal pesticide dosage by the basic economic criterion: equate the marginal costs of pesticide application with the marginal revenue of the action. This is illustrated in

Figure 11. The figure depicts the marginal revenue (*MR*) and marginal cost (*MC*) of pesticide application. Marginal cost (the cost of applying one more unit of pesticides) is constant, whereas the marginal revenue (the benefit from applying the additional unit) is downward sloping. The optimal pesticide quantity (z^*) is at the intersection of these two curves.

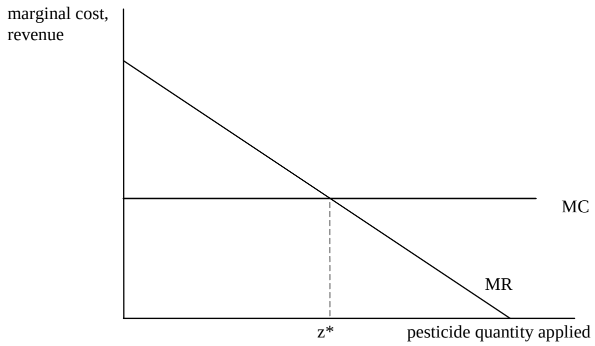

Figure 11. The optimal quantity of pesticide application.

The idea behind this thinking is simple: if the additional benefits of spraying one more unit are greater than the additional costs incurred in doing so, then it pays off to carry out spraying that unit. As private marginal costs are likely to be constant (i.e. unit price of pesticides does not change the more units you apply) and private marginal revenues are reduced the more units you apply (due to diminishing marginal productivity of pesticide use) there comes a point when no more should be applied. This is the level marked z^* in Figure 11 and it represents the privately optimal level of pesticide use.

Some twelve years after Hillebrandt's application, Headley introduced the concept of an economic threshold (Azzam et al. 1995; Carlson and Wetzstein 1993). Again, the marginal cost of control is equated to the marginal value product of control. The point now, however, is that pesticide application may not be profitable until a certain threshold pest population size or concentration is reached. At low pest concentration levels it does not pay off to apply the pesticide, because the marginal revenue from doing so is less than the associated marginal cost. In other words, there is a minimum population concentration N^* below which pesticide application is not profitable. This is the economic threshold level of pesticide application in this case. A simple example of a threshold model can be presented as follows (after Carlson and Wetzstein 1993):

$$\pi_{NO} = p\,(q - DN) \qquad (1)$$

$$\pi = p\,[q - DN\,(1 - v)] - p_z \qquad (2)$$

Producer profits without control π_{NO} are the (constant) price of output p times the potential yield without the pest q, from which the amount of pest damages is subtracted. This damage is equal to per individual damage done by the pest D times the pre-control pest density N.

Producer profits with control π are the (constant) price of output p times the potential yield without the pest q, from which the amount of pest damages is again subtracted. This damage is now reduced by the control actions, and is equal to per individual damage done by the pest D times the pre-control pest density N adjusted by the percent reduction in pest numbers due to control (1-v). From this expression the (constant) cost of control p_z is subtracted.

The threshold population size N^* can be calculated by equating these two functions. By doing this, it is possible to find the population size at which the profits with control are exactly equal to profits without control. With a pest population any higher than this, the profits with control are greater than without control, and hence the population level N^* is the economic threshold level above which control is profitable. The resulting formula can be reduced to

$$N^* = \frac{p_z}{pDv} \tag{3}$$

At this population level the marginal cost of control (p_z) is just equal to the marginal revenue of control ($pvDN^*$).

This type of decision models may be considered from either private or social point of view. When social perspective is taken, the term cost is understood more widely and for instance the environmental impacts of pesticides can be included in the analysis. The private producer naturally is unlikely to include this social component in his calculation, and thus the need for social guidance can be analysed by comparing the private and social optima.

Decision models have been used fairly extensively in the context of agri- and horticulture. For instance, Binns et al. (1992) estimate the threshold level in the case of Colorado potato beetle to be four to eight larvae per stalk, depending on the growing conditions. Hansen (2004) calculates the thresholds level for pollen beetles (*Meligethes aeneus*) in spring oilseed rape (*Brassica napus*) crops in Denmark, and Naranjo et al. (1996) analyse the impact of crop prices, control costs and efficacy of control on the thresholds for tobacco whitefly (*Bemisia tabaci*) in cotton in the United States. Azzam et al. (1995) apply the approach to deal with livestock diseases and Saphores (2000) discusses decision models when pest dynamics are stochastic. Any temporal model should take into account also future development of pest resistance to chemical control substances, as well as future development of the plant resistance against the pest (Shtienberg 2000).

Doyle (1997) presents some criticism of threshold models in the case of weeds. Much of this criticism is likely to apply to other harmful organisms. First, they depend on experimental evidence at weed levels that may be of little use in reality. More generally, they can be criticised for being limited to the conditions at which the experimental measurements were carried out (Kropff et al. 1995). Second, Doyle (1997) argues, most decision models assume uniform distribution of weeds. Third, there is often considerable uncertainty regarding the weed density (with pre-emergence herbicides), the crop loss function and the herbicide dose-response function. Due to this uncertainty producers often apply control in such a way that the actual threshold becomes irrelevant. Finally, inclusion of social costs of chemical control may increase the threshold to such high levels that significant crop losses result, and as such the threshold level becomes meaningless for the producer (Doyle 1997).

3.1.2 Production losses

Invasions may cause damage to various anthropogenic production processes. A well-known example is the zebra mussel (*Dreissena polymorpha*) in the Great Lakes of the United States. The species spread from Europe in ship ballast and has subsequently spread rapidly within the United States. In addition to competing with native flora and fauna, the species results in direct economic damage by blocking power plant intake pipes. The annual costs are estimated to be about US$1 billion (Pimentel et al. 1999; 2005). Another notorious example is the invasion of Guam by the brown tree snake (*Boiga irregularis*). It arrived on the island in the landing gear of the US military aircraft. In addition to causing the extinction of several native bird and lizard species, the snake causes frequent power outages on the island by short-circuiting power lines. The power outages alone are estimated to cost US$7 million a year to the power utility and its customers (Pimentel et al. 1999; 2005; Pimm 1991).

Examples from agri,- silvi- and aquaculture abound, so we shall here give just one example of each. A more detailed discussion on cost-benefit analyses of agricultural IAS is given in Section 3.4. In agriculture, Naylor (1996) discusses golden apple snail (*Pomacea canaliculata*) which has invaded the rice production systems in many East and Southeast Asian countries. The snail can spread through the irrigation network and impacts on the yield by feeding on rice seedlings. Naylor (1996) calculates the cumulative present value costs caused by the snail to agricultural production to be between US$425 and US$1200 million in the Philippines.

In silviculture, MacLeod et al. (2002) analyse the threat presented by Asian longhorn beetle (*Anoplophora glabripennis*) to European hardwood tree species. The adults feed on the bark of small twigs as well as on leaves and petioles, whereas the later-stage instars move into the woody tissues and create tunnels inside the tree. In China, the beetle is among the ten species that cause the greatest economic damage to *Populus* trees. It spreads in wood packaging material, and the projected damages in Europe could be significant: about 90% of the wood in the infested poplar tree areas could be downgraded in quality and hence lose about half of their value (MacLeod et al. 2002).

In aquaculture, Knowler and Barbier (2000) and Knowler (2005) address a comb jellyfish Leidy's comb jelly (*Mnemiopsis leidyi*) which invaded the Black Sea, arriving from the US in ship ballast. It affects the ecosystem through competition with native fish for zooplankton. The impact of the species on the commercial anchovy (*Engraulis encrasicolus*) fishery has been dramatic: the annual rents from the anchovy fishery have declined from US$ 17 million to US$ 0.3 million. The present value costs caused by the jellyfish are several hundred million US dollars.

Thus, IAS are often costly directly by interfering with various production processes. This damage category has perhaps been studied the most in socio-economic sciences, most likely due to the fact that production losses are relatively easy to observe and quantify in monetary terms. Thus it is often possible to make a detailed and fairly accurate analysis of production related costs. Production that relies integrally on natural resources – including agri-, silvi-, horti- and aquaculture – is evidently most at risk, but it is worth noting that also production sectors such as electricity generation, nature tourism and transportation can be affected.

We now review some models that may be used to analyse the production impacts of agricultural pests, including insects, diseases and weeds. Note that some of the model types presented here do not deal exclusively with invasive pests. If we are interested in pest impacts on production (for instance crop damages), there are no intrinsic reasons to differentiate between native and non-native pest impacts in the models. It is only when we wish to account for pest management and the aggregate policy response that the model needs to consider the origin, spread and other specific characteristics of the pest.

Pest impacts can be modelled from a variety of viewpoints and with varying degrees of integration of different aspects.[19] Below we briefly discuss ecophysiological models, yield-loss models and damage functions, which all relate integrally to the extent of production related damages.

<u>Ecophysiological models</u>

When we are interested in the impact of a dispersing species we need to account for both the ecology of the pest species and the process we are interested in from anthropogenic perspective – for instance growth of agricultural crops. Efforts to link pest and crop models started in the 1980s (Kropff et al. 1995). Using ecophysiological crop models it is possible to examine the issue in an integrated fashion. For instance, plant dry matter production per area per day can be calculated from carbon dioxide assimilation (once respiration is subtracted). The effects of the pest can then be accounted for through, for instance, reduced photosynthetic area. This way we can estimate the reduction in growth of the resource caused by the pest (Kropff et al. 1995).

The actual damage mechanism depends on both pest and crop characteristics. The general mechanisms include for instance: i) resource competition; ii) reduction in the assimilation rate; iii) tissue consumption; and iv) hampering of water uptake. Pests are not easy to assign to these groups, however, since they may affect the plant in several ways (Kropff et al. 1995).

Two types of ecophysiological models can be distinguished (Kropff et al. 1995). The first type estimates the daily dry matter production by the plant based on leaf photosynthesis and respiration. In order to

[19] We leave aside for instance predator-prey (e.g. Gaucel et al. 2005), parasitoid-host (e.g. Gubbins et al. 2000; Grasman et al. 2001) and epidemiological (e.g. Anderson and May 1979) modelling frameworks.

do this, these models utilise information on light absorption and radiation at different heights at different times of the day. Effects of the pests can then be introduced through their impacts on, for example, leaf photosynthesis and respiration. The second type deals with modelling dry matter accumulation using absorbed radiation directly by the canopy. Pest effects can in this case be introduced through their impact on radiation use efficiency of the plant.

In an integrated approach the models of pest dynamics and crop ecophysiology need to be linked. The point of linkage is naturally system specific and can be for instance related to resource capture by the plant (light, water, nutrients), some plant process (photosynthesis, respiration, translocation) or some state variable (biomass, leaf area) (Kropff et al. 1995). For instance, in the case of the Colorado potato beetle, an ecophysiological model can be used to estimate the reduced dry matter production by the potato plant due to the decreased photosynthetic leaf area. The pest population dynamics model on the other hand includes the pest feeding on the potato leaf as a constituent of the pest population growth. The linking point for these two models is then the potato plant leaf area which is a constituent of both models.

Yet, this approach is only integrated as far as ecology of the two species is concerned – the economic components remain missing. Thus, in addition to the two ecological components of the model (host plant growth and pest population dynamics) an economic component should be included in the integrated model in order to assess the pest impact on human systems.

Yield-loss models

Yield-loss models link the estimated loss of yield to each level of pest or disease intensity (Shtienberg 2000). In other words, yield loss models can be considered as economic equivalents of the ecophysiological models, where the pest intensity was linked to impacts on plant physiology. In yield-loss models this is extended to economic impacts of those physiological changes.

The approach is in principle similar also to economic threshold models, but the objective is slightly different. In economic threshold models the pest population level at which pesticide application becomes profitable is the focus of interest. Yield-loss models on the other hand try to estimate the issue from a wider perspective than merely when to spray. As it links the pest population level to the magnitude of yield loss, it allows consideration of various management strategies with different costs and producing different levels of crop loss. The yield-loss approach can thus be especially useful for cost-benefit calculations where different strategies impose different pest population levels and different types of costs, perhaps to different agents at different points in time. The approach can also be used to estimate whether total eradication of the pest is economically viable, i.e. what are the benefits of eradication compared to its costs as well as to the costs of adaptation.

Yield-loss models have been used extensively. For example, Willocquet et al. (2000) build an extensive yield-loss model for rice, which they say works for various pests and conditions and can be applied to other crops. Their usefulness is also not restricted to the present conditions. Shtienberg (2000) discusses forecast models with reference to yield-loss models. These can be used for predicting whether there will be yield losses in particular conditions. Different environmental conditions correlate with different levels of pest infestation, and thus can be used to estimate the expected magnitude of crop losses. For instance, Goudriaan and Zadoks (1995) discuss the global climate change and the consequent agro-ecosystem response. They consider the effects of climatic change on crop production, damage done by different types of pests and the distribution of those pests and crops. Such models are to a large extent based on meteorological factors and naturally work very differently for different types of pests. In fact, Shtienberg (2000) discusses the models with reference to diseases, which are easier to forecast based on meteorology than pest outbreaks.

Damage functions

Damage functions are actually simplified yield-loss models. They are discussed in more detail in Lichtenberg and Zilberman (1986), Mitchell (2001) and Carlson and Wetzstein (1993). A damage function was already encountered in equation (3) when decision models were discussed. In general, yield-loss models and damage functions in particular can be seen as a straightforward method of linking the ecological and economic model components into an integrated bioeconomic model. In damage functions a yield-loss model can be incorporated into an economic production function. Damage function approach takes advantage of a standard production function, say $q = q(x)$, where q is the quantity produced and x is the quantity of standard inputs. This function can then be modified such that it also takes the pest damage into account. For instance,

$$q = q(x)\, D(N) \qquad (4)$$

$q(x)$ now represents the *potential* output in the absence of the pest and $D(N)$ is the damage function in which N denotes the post-control population density of the pest. It can generally be assumed that the higher the post-control pest density, the higher the damage. The higher damage then impacts negatively on the output produced, which *ceteris paribus* leads to lower producer profit.

For example Brown et al. (2002) explore a model based on a damage function. In their case there is a source area of a disease, which is transmitted by a vector to adjacent agricultural production areas in which crop damages occur. These follow a simple damage function of the form $D(N(loc))$ where $N(loc)$ denotes the insect population at location *loc*. The model examines the behaviour of the farmer in relation to width and type of the barrier crop between the farmed area and the source area.

Damage functions can feature in a wide range of different models and can be expressed in various functional forms. They can for instance be either additive or proportional (Mitchell 2001). Additive damage functions are of the form $q = q - D$, where the amount of damage D in physical units is simply subtracted from the potential output q. Proportional damage functions on the other hand are of the form $q = q(1\text{-}D)$, where damage D is now expressed in proportional terms, $0 \leq D \leq 1$.

Mitchell (2001) argues that proportional damage functions are especially suitable for competitive pests such as weeds. For predatory pests such as insects the form of the ideal damage function depends on the level of the yield in the absence of the pest as well as on the functional response of the crop to the pest presence. Mitchell (2001) goes on to argue that in general the appropriate form is neither additive nor proportional, but may include elements of both. He also demonstrates through an empirical study of the European corn borer (*Ostrinia nubilalis*) and Bt corn that using the wrong type of damage function may result in a substantial error in results. Despite this result, in most studies the form of the damage function is rarely based on findings of ecological theory or statistical analysis guided by it (Mitchell 2001).

In addition to being merely additive or proportional, the damage function can be a complex function that combines pest dynamics and an ecophysiological model, and thus becomes in effect a yield-loss model. Preferring to avoid additional uncertainty caused by this complexity, this study adopts a simple proportional damage function. This decision can be justified by the fact that – at least to our knowledge – only proportional damage estimates are available for the Colorado potato beetle.

3.1.3 Secondary market effects

Secondary market effects take place through the domestic or international market of the (agricultural) product that is affected by the IAS. These effects are possible if the invasion results in damages to a production process or consumer perception of the product. Detailed discussion on the topic is knowingly left out from the scope of this study, but let us briefly observe some possible basic impacts. Discussion with diagrams is presented in Appendix 2.

If the IAS impacts on some production process, typically more inputs are needed to produce the same quantity of outputs as prior to the invasion. These inputs (for instance control substances as well as additional labour and machinery) are costly, and thus the general implication is that the costs of production increase. Depending on the market structure, some share of these additional costs is passed on to consumers. The same effect takes place if the invasion results in production losses to such an extent that the prices increase because of the diminished quantity supplied. As the product prices increase, the consumers suffer a loss of consumer surplus, because they have to pay more for the product. Also producers may suffer from production losses and control costs – as discussed earlier. What in the end happens to producers and consumers depends on the market structure. The producer and consumer impacts of increased costs are presented below under different types of market structure.

To start with, consider the situation in which there is no foreign trade and supply and demand are both elastic. An invasion induces a leftward shift in the supply curve: at each price level less is supplied as production costs have increased. If neither the supply nor the demand curve is perfectly elastic or perfectly inelastic, the shift in the supply results in consumer surplus being reduced. Hence, the consumers unambiguously lose in the case of an invasion. Part of the consumer loss goes to producers and part to overall welfare loss. The overall impact on producers is unclear and depends on the market structure.

If supply is perfectly inelastic (vertical supply curve), the situation is to a large extent similar as in the previous case. Perfectly inelastic supply means that there is a fixed quantity of the good that can be produced. In such a case shift of the supply curve results in consumer surplus being reduced. Hence, again the consumers unambiguously lose in the case of an invasion and the impact on producers is still unclear.

If supply is elastic but demand is perfectly elastic (horizontal demand curve), change in the supply curve results in no consumer surplus effects. This is because due to the perfectly elastic demand, any price changes are absorbed by the producers and consumers remain unaffected. If demand is perfectly elastic, it means that with any price above the demand curve none of the consumers would be buying anything domestically. The price cannot be set above the demand curve, if the producers are to sell any quantity. This is the only case in which the consumers are unaffected by the invasion.

Let us now add foreign trade (imports) to our discussion of domestic market impacts. World price is assumed horizontal (any quantity can be provided internationally at that price) and domestic supply has the standard upward-sloping form. The world price is assumed to include the transportation costs. There are three possible cases regarding the relationship of domestic and world prices.

<u>1. Pre- and post-invasion domestic prices above world price:</u> The world price may be lower than the domestic price at the domestic market equilibrium. In such a case the impact of the invasion is that the market equilibrium remains otherwise the same as in the standard case above, but the share of domestic production is reduced. The consumers are thus not affected since they can buy at the same world price as before. The domestic producers on the other hand unambiguously lose in producer surplus. The gainers in this case are the international producers.

<u>2. Pre- and post-invasion domestic prices below world price:</u> In this case the domestic equilibrium price is below the world price. This may be the case when price transfers are imperfect, for instance if the international transportation cost is large relative to the product price. This may to some extent be the case in Finnish potato markets. Since following the invasion the post-invasion equilibrium is still below the world price, standard domestic market analysis applies. In other words, whether there is or is not a world price is irrelevant in this case.

<u>3. Only pre-invasion domestic price below world price:</u> The third case is when the initial price is below the world price but the domestic post-invasion equilibrium is above the world price. In other words, the invasion increases production costs such that it becomes profitable to import some quantity of the product. The consumers would lose in consumer surplus, but since the world price acts as a maximum price, the impact is not as large as in the second case above. For the domestic producers the impact is ambiguous and depends on how far from the world price the pre- and post-invasion domestic prices are.

A final point to note about the domestic market effects is that in cases with no foreign trade, they are primarily transfers from consumers to producers or vice versa[20]. If we are only concerned about aggregate figures, market effects through prices do not count as a cost as such. If we are concerned about the distribution of income, then they may count as a cost or a benefit (for instance, a transfer from the rich to the poor could count as a cost under some circumstances, even if it is only a transfer from the society's point of view). With foreign trade added, the domestic market effects may act as a cost if we are concerned about the specific country in question. This is because some proportion of income may be transferred to international producers. Again it is, however, primarily a transfer with one country benefiting and another losing. It depends on the precise market structure as well as our point of view whether such impacts should be counted as costs (or benefits) or not.

As for international market effects, Lord Farrer pointed out already in 1881 that:

> "The true test of the value of Free Trade to England, or to any other country, is not whether she is progressing faster, or even doing a larger trade than another, but whether she is doing better herself with Free Trade than she would do without it; and whether, in her relation to other nations which are not Free Traders, she or they derive the greater benefit from their respective commercial systems." (Lord Farrer 1904)

It is reasonable to argue that free trade is not a goal in itself, only the means for a better livelihood. If the negative side effects of free trade, including invasions by exotic organisms, become large relative to the benefits, some kind of trade protection is well justified. Many IAS are fearsome for countries that have thus far managed to stay free of them. The case is all the more so if the 'clean' country is dependent on the activity that the species threatens. For instance, for Finland, which still is relatively dependent on its forestry sector, an invasion by the pinewood nematode (*Bursaphelenchus xylophilus*) would have significant impacts. Such countries are likely to take action to protect themselves against the risk, and these protective actions affect international trade flows: if there is no outright ban on imports, they will at least become more expensive due to surveillance and quarantine procedures.

Let us consider this situation from the importing country point of view, assuming elastic demand and domestic supply. From purely supply and demand point of view (i.e. excluding the 'real' reasons for the protection system, such as protecting animal, plant or human health), the system is equivalent to the price of imports increasing. It is thus a fairly typical non-tariff barrier (NTB) that results in an upward shift in the effective world price.

Assuming that the world price is below at least the post-invasion domestic market equilibrium[21], the effect of the protection system as such is to decrease the equilibrium quantity and increase the equilibrium price. In both pre- and post-invasion cases, the share and quantity of domestic production increase relative to the situation in which no protection system exists. Thus the system gives the domestic producers an advantage they did not have prior to the protection system. Consumers on the other hand lose in consumer surplus because the price increases. The additional expenditure goes to domestic producers, not their international counterparts.

For the protection system to be internationally justifiable (compliant with the WTO rules), it has to serve its primary purpose, i.e. in this instance protect human, animal, plant or environmental health. Thus, from biosecurity point of view, the price increase caused by the introduction of the protection system can be considered to be a risk premium that has to be paid if we wish to protect ourselves from the threat posed by IAS. At best this protection can prevent the shift in the domestic supply curve due to the invasion induced additional production costs. In such a case the domestic producers would gain a double benefit. First, they would not face the increasing costs implied by the upward shift in the domestic supply curve. Second, they would enjoy the benefits of increasing effective world price, which would increase the market share of domestic producers. If the increase in import price is large enough, it is even possible that the domestic producers end up producing the whole amount demanded.

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[20] Naturally crop losses and increased input requirements count as costs, but the market impact here refers to how the price responds to these changes and who ends up paying the bill. In addition, under certain market situations some deadweight loss may materialise due to decreases in supply.

[21] By this we mean the intersection of the domestic supply and domestic demand curves – the equilibrium that would be effective if there was no international trade.

From the point of view of an exporting country the situation is somewhat different. The analysis above can be extended to consider a case in which increased domestic production costs result in a loss of market share in world markets. This is likely to result in losses to domestic producers. For consumers the result is ambiguous as it depends on what happens to domestic prices – they may even decrease if the supply is diverted from exports to domestic consumption.

More interestingly, there may be effects that are likely to be far more important than the mere loss of international market share caused by an increase in production costs. These include the impacts of international regulation and reputation. A country infested by a potentially dangerous IAS is likely to find its foreign commerce restricted in products that may harbour and spread the IAS in question. This has been illustrated by for instance bovine spongiform encephalopathy (BSE) in the United Kingdom or more recently by the avian influenza in Turkey and Rumania, who both have seen their bird-related exports no longer accepted by the European Union.

On the other hand, a protection system against an invasive pest may promote exports of the domestically produced product. This is the case in for instance the European Union protected zone system, where imports of pest-related products from outside the protected zone system or designated buffer zones are restricted or banned. A protected zone exporter on the other hand can export wherever s/he wants to.

The reputation of a country as a safe, pest-free producer that does not need to rely extensively on chemical control substances may earn that country a comparative advantage in marketing certain products. This kind of an advantage can be lost following an invasion, and it is well known that losing a reputation is quick and easy but regaining it requires a lot of time and effort.

Most of the discussion above (apart from the points made about the reputation) deals with the supply side effects. As the brief discussion on reputation suggested, IAS or fear of them may also impact the demand side of markets. Sometimes the demand side responses are warranted, but it is also possible that unfounded fear may result in significant economic costs. There is no space to discuss these further here, but their importance should be borne in mind, especially in relation to various diseases.

3.1.4 Health, environmental and cultural effects

The final IAS cost category deals with health, environment and culture related costs. Some of the impacts were already mentioned in Chapter 2 when the physical impacts of IAS were discussed. However, these physical impacts can also influence human well-being in various ways, and thus they should be considered also as economic costs. In fact, differentiating between the physical impacts and the economic impacts may sometimes be fairly difficult.[22] Some examples of these effects are given below.

<u>1. IAS can act as vectors of human disease</u>
Invasive alien species may either spread human diseases (zoonoses) or themselves be categorised as such.[23] This category can be exemplified by the Asian tiger mosquito, already discussed in Chapter 2. In addition, many pathogens themselves can be categorised as invaders, one of the most devastating ones being the human immunodeficiency virus (HIV). Another topical and possibly quite devastating example is the recent spread of the avian influenza in Asia and Europe. The economic costs materialise through for instance increased number of sick-days, lowered productive output and increased pain and suffering.

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[22] Consider for instance the case of human diseases. The physical impact of the disease is the impact on the infected person. The economic impact is the subsequent loss in well-being of the person (as well as loss of his/her labour input).
[23] Remember footnote 9.

2. IAS may alter ecosystem structure and processes
The types of changes that IAS may cause in natural ecosystems were already discussed in Chapter 2. Those changes may translate into economic impacts in various ways. For instance, if a sympathetic species is driven to extinction, there may be a loss of welfare suffered by certain groups of people. IAS induced loss of biological diversity will have economic impacts, and IAS may also reduce possibilities for recreation or nature based relaxation.

3. IAS may affect cultural heritage
In addition to the fact that IAS may cause ecological degradation and disruption in the ecosystems they invade, it may also be that people suffer a direct loss of welfare because of that change. Such can be the case if, for instance, IAS transform a traditional heritage biotope into an ecosystem dominated by an exotic species. On the other hand, if a visually attractive IAS has been around for some time, it may be that it has acquired a status of an accepted species by the general public, who then oppose any attempts to control the species. The case of lupin (*Lupinus* sp.) in Finland resembles this situation, as does the case of invasive grey squirrel (*Sciurus carolinensis*) and native red squirrel (*S. vulgaris*) in Europe (Bertolino and Genovesi 2003) or the case of Pacific rats (*Rattus exulans*) within the Maori population in New Zealand (McNeely 2001).

A feature that is common to most costs in this category is that they may be very difficult to value. In many cases non-market valuation using either stated or revealed preference methods is required to estimate the costs. Again, there is no space to go into this issue here. The interested reader is referred to Kopp et al. (1997) and Krupnick (2004).

3.1.5 Policies, aggregation and model choice

We have now discussed cost categories and models that can be combined to produce a fairly functional economic analysis with a bioeconomic model. However, we need to bear in mind that in many cases (especially in those that deal with agricultural production) the economic models approach the issue from a private point of view. Hence, we need to make additional modifications if we want to aggregate the farm level models to a regional or national level, for instance to analyse the impact of various policies.

In aggregation at least three issues should be taken into account. First, pest control – in many ways similar to vaccination – has public good properties. The producer, when protecting his crop, not only protects himself against the pest, but that protection also extends (unintentionally) to the neighbouring farms. The protected field thus becomes in effect a barrier crop between the pest and the unaffected areas. Second, pesticide use may have negative impacts that are external to the private producer. These include possible implications for the environment or consumer health. Third, division of income between different producers as well as between producers, consumers and taxpayers is affected by the presence of the pest and the type of control policy adopted.

Because of these wider issues, it would be beneficial if the bioeconomic model was built in such a way that it can be easily aggregated to the social level. In our opinion the role of empirically applied economic models is to assist not only the producer, but also – and perhaps more importantly – the policy making process such that national or regional policies can be designed and implemented in such a way that some indicator of welfare can be increased. Nevertheless, many studies of pest control strategies do not include both economic and policy considerations. In our opinion both are necessary: the economic component to provide the formal structure, and the policy component to address the aggregate costs and benefits of various alternatives. The importance of the policy component is put succinctly by Perrings (2000):

> "Historically, many evaluations of control options have calculated the ex post benefit-cost ratios for either successful invaders or effective controls. This is tantamount to calculating the ex post value of a winning lottery ticket. It tells nothing about the efficiency of the original decision to buy the ticket. It cannot guide ex-ante decisions about when to control and when not to control. Nor can it guide the choice between control options."

According to Doyle (1997) weed models have traditionally concentrated on three questions:

i) level of infestation above which control measures are justified (threshold model)
ii) relationship of the level of weed infestation and crop losses (yield-loss model)
iii) level of control required to contain the infestation or to eradicate the weed

The third category of models can draw widely from epidemiology where much work has been done on this. Decision and yield-loss models on the other hand constitute an integral part of a bioeconomic model. As Shtienberg (2000) puts it:

> "A management action is justified only if the disease is observed in the field at an intensity higher than the action threshold level, and if the yield loss model suggests that the benefits gained from applying the management action would exceed the cost."

The differences between the models discussed above are not clear-cut and the division may in many cases be rather artificial. Nonetheless, an ideal model for the purposes of studies such as the present one requires four components: i) pest dynamics; ii) ecophysiology of crop production; iii) production function; and iv) social aggregation. The first two combined produce a yield-loss model, which can be incorporated to the production function as a damage function. Finally, the farm level production function should allow aggregation to a social level to allow policy analysis. The level of complication included within each component may vary, but all the components in some form are essential.

3.2 Managing invasive alien species

As indicated, IAS may impose various costs on the society. This alone does not mean that the society should do something about the issue. However, it is the market failures (externalities and public good aspects) involved that dictate that the market does not take care of the problem. In addition, when considering the costs we also need to bear in mind the positive effects of some IAS. It is thus appropriate to aim for, in the words of Perrings (2000), a regime which "allows the social benefits of new introductions, whilst protecting society from the associated risks."

Barbier and Shogren (2004) explore the linkage between growth of an economy and the endogenous risk of biological invasions. They conclude that, on basis of their results, it is unlikely that a decentralised economy produces the socially optimal level of self-protection by households against IAS. Optimal self-protection can happen only if there exists a policy that corrects all consumer and producer impacts of an invasion. Thus, because of externalities and public good properties there is a role for the society in invasive alien species policy.

IAS control is a public good of the 'weakest link' type (Perrings et al. 2002), or rather of the 'weaker link' type (Burnett 2005). It is a public good because it is both non-excludable in production and non-rival in consumption. It is non-excludable because once protection against an invading species is provided, any one member (person, producer, company or state) cannot be excluded from enjoying the benefits. If the pest is prevented from invading, nobody can be prevented from enjoying the protection service. Further, it is non-rival because any one member's consumption of protection does not reduce the amount of protection enjoyed by others. Because of these two properties it is difficult to charge a price from consumers of the protection service, and hence public goods are typically under-provided by the free market.

Moreover, protection against IAS is of the 'weakest link' type because its effectiveness depends on the weakest link in the protection chain. It does not matter how well other parts of the chain provide protection if the species gets into the country through the weakest control point. Stretching this argument over a wide scale, we could soon conclude that globally, if one country provides zero protection, then the level of protection is zero for the whole world. This obviously can be questioned, and hence Burnett (2005) has described IAS protection as a weaker link public good. In this case the investment of those who invest more on protection is negatively affected by those who invest less, but those who invest more are still better protected against IAS than those who invest less (Burnett 2005).

More technically, for the weakest link public goods the lowest contribution determines the overall quantity of the public good produced, whereas for the weaker link the lowest contribution has the largest marginal effect on utility, followed by the second lowest contribution and so forth (Arce M. and Sandler 2001). Nonetheless, the public good property partly explains the need for the involvement of the state in protection. How critical a factor the weaker link property is depends on the characteristics of the species and the regions. Burnett (2005) argues that the characteristics that favour using the weaker link approach include: i) shared borders between two places; ii) heavy movement of goods and people between the places; and iii) the probability of invasion to one place increases as the species becomes present in the other place.

This section formalises what exactly is the management challenge in the case of IAS that are harmful to production. The simple analytical presentation below demonstrates the externality present in the invasion event.[24] Assume an area with a total production area of A_{TOT} hectares. An invasive alien pest is introduced to a subset of this area, with a total of A_t contaminated hectares ($0 \leq A_t \leq A_{TOT}$). Assume pest control costs are the only type of production cost that there exists. Any impacts on world price are assumed away. The per hectare producer profit in the non-invaded area is

$$\pi_{NOINV} = pq_{NOINV} \tag{5}$$

The per hectare profit in the non-invaded area π_{NOINV} is simply the (constant) price of the agricultural product p times the per hectare quantity produced in non-invaded area q_{NOINV}. In the invaded area the per hectare producer profit is

$$\pi_{INV} = pq_{INV}(z) - p_z z \tag{6}$$

The per hectare profit in the invaded area π_{INV} is equal to the (constant) price of the agricultural product p times the quantity produced per hectare in the invaded area q_{INV}, which is now dependent on the magnitude of pest control z. From this the costs of control (per unit cost of control p_z times the magnitude of control per hectare) is subtracted. The producer objective is to

$$\max_z \pi_{INV} = h_{INV}\left[pq_{INV}(z) - p_z z\right] + h_{NOINV}\, pq_{NOINV} \tag{7}$$

Each producer maximises the per hectare profits in their production area, multiplied by their total production hectares depending on whether they have been invaded (h_{INV}) or not (h_{NOINV}). The invasion is assumed exogenous, in other words the private producers cannot *a priori* prevent the pest from invading their fields. More precisely $h_{INV} = h_{INV}(\xi)$, where ξ represents the exogenous magnitude of the invasion. The private optimum can be acquired from the first order condition

$$\frac{\partial \pi_{INV}}{\partial z} = h_{INV}\left(p\frac{\partial q_{INV}}{\partial z} - p_z \right) = 0 \tag{8}$$

The society's objective is to maximise total welfare Π (assumed equal to producer profit for simplicity)

$$\max_z \Pi = A_t\left(pq_{INV}(z) - p_z z\right) + (A_{TOT} - A_t)\, pq_{NOINV} \tag{9}$$

Now, the overall magnitude of the invasion A_t depends on two factors: the original (stochastic and exogenous) size of the invasion ξ and the amount of control z (which thus measures the intensity of control) undertaken by the representative producer

[24] For a more thorough way to formalise the issue, see Burnett (2005). For more discussion on weaker-link public goods, see Arce M. and Sandler (2001).

$$A_t = A_t(\xi, z) \qquad (10)$$

Note the difference here to the private case. The overall invasion area depends also on intensity of pest control by private producers, whereas in the private case the producers merely control the pest to the stage that is optimal for them. Hence (10) becomes

$$\max_z \Pi = A_t(\xi, z)\left(pq_{INV}(z) - p_z z\right) + (A_{TOT} - A_t(\xi, z))pq_{NOINV} \qquad (11)$$

The first order condition for the social optimum is

$$\frac{\partial \Pi}{\partial z} = \frac{\partial A_t}{\partial z}\left(pq_{INV}(z) - p_z z\right) + A_t\left(p\frac{\partial q_{INV}}{\partial z} - p_z\right) - \frac{\partial A_t}{\partial z}pq_{NOINV} = 0 \qquad (12)$$

The difference Δ between social (12) and private (8) optima is then

$$\Delta = \frac{\partial \bar{A}_t}{\partial z}\left[p\left(q_{INV}(z) - \bar{q}_{NOINV}\right) - p_z z\right] + \left(A_t - h_{INV}\right)\left(p\frac{\partial q_{INV}}{\partial z} - p_z\right) \qquad (13)$$

The first term in expression (13) represent the impact of z in reducing the losses (control costs and crop damages) through its impact of reducing A_t, the area invaded. The second term denotes the impact of z in reducing the private losses of producers in the invaded area A_t, excluding the area of the producer in question (h_{INV}), which was already accounted for in expression (8). Hence, the first term denotes the positive impact of control in reducing the spread of the pest, and the second term denotes the positive impact of z in reducing the losses of all other producers.

Both terms in expression (13) are non-negative provided that two conditions hold. First, the impact of control on price times reduced production losses must be no less than the cost of control ($p\partial q_{INV}/\partial z \geq p_z$). This makes sense: the private producer would not apply control if the per unit benefits of control in terms of reduced damages were not greater than the per unit cost of control. Second, the invaded area has to be greater than the invaded area in the single producer's premises ($A_t \geq h_{INV}$). This also makes sense: if only one producer is affected, then there are no impacts on other producers in terms of crop losses (which is what this second term measures), and hence there is no divergence between the social and private optima in this respect. Note that even if this is the case, there may be divergence in the overall optima, since the impact of the first term of (13) may outweigh the second term.

Since condition (13) is the difference between social and private optima, it needs to be added to the private condition to make it match the social condition. As it is non-negative, it implies that the level of protection in the private optimum is too low – too little protection is provided by the private actor. This is because they do not take into account the positive effect that protection (z) has on the spread of the pest (i.e. its impact on A_t). When making the control decision, the private producer only looks at his/her objective function, where A_t does not feature. Thus, the decision to use control is made with no regard to its beneficial impact on A_t. This in essence is the externality associated with invasive alien species and their control.

We have now discussed in basic terms what the IAS management problem deals with. There is an externality because private agents only consider the benefit of protection to themselves and not on others, and through their sub-optimal protection other agents suffer for the pest more than is socially optimal. There is also a public good aspect in protection, as nobody can be excluded from enjoying the benefits of protection and there is no rivalry in consumption of protection.

3.3 Invasion models

In this section we briefly discuss some issues that are specific to IAS and not to native pests or weeds. Ecological invasion models in general are discussed in Williamson (1989). He highlights four uses of ecological models: i) predict the success of potential invaders; ii) explain what has been observed; iii) indicate the possible behaviour of ecological systems subject to invasions; and iv) highlight gaps in the current knowledge.

In terms of economics and policy, IAS can be considered for instance using the frameworks of multiattribute decision analysis (Maguire 2004), risk assessment (Andersen et al. 2004a,b; Landis 2003; Renn 2005) or cost-benefit analysis (Mumford et al. 2000). We discuss the existing literature under three headings, namely i) prediction and screening of invasions; ii) factors affecting vulnerability of the ecological-economic system; and iii) optimal control under various circumstances. The first category deals essentially with the characteristics of species and pathways that they may use in invasion. The second category deals with the characteristics of the receiving system. Finally, the third category involves various control actions available once the species has already invaded. The review below is by no means complete, but provides some indication of the topics that are involved in IAS economics.[25]

3.3.1 Prediction and screening

In terms of prediction and screening, some basic ecological factors were already discussed in Chapter 2. Here we discuss two further economic issues, related to the optimal screening procedures and control of intentional introductions.

Optimal screening procedures and different invasion pathways are the focus of many economic studies. Invasion pathways can be divided in broad terms into transportation related pathways (e.g. shipping, military, mail), living industry pathways (e.g. plants, animals, food, pets) and miscellaneous pathways (Campbell and Kriesch 2003). Inspection services are under pressure from the constantly increasing import quantities as well as in many cases from the government to reduce phytosanitary inspections in face of a limited budget. Further complications arise from the diverse range of imported goods and their origins. For countries in which agricultural trade is important, it is nonetheless vital to maintain an appropriate level of protection (as discussed briefly in Section 3.1.3). The question then is how to establish efficient border protection measures.

Moffitt et al. (2005) discuss the issue in analytical terms in the face of severe uncertainty and resource constraints. The basic idea is that a border inspector receives a shipment with a given number of crates, and having no resources to inspect all the crates has to decide how many crates to inspect. The probability that a crate is infested is unknown. They use a hybrid info-gap model with stochastic dominance to come up with a cost effective protection protocol.

Surkov et al. (2005) study the issue from an applied perspective. Their main research question is "how available resources can be allocated for inspection of imported ornamental plant commodities such that the phytosanitary risks associated with these commodities are minimised". Their results suggest that in the face of resource limitations, it would be economically sensible to switch resources from inspecting more pathways to inspecting fewer, specific, pathways. The same issue is studied by Janssens and Westerman (2005) in the case of Dutch agriculture. They study two options for reducing phytosanitary inspections, namely i) transferring the responsibility to private sector; and ii) reducing the number of inspections by relating the inspection intensity to risk analyses for different invasion pathways. They point out that challenges are presented by the conflicting private and public interests and the current lack of freedom in implementing new regulatory concepts within international regulations of the European Union and the International Plant Protection Organisation.

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[25] There is an increasing body of literature developing on IAS economics. A couple of years ago it would have been possible to review almost all the articles concentrating strictly on IAS and economics. Today this is not possible. Thus, we shall here discuss some articles under the three heading mentioned that introduce the various topics in question.

An altogether different question is whether we would be better off ignoring the prediction rules totally. Smith et al. (1999) use decision theory to derive the optimal screening procedure, i.e. when to ignore the advice of the screening process. Their point is, briefly, the following. If for instance rain can be predicted at 90% accuracy (which at first feels fairly impressive), but normally rain occurs only on 1% of all days, the times that the system erroneously predicts dry days as rainy (10% of 99%, i.e. 9.9%) is much greater than the rate at which it correctly predicts rainy days as rainy (90% of 1%, i.e. 0.9%). Thus, provided that the outcome of predicting a rainy day erroneously as a dry day is not catastrophic, we would be better off ignoring the predictions altogether. This property materialises when the so-called base-rate of an event (1% in the example above) is low (Smith et al. 1999).

This is often the case with invasions: Smith et al. (1999) calculate base-rates of 0.007% – 17% for invasive weeds in Australia. They show that if, for instance, the pest risk assessment system has an accuracy of 85%, its recommendation would be better-off ignored unless the damage caused by the species is at least eight times the damage caused by not introducing a potentially useful harmless species. The policy implication is that under certain circumstances the society would be better off concentrating on controlling and eradicating casual and naturalised species rather than trying to predict the pest status at the import stage. Having said that, for instance in aquatic invasions where establishment may be irreversible, acceptability of intentional introductions in the first place should be questioned (Smith et al. 1999).

Intentional introductions of IAS are also discussed by Thomas and Randall (2000), who apply a principal-agent model to study the issue. The principal is a risk-neutral public agency and the agent is the individual or agency that introduces the species. They point out that in a perfect world the damages could be avoided through either perfect ex-ante information that would result in only beneficial introductions or through perfect revocability that would make it possible to cancel ex-post any harmful introduction. Their approach deals with a mixture of imperfect ex-ante information and imperfect revocability, and they suggest that current procedures should be improved to focus more on revocability and less on seeking ex-ante full information (Thomas and Randall 2000).

3.3.2 Vulnerability of the ecological-economic system

Whereas the previous section discussed studies that concentrate mainly on the characteristics of the invasion pathways, this section reviews studies that discuss the economic factors that affect the vulnerability of the receiving system to invasions (ecological factors were already discussed in Chapter 2). These factors include economic activity, diversity of the productive resource base and protective actions through for instance tariffs.

The level and type of economic activity is an important factor affecting the vulnerability of the receiving system. Levine and D'Antonio (2003) show how trade accumulates new species in the United States in a similar fashion to standard species-accumulation curves used in ecological sampling. Dalmazzone (2000) and Baiocchi and Dalmazzone (2000) examine whether available data supports the hypothesis that economic activities determine the rate of species invasions, and if so, which particular activities are most important. They argue that, despite the rather weak dataset available, disturbances associated with economic activities (including land tenure, level of GDP and population density) seem to be important in determining the vulnerability of the system to invasions. On the other hand, variables related to trade are not found to be statistically significant. They acknowledge that the conclusions derived from their analysis need to be verified using a stronger dataset. However, even with this weakness, the study is an important attempt to look at the connection between key economic variables and biological invasions.

In a similar fashion, Vilà and Pujadas (2001) use a regression analysis to study the relationship between land-use and socio-economic parameters and density of alien plants in Europe and North Africa. They find a statistically significant relationship between import value and alien plant density, as well as between Human Development Index and alien plant density, which together explained about 60% of the variation in alien plant density. However, as the authors caution, relationship does not necessarily imply causality.

On the other hand, Costello and McAusland (2003) show that freer trade can in fact reduce the damage from unintentional biological invasions. This is because although freer trade results in increases in the quantity traded, and hence the probability of introductions, it also changes the production mix of goods. If, for instance, as a result of freer trade less agricultural products are produced, then the damages from an invasion by an agricultural pest will be on aggregate smaller than under restricted trade. On the other hand, also the opposite is true. If a country specialises in agricultural production, the potential costs of an invasion increase. The authors also acknowledge that crop damage may be a poor proxy to total damage caused by IAS. Furthermore, their arguments are not sustainable at a larger scale, where production can no longer move to new pest-free areas.

In addition to trade, diversity of the productive base is important in determining the vulnerability to invasions (remember the discussion of resistance and resilience in Chapter 2). Laxminarayan and Weitzman (2002) discuss multiple drug use in medication. Diversification of the drug base helps to counter the endogenous risk of development of resistance to any single drug. In a similar fashion, Weitzman (2000) shows how the decision to plant more of a widely grown crop increases the endogenous risk of new pathogens evolving to attack that crop globally. In other words, there is a long-run trade-off between increasing profitability due to concentration on high-yield crop varieties and increased risks of endogenous evolution of new pathogens from doing so. Using a game-theoretic framework, Heal et al. (2004) discuss why we may systematically choose too little diversity. They indicate possible options for policy intervention to correct the market failure. Their suggestions include a homogeneity tax (or a diversity subsidy) and redefinition of property rights by, for instance, issuing tradable permits for the use of the crops that are most popular in the region.

Finally, the vulnerability of the receiving system can be managed through for instance prohibitions and tariffs. Knowler and Barbier (2005) show that preventing trade in exotic species with beneficial impacts is not economically sensible. They study horticultural trade and develop a model dealing with a private plant breeding industry that imports an exotic plant species into the area. They discuss the use of market instruments, including a Pigovian tax, to regulate the industry and protect the society from the associated risks. The results from their empirical assessment of the saltcedar (*Tamarisk* spp.) in the United States indicate that to achieve the social optimum, the mere presence of risk associated with imports does not warrant prevention of commercial sales of exotic plant species with beneficial effects for consumers.

The use of tariffs to control invasions has been discussed by various authors. Paarlberg and Lee (1998) discuss the link between import tariffs and the level of health risk from imports with special reference to the foot and mouth disease. They show that the level of tariffs is very sensitive to the risk of importing a contaminated product, as well as the expected magnitude of the spread of the disease. McAusland and Costello (2004) show that the optimal level of the tariff increases in the infection rate of the traded goods, but at high levels of infection the optimal level of inspections decreases with the infection rate. In fact, they find that it is always optimal to employ tariffs, but there are plausible circumstances in which inspections should be optimally set to zero. This occurs when most incoming goods are infected, and it is better to let them in without any inspections and instead charge a high tariff equal to the expected damages. Finally, if future impacts of IAS are accounted for, more stringent inspections are optimal, although the rate of tariffs may move in either direction (McAusland and Costello 2004).

The regulator may also choose too high a tariff. Using a political economy model, Margolis et al. (2005) show that private actions result in the regulator choosing a tariff level that is larger than the socially optimal level. This gap represents the level of disguised protectionism. However, the authors point out that in reality the information requirements to differentiate legitimate public good protection from disguised protection are vast.

3.3.3 Optimal control

Having discussed the properties of origins, pathways and recipients of invasions, the final literature category to be discussed includes studies that examine what to do once an IAS is in the country. Optimal control of invasions has been widely modelled. Extensions of this approach include optimal control with stochastic effects and under ignorance. This category was already discussed to an extent in Section 3.1.1, but in that discussion there was no explicit differentiation between native and invasive species. Therefore, in this section we discuss some studies that deal with IAS.

Perrings (2000) establishes the conditions under which allowing establishment and spread of IAS is optimal. He emphasises that the invasion dynamics are not the only important issue determining optimal control, since also the relative costs and benefits of native and non-native species are important. Jensen (2002) analyses a dynamic model of protection against an invasion, and once invasion has occurred, its control or damage reduction. The society should, he argues, explicitly account for the trade-off between present expenditures to protect ourselves from the invasion, and future expenditures to control or reduce the damages from the few harmful invasions. He concludes that protection is optimal if and only if the cost of the invasion is large enough. He further argues that this conclusion holds regardless of whether that cost is known for certain or only in distribution (Jensen 2002).

An empirical application is provided by Brown et al. (2002), who analyse optimal pest control given spatial nature of the problem, using a case study of Pierce's disease on grapevines. The disease is caused by bacterium *Xylella fastidiosa*, which is transmitted by leafhoppers. In their system there is a barrier crop that prevents the pest from spreading, and they point out that if such a barrier crop exists, pest damage can be significantly reduced. The benefits of using the barrier crop depend on, for instance, the value of the protected grapevine output and barrier effectiveness. The authors also point out that if the lands are divided among different owners, coordination is important and any barrier crop related actions are likely to have spillover impacts on neighbouring owners (Brown et al. 2002).

Olson and Roy (2002) extend the analysis to include stochastic effects. They analyse the circumstances under which eradication of an IAS is or is not optimal, given that the natural growth and spread of the invader are subject to stochastic changes. They show that if the discounted expected invasion growth rate is greater than one, it is optimal to eradicate small invasions even if the marginal costs of control are large relative to the marginal damages. This way a rapid growth in costs in the future can be avoided. For large invasions that necessarily have marginal growth rates of less than one, interaction of the different variables determines whether eradication is optimal or not. Eiswerth and van Kooten (2002) augment stochastic analysis by an expert survey to analyse optimal management strategies under uncertainty. They show that in the case of yellow starthistle (*Centaurea solstitialis*) spread-control strategies are optimal, whereas eradication is not. Their main point is that decision-making under uncertainty can be analysed even when hard data are missing, if the framework is complemented with verbal descriptors by experts of the growth and damages caused by the species.

Optimal control under ignorance has also been studied theoretically. Horan et al. (2002) focus on pre-invasion controls and argue that due to small probabilities involved, irreversibility of the outcomes and the novelty of the events leading to incomplete information, decision models based on expected utility theory have limited value. They discuss optimal pre-invasion control using both ignorance and risk-management models. One outcome of the comparison of these two frameworks is that in ignorance framework the extreme low-probability outcomes are weighted more heavily than in the expected-utility framework, implying a precautionary approach.

3.4 Studies on pre-emptive vs. reactive control

The previous sections have already hinted at the problem of whether invasions should be prevented in the first place, or whether eradication or control after the invasion is optimal. This issue of pre-emptive control (prevention, mitigation, avoidance[26]) versus reactive control (treatment, adaptation, amelioration) has been discussed in various papers and contexts. Olson and Zeckhauser (1970) brought up the issue already 35 years ago: "The cost of moving away from or otherwise adjusting to the diseconomies may be less than the cost of preventing or limiting the diseconomy at its source".

In a relatively early paper, Butler and Maher (1986) undertake a theoretical analysis of the issue. Somewhat confusingly, they call pre-emptive actions "abatement" and reactive actions "damage prevention". The logic is that in their analysis it is the industry that undertakes abatement and an individual (the victim of the pollution) that undertakes reactive control, and in that way this action actually is damage prevention for the individual. The authors argue that by not taking the actions by the victims of an externality into account, the society may end up devoting too many resources to pre-emptive control. This is analogous to findings of Margolis et al. (2005) who show that unaccounted private actions result in the regulator choosing a tariff level that is larger than is socially optimal. Further, Shogren (2000) argues that once we acknowledge that people do adapt, assuming otherwise may lead to biased results. Butler and Maher (1986) also bring up the issue of distribution of costs and point out that if compensation is paid to the victims of the externality, it should not be based on uncorrected marginal damages, as this would induce the victims to undertake too little reactive control.

Barrett and Segerson (1997) discuss the issue in relation to activities that result in environmental externalities, which could be reduced either through prevention prior to their occurrence or treatment after the occurrence. They discuss both the case where the effectiveness of treatment is known and where it is uncertain. In addition to Pareto efficiency, there are other objectives that policies may seek, including minimising damages subject to a budget constraint or minimising expenditure subject to a given damage level. The authors discuss these objectives and show that they are constrained versions of Pareto efficiency and result in second-best outcomes.

Barrett and Segerson (1997) show that given these other objectives, some factors affecting the relative desirability of prevention versus treatment may affect the decision in ways that differ from how they function under Pareto efficiency. For instance, if the probability of contamination increases, optimal magnitude of treatment under Pareto optimality is unaffected, whereas under the maximum damage constraint optimal treatment magnitude unambiguously increases regardless of what happens to the level of prevention. In a similar fashion, an increase in the uncertainty about the effectiveness of treatment does not change the optimal levels of either strategy under Pareto optimality, whereas under a budget constraint it may lead to an increase in the level of prevention and a decrease in the level of treatment.

Leung et al. (2002) use stochastic dynamic programming to study how to devote resources between prevention and control efforts given uncertain invasion events. They apply their general model to the case of Zebra mussel (*Dreissena polymorpha*) – an aquatic species that spread from Europe in ship ballast and has subsequently spread rapidly within the United States. As mentioned earlier, the species damages power plants by blocking their water intake pipes. The authors show that the society could be made better off by spending up to US$ 324,000 annually to prevent the invasion of a single hypothetical lake with a power plant. This figure can be compared to US$ 825,000 that the US Fish and Wildlife Service spent on all aquatic invades in all US lakes in 2001 (Leung et al. 2002).

Kim et al. (2005) also model the optimal allocation of resources between prevention and control with uncertainty in the arrival and discovery time of the invasive species. Their aim is to find how resources should be devoted between actions before and after the discovery of the organism. Their analytical findings suggest that it is efficient to invest on prevention before – rather than after – the discovery. After the discovery, they argue, prevention and control are complementary when the population size is small, but become substitutes as the population size increases. This seems consistent with the findings of Olson and Roy (2002) discussed earlier. The optimality condition requires that the marginal costs of

[26] Note, Barrett and Segerson (1997) use the term mitigation to mean reactive control, whereas for instance Perrings et al. (2002) and most others use it to mean pre-emptive policies. Where confusion may arise, we have replaced the terms used by authors by 'pre-emptive control' or 'reactive control'.

control equal the marginal benefits of reductions in the intrinsic rate of growth of the population, and the marginal costs of prevention equal the marginal reduction in the rate of subsequent arrivals (Kim et al. 2005). The authors also find that the efficient total amount of resources that is spent (on prevention and control) decreases with the increasing population size of the invasive species, but increases with the intrinsic rate of growth of the population as well as with the rate of new discoveries.

Two applications outside environmental economics include Kaya (2004) and Keohane and Zeckhauser (2003). Kaya (2004) discusses the US cocaine epidemic and considers a case where prevention and reactive control cannot be applied at the same time. He shows that regardless of the scenario used, the best strategy to bring the epidemic down to a specified target level is "first prevention, then treatment". Keohane and Zeckhauser (2003) discuss the issue with reference to terror defence by the society and individuals. In addition to targeting what the authors call "stock of terror capacity", the governments can fight terror by seeking to prevent exposure to attacks or to reduce harm if an attack occurs. The terms the authors use for these are avoidance and amelioration. This application may seem somewhat distant from the original idea, but to quote the authors: "two other defensive measures [are] available to governments: averting actions, which reduce the likelihood of a terror attack; and amelioration, which lessens the damages in the event of an attack" (Keohane and Zeckhauser 2003). This is exactly the same as what Perrings (2005) and Perrings et al. (2002) point out when they state that whereas pre-emptive control aims to reduce the likelihood of an invasion, reactive control aims to reduce the impact of an invasion.

Lichtenberg and Penn (2003) discuss prevention versus treatment in the case of groundwater contamination. They show that prevention is not always the most cost-efficient strategy in the case of agricultural pollution. This is so when there are multiple sources of emissions, multiple sites affected and a widely adopted precautionary approach to uncertainty. They also undertake an empirical analysis of nitrate contamination of drinking water wells in Maryland, USA and find that treatment of the well water alone is the most efficient strategy for dealing with the pollutant, the preventative option being utilisation of agricultural best management practices.

The findings of Lichtenberg and Penn (2003) are somewhat contrary to the commonly held belief that prevention is always more cost-efficient than ex-post treatment. The authors also show that, somewhat counter-intuitively, increased concentration on prevention may lead to more reliance on treatment. Their main point, however, is the same as the one that we try to argue in the present study:

> "The main lesson to be drawn is that there is no sound justification for basing policy on a *presumption* that prevention is more cost effective than treatment; rather, the least-cost mix of prevention and treatment is an empirical question." (Lichtenberg and Penn 2003)

Having said that, in many occasions preventative actions are a good strategy, given the uncertainties involved and the difficulties in eradicating most IAS reactively. This approach is forwarded by for instance the intergovernmental scientific advisory body established by the CBD (Perrault and Carroll Muffett 2001). However, we should not take for granted that one of the strategies is by necessity superior. As implied by the paragraphs above, it seems that the particular conditions surrounding the case determine the economic viability of different policies. In addition, international agreements such as the SPS agreement often require an analysis of the problem at hand to justify any trade restrictive practices. Hence economic analyses are warranted.

Table 6 presents seven cost-benefit analyses carried out to assess the possible impacts of invasions in agriculture and in one case of grazing. The articles deal with the screwworm fly (*Chrysomya bezziana*) in Australia (Anaman et al. 1994), the leafy spurge (*Euphorbia esula*) in the Great Plains of the US (Bangsund et al. 1999), the tobacco whitefly (*Bemisia tabaci*) in England and Wales (Morgan and MacLeod 1996), the melon thrips (*Thrips palmi*) in England (MacLeod et al. 2004), the western corn rootworm (*Diabrotica virgifera virgifera*) in England and Wales (MacLeod et al. 2005), the tomato spotted wilt tospovirus and its main vector western flower thrips (*Frankliniella occidentalis*) in Finland (MAF 2003d) and the Colorado potato beetle in England (Mumford et al. 2000).

Species, area, effects and reference	*Assessed policies, time horizon and discounting*	*Impacts accounted for*	*Uncertainty*	*Main result and policy recommendation*
Screwworm fly in Australia - parasite of mammals - Anaman et al. 1994	- 12 strategies with differing assumptions regarding sterile insect technique factory - 30 years time horizon - 6% discount rate	Production and control costs, secondary market impacts Direct producer losses such as stock deaths, reduced fertility, delayed sales of struck animals, wool losses and increased producer control costs. Supply reductions of livestock products and control costs are an input to another model that determines changes in producer and consumer surplus.	Different values for invasion probability and key variables. Impact on optimal strategy discussed.	Policy recommendations conditioned on invasion probability are made. Authors state that additional protection (compared to current level) is likely to be economically efficient.
Leafy spurge in the Great Plains (US) - perennial weed, spreads rapidly and displaces native vegetation - problem on untilled lands - Bangsund et al. 1999	1. Gross benefits from biological control of leafy spurge 2. Costs of not undertaking it - analysis extends to 2025 - no discounting is reported	Production and environmental costs, secondary market impacts In grazing land, the change in grazing capacity translates into change in income of stock growers and landowners and in production outlays by producers. In wildland, the changes in wildlife populations and watershed benefits translate into changes in wildlife associated recreation and in soil erosion and water quality. Both primary and secondary impacts included. Regional impacts estimated with an input-output model for 17 sectors.	No sensitivity analysis of any kind is undertaken.	Only considers benefits of biological control and hence BCRs cannot be computed. No direct policy recommendation. Generally talk in favour of undertaking the project. Inclusion of an input-output model to analyse the secondary impacts (e.g. jobs) is rare. Results indicate that these may be substantial.
Tobacco whitefly in England and Wales - crop losses due to feeding and spread of tomato yellow leaf curl virus - Morgan and MacLeod 1996	1. Eradicate tobacco whitefly and control the virus 2. Do not undertake these actions - static one year analysis	Production and control costs Impacts include tomato crop loss (the virus may result in losses of up to 80% in young tomatoes), quality loss and control measures, all depending on the spread scenario. Gross margin budgets are used to estimate impacts for a south-east England grower profile, and the impact on national tomato industry is estimated by scaling up the impacts.	Sensitivity analysis includes use of four spread scenarios.	Report only gross margins for each scenario, without considering BCRs. Recommend careful maintenance and development of effective monitoring and control programmes.
Melon thrips in England - pest of ornamental and vegetable crops - transmits viruses, causes crop and quality losses - MacLeod et al. 2004	1. Costs of eradicating the invasion in 2000 2. Costs that would have occurred with no eradication - 10 years time horizon - discount rate 6%	Production, control and environmental costs, secondary market impacts For eradication, includes direct costs of insecticides, water for diluting chemicals and inspection measures as well as government measures related to the eradication campaign. For the alternative, both direct and indirect effects (research costs, cost of technology transfer, social and environmental effects and export losses) are considered.	Low/high impact analysis is undertaken to account for uncertainty. Two spread scenarios are analysed.	BCRs 4:1 to 19:1 without export losses and 95:1 to 110:1 with export losses. Conclude that continuing the exclusion policy is cost effective Lost export earnings explicitly accounted for. Results indicate that these may be substantial.
Western corn rootworm in England and Wales - pest of grain maize - larvae feed on roots of maize plant, reducing nutrient intake and growth - MacLeod et al. 2005	1. No implementation of the EC management measures 2. Implementation of the EC management measures - 10 years time horizon - discount rate 3.5%	Production and control costs In the first alternative, yield losses and insecticide costs are included. In the second alternative, the EC measures incorporated through reduced spread rate. Special protection measures (e.g. crop rotation) required in Focus Zone within 1 km and Safety Zone at 1-6 km from the infestation. No yield losses, as mandatory procedures are assumed to keep the pest below an economic threshold. Insecticide costs included, but additional income from land released by maize rotation is not. Effects on seven categories of producers estimated and scaled up to national level.	Sensitivity analysis includes use of three spread rates and three levels of yield losses. Monte Carlo simulation with 10,000 iterations.	BCRs between 0.14:1 and 0.17:1. Conclude that no economic justification to implement the measures in England. Authors note that changes in policies and climate may result in maize production areas in England increasing, increasing the potential losses.
Tomato spotted wilt tospovirus in Finland - virus of ornamental and edible plants - western flower thrips the most important vector - MAF 2003d	1. Continue protected zone 2. Abandon protected zone - ex-post of last 5 years - ex-ante of 10 years - no discounting is applied	Production and control costs Ex-post analysis compares the costs of protection over the last five years to estimated benefits (avoided costs). Avoided costs are derived in two ways: i) by multiplying the value of host plant production by probability of tospovirus presence; and ii) calculated as 1% of the yield, multiplied by probability of tospovirus spread. Control costs (assumed similar to control and inspection costs under the protected zone) added to crop losses.	No sensitivity analysis, apart from the two different approaches (ex-post vs. ex-ante) and two treatments within each approach.	Ex-post BCR 2.1:1 to 2.4:1. Ex-ante BCR 4:1 to 37:1. Recommends maintaining protected zone. Economics simple: e.g. two spread scenarios produce the same cost estimate, despite totally different spread profiles.
Colorado potato beetle in England - pest of e.g. potatoes, tomatoes and eggplant - Mumford et al. 2000	1. Continue protected zone 2. Abandon protected zone - 30 years time horizon - discount rate 6%	Control costs Inspection and control measures in adaptation and government expenditure in prevention. Crop losses are not included. Costs of protected zone are assumed constant.	No sensitivity analysis of any kind is undertaken.	BCR 7.5:1. Recommends maintaining current exclusion policy. Ignores climatic change, development of pesticide resistance, crop losses, costs of environmental contamination and research. Impacts on organic production, gardeners and trade and distribution of costs and benefits are discussed qualitatively.

Table 6. Cost-benefit analyses conducted on invasive agricultural species.
NPV denotes net present value, BCR denotes benefit-cost ratio.

The main point here is to present existing studies that are in principle similar to the current study and discuss economic issues related to policy alternatives that are similar to the policy alternatives analysed in this study. The policy setting in two of these studies (Colorado potato beetle and tomato spotted wilt tospovirus) is exactly the same as in the present study, whereas in the other studies the analogy of pre-emptive versus reactive control is similar, although the exact policy environment and the institutions involved may be slightly different.

The studies are reviewed bearing in mind the basic steps of cost-benefit analysis: i) specify the set of alternative projects; ii) decide whose benefits and costs count (standing); iii) catalogue the impacts and select measurement indicators (units); iv) predict the impacts quantitatively over the life of the project or policy; v) monetise all impacts; vi) discount benefits and costs to obtain present values; vii) compute the net present value (NPV) of each alternative; viii) perform sensitivity analysis; and ix) make a recommendation based on the NPV and sensitivity analysis (Boardman et al. 2001).

<u>Specify the set of alternative projects</u>: In many of the above cases, it is the current policy of pre-emptive control (including eradication) that is assessed against the alternative of allowing the species to invade the country. There are hence usually only two (mutually exclusive) policy alternatives. The benefits of the current policy can primarily be considered in terms of costs avoided. The study on the screwworm fly is a notable exception, as it considers a wide range of alternative protection strategies.

<u>Decide whose benefits and costs count</u>: Whose costs and benefits are included in the study is generally poorly indicated, and it is not in any of the above cases done explicitly. Of course, when one reads the studies thoroughly it is possible to find out which parties are included. However, for instance the role of taxpayers and consumers is often poorly presented. Furthermore, the gainers and losers are often not identified separately. Instead, only the aggregate costs and benefits are reported, without an indication as to how those costs and benefits are distributed in the society.

<u>Catalogue the impacts and select measurement indicators</u>: It is not always straightforward to see which costs are included in the analyses. This is primarily due to the studies not having a formal structure presented in analytical terms. On the other hand the analytical papers often are not or cannot be applied to real-life cases. Hence, in our opinion, a neat combination of analytical and empirical assessment is required, resulting in applicable analytics or formalised empirics, depending on one's point of view. As discussed in Section 3.1, impacts of IAS can be roughly divided into i) control costs; ii) production losses; iii) secondary market effects; and iv) health, environmental and cultural effects. It is often the first and second categories that are included in cost-benefit analyses. The simple reason for this is that they are the ones easiest to monetise and hence analyse quantitatively.

<u>Predict the impacts quantitatively over the life of the project or policy</u>: Prediction of impacts involves estimation of uncertain future events. These can be simulated, giving the variable values a mean and a distribution and checking what happens. They may also be estimated using best-guess estimates by experts. The above studies primarily seem to use educated guesses for different values, some relying on literature, some on pre-existing models and some on expert opinions. Uncertainty can be included in the analysis at this stage to some extent, by assigning different probabilities to different events.

<u>Monetise all impacts and compute the net present value</u>: Monetisation of different impacts is usually not too difficult, because the impacts are often already *chosen* such that they are easy to monetise. This is in general the case with the studies above, although in the cases of the leafy spurge and the melon thrips certain secondary impacts are included. The inclusion of export losses in the assessment of the melon thrips affects the results dramatically, yet such effects are not considered at all in the fairly similar cases of the Colorado potato beetle and the tobacco whitefly. The same applies to assessment of secondary impacts in the case of the leafy spurge. It is thus noteworthy how remarkably the results are affected by inclusion of impacts that are often left unconsidered.

Hence, it is important to try and include as many impacts as possible in the analysis. Instead of ignoring the hard-to-monetise impacts, they should be included as possible impacts and discussed at least qualitatively if monetisation proves too difficult or controversial. Ignoring such costs altogether is seldom good for the reliability of the results retrieved. Additional difficulties include for instance the development of prices in the future, which may be difficult to predict and to take into account. Sometimes also getting the prices right in the first place is difficult if those prices do not exist or if they are distorted. Also future inflation levels may be difficult to predict, especially in developing countries.

In addition to the net present value figures, four of the studies report also benefit-cost ratios for the policy alternatives. We see these ratios as a good way to report the results, due to them being fairly easily computed and additional information being conveyed in them.

Discount benefits and costs to obtain present values: The study on the tobacco whitefly includes a static analysis, in which no discounting is needed. Whether a static analysis is appropriate depends once again on the particular circumstances. In a temporal assessment, discounting is generally warranted. In one study above it is not reported whether discounting is applied and at what rate, and in one study it is certainly not applied. As for which discount rate to use, the issue of value uncertainty arises. Three of the studies apply a rate of 6%, the rate earlier recommended by the British Treasury for public projects, and one applies the rate of 3.5%, the current recommendation.

Perform sensitivity analysis: We are dealing with inherently uncertain matters, yet in many occasions nothing is done to include that uncertainty in the analysis. Even basic sensitivity analysis where the input values are varied by a given percentage in either direction would be a good start, and would give some indication as to how stable the results are. The screwworm fly, the western corn rootworm and to some extent the melon thrips studies are the only ones in which satisfactory sensitivity analysis is carried out. Further, even if we are fairly confident that on average our input variables are reliable, reporting only the expected output values may be dangerous. The notorious example is the building of a bridge such that it can only support the weight of average traffic flow. Consideration of distribution of input and output variables (and especially the extreme values) is important, and should always be reported, even if only briefly in words.

Make a recommendation based on the NPV and sensitivity analysis: Science carries a responsibility. If we are making a study regarding the economic viability of a project or policy, we should give, to the best of our knowledge, a policy recommendation. It can naturally be conditional on for instance probabilities, as in the screwworm fly study. It is not us researchers who make the decision, but it is us who should interpret what our analysis tells us in terms of policy guidance. On the other hand, if no sensitivity analysis of any kind is conducted, the reluctance to make clear policy recommendations is somewhat understandable.

Bearing these points on mind, it is now finally the time to start considering the case presented in this study. The presentation starts by first considering the conceptual framework and the analytical model (Chapter 4) followed by the empirical analysis (Chapter 5).

4. THE ANALYTICAL MODEL

4.1 Model preliminaries

The aim in this study is to construct a theory-based simulation model capable of comparing alternative control strategies ex-ante. The main purpose is to evaluate the viability of two specific policy options when facing uncertainty together with local and global change. The interest is in seeking simple models that first describe production at the farm level with and without the pest. These can then be aggregated over a larger area and different policy options added to the model. The policy options impact differently on production and imply different costs and benefits and different parties (consumers, producers, etc.) to whom the cost and benefits accrue. The model presented is purposefully simple in order to facilitate a straightforward direct application later in the study. Yet, as we shall see, even such simple models can generate fairly robust suggestions regarding the optimal control policy.

The policy response to the invasion is assessed using a basic ex-ante cost-benefit framework. The framework compares the expected costs of pre-emptive control with the expected costs that could ensue if a particular invasive alien species was allowed into the country (reactive control). As discussed earlier, these costs may include some or all of the following: i) control costs; ii) production losses; iii) secondary market effects; and iv) health, environmental and cultural effects. For reasons explained later in detail, we assume in the empirical section explicitly and in this theoretical section implicitly that only costs in the first two categories (control and production costs) take place.

The idea of the model is that an agent harmful to production threatens to invade some proportion of the production area, and affect the society through its impacts on producers and consumers. It can be prevented from establishing or invading by some costly means, but it is also possible to leave its control entirely for decentralised actors. The agent decreases production, but can be controlled by some costly means with a control success of 0-100%. The agent could thus be, for instance, a pest that is controlled with pesticides or a weather phenomenon such as a flood that is controlled with physical structures. The discussion below deals with an agricultural producer, but with appropriate adaptations it could be adapted to for instance silvi-, horti- or aquacultural production.

A pollution model approach by Barrett and Segerson (1997) can be adapted to the case of plant health and invasive pests. Their model is adaptable to the present case when it is supplemented by a production function with an incorporated damage function. Furthermore, as the invasion primarily imposes costs on the society, the model deals with costs and considers possible benefits as negative costs. The model is dynamic regarding the state variables, but the opportunities for decision-making are restricted, i.e. only at the beginning of the analysed period a decision is made as to how to control the invasion. That decision is then maintained. Dynamic impacts are included through pest spread and several climatic and ecological trends, but not through temporal switches in the control strategy.

In other words, our policy problem has a temporal nature as it includes interactions between actions taken today and the impacts of those actions experienced in the future in light of uncertainty. Therefore, the temporality must be taken into account in the modelling exercise. The variables used in such models can be divided as follows (Kann and Weyant 1999):

1. Set of physical state variables (economic and climatic indicators) [P]
2. Set of control variables (describing the policies) [C]
3. Set of information variables (in models that include learning) [I]

In our model the physical [P] characteristics are updated at every period, whereas information [I] and control [C] variables are updated only at a limited number of periods – in our case solely in the first period. Thus our model can be considered to be a kind of Single-Period Decision Analysis model as categorised by Kann and Weyant (1999). In our case, instead of evaluating all (infinite) states of the world, we try to evaluate a large number of states for the two discrete policy alternatives. The reliability of the model is assessed through sensitivity analysis of key variables and their impact on results, sensitivity analysis on which variables affect the outcome most and, finally, a discussion on which inputs we know least of.

We analyse the two alternative policy strategies in their pure forms, and their spatial or temporal combinations are not allowed. The assumptions of the model are as follows[27]: i) reactive control is only damage reducing, not production enhancing; ii) strategies have no external costs or benefits; iii) prevention costs can be fully transferred to consumers; iv) producers are price-taking profit maximisers; v) international price transfers may be imperfect, i.e. prices are allowed to increase due to damages; vi) the demand curve is linear over the price range considered; vii) price changes are fully transferred to consumers; viii) control costs are linear; ix) the society is a risk neutral cost minimiser; and x) the pest is host-specific and causes no external health, cultural, ecological or food safety damage.

The society invests resources in managing IAS. The objective of the society can be, for instance, to i) minimise unconstrained total costs; ii) minimise expenditure subject to a given level of damages; iii) minimise damage subject to available funds; or iv) minimise the difference between periods, i.e. reduce variability (Barrett and Segerson 1997). At this point, we find the first criterion of unconstrained cost minimisation a reasonable one to use, although it is worth pointing out that even this basic framework allows consideration of various objectives.

4.2 Pre-emptive control costs

In the case of pre-emptive control the economic cost consists of the fixed and variable costs of the protection system which aims to prevent the pest from establishing. Protection system may also partially fail, and some pest infestations carry over to the following year. The expected total costs are estimated as follows[28]

$$E(TC_1)=\sum_{t=1}^{T}\frac{C_F+C_{Vt}(A_t,I_t)}{(1+r)^{t-1}} \tag{14}$$

$$A_t=\gamma_t A_{INITt}+\omega_{t-1}w_{t-1}\theta_{t-1}A_{t-1} \tag{15}$$

The expression to the right of the summation sign estimates the discounted annual costs of pre-emptive control. The annual costs are discounted at discount rate r and summed up over the years $t = 1$ to T to estimate the total expected present value costs.

Due to uncertainty regarding the magnitude of the pest invasion and other environmental stochasticity, it is appropriate to talk about expected total costs ($E(TC)$). These consist of the annual fixed costs of pre-emptive control (C_F) and the annual variable costs of pre-emptive control (C_{Vt}). The fixed costs of pre-emptive control are costs that are independent of the invaded area. In other words, whether there is no invasion, a small invasion or a large invasion does not affect the fixed costs in any way. Furthermore, they are assumed constant over time (no t subscript).

The variable costs of pre-emptive control, on the other hand, depend on the eradicated area and the number of inspection visits. Hence C_{Vt} are affected by the area invaded and eradicated (A_t), which is measured by the production hectares invaded, and by the number of inspection visits (I_t) needed for control and surveillance ($\partial C_{Vt}/\partial A_t > 0$, $\partial C_{Vt}/\partial I_t > 0$). Note that we also implicitly assume that the resulting crop losses remain so small that they do not imply price effects.

The area eradicated A_t depends on the probability of the invasion γ_t ($0 \le \gamma_t \le 1$) in any one year multiplied by the invasion magnitude (i.e. the size of the invasion coming from outside the system) in

[27] These assumptions are further discussed in Appendix 3.

[28] On notation: small case t is used to denote that the particular variable can take different values in different points in time. If a variable does not have subscript t, it is assumed constant over time.

the present year (A_{INITt}). It is also possible that the protection system has failed in the previous year, and some proportion of the area invaded in the previous year is still invaded. This is determined by the failure probability of the protection system ω_t ($0 \leq \omega_t \leq 1$), the proportion of the area in which protection failed w_t ($0 \leq w_t \leq 1$) and the winter survival of the beetle population θ_t ($0 \leq \theta_t \leq 1$). Hence the area in which variable costs of protection ensue also depends on the invaded area that is being carried over from the previous year $\omega_{t-1}\, w_{t-1}\, \theta_{t-1}\, A_{t-1}$ due to failure of the protection system.

4.3 Reactive control costs

In the case of reactive control, the model considers changes in producer and consumer surpluses. Producer surplus changes result because of price changes, pest control costs and the value of lost production. Consumer surplus changes are caused by invasion induced increases in product price. The costs are calculated as follows

$$E(TC_2) = \sum_{t=1}^{T} \left(\frac{\Delta PS_t + \Delta CS_t}{(1+r)^{t-1}} \right) \tag{16}$$

The annual change in producer surplus (ΔPS) is evaluated through impacts on the producer objective function, and by considering the ensuing change in aggregate profit as the cost of the policy. The annual change in consumer surplus (ΔCS) is evaluated through price impacts. Before looking at these, it is necessary to consider how the size and spread of the invasion are determined.

Both pre-emptive and reactive control costs depend on the area invaded. However, in reactive control the overall goal of total eradication can no longer be achieved due to public good nature of control, and thus the pest is able to spread within the agricultural network. Two different spread scenarios are analysed, differing on the functional form of spread. In addition, a special case with no winter survival (and hence no spread) is analysed. The scenarios are:

Scenario 1: non-linear spread, restricted by the total production area;
Scenario 2: linear spread, restricted by the total production area;
Special case: no winter survival, restricted by the size of the invasions.

The spread of the pest in Scenario 1 (non-linear spread) is based on a typical biological growth function. The population size at time $t+1$ (N_{t+1}) depends on the population size at time t (N_t), the reproductive rate of the species (R) and the carrying capacity of the system (K) (Begon et al. 1996b):

$$N_{t+1} = \frac{RN_t}{\left(1 + \frac{(R-1)N_t}{K}\right)} \tag{17}$$

In the simulation the area invaded A_t (measured in hectares) is used as an approximation of the population size N_t. Hence in the analysis it is the area invaded, not the pest population, which grows. In addition to spread of the existing population, new random invasions are allowed just like in the case of pre-emptive control. The difference equation for the development of the invaded area in Scenario 1 is as follows (in spread expressions 18 and 19, superscript 1 and 2 denote the corresponding scenario).

$$A_t^1 = \gamma_t s_{INITt} A_{INITt} \left(1 - \frac{A_{t-1}^1 \theta_{t-1}}{A_{TOT}}\right) + \frac{A_{t-1}^1 s_{t-1} \theta_{t-1}}{\left(1 + \frac{(s_{t-1}-1) A_{t-1}^1 \theta_{t-1}}{A_{TOT}}\right)} \tag{18}$$

As in the case of pre-emptive control, the area invaded A_t^1 depends on the probability of the invasion γ_t ($0 \leq \gamma_t \leq 1$) multiplied by the invasion magnitude in the present year (A_{INITt}). However, in addition there is an initial year spread multiplier s_{INITt} which accounts for the fact that in the case of reactive control the pest spreads already in the first year, due to imperfect control measures. In the case of pre-emptive control this first year spread is not taken into account, as it is assumed that the coordinated and timely control measures can curb any spread. Hence, the area invaded in the initial invasion year is always somewhat larger under reactive control than under pre-emptive control.

The term $\left(1-\frac{A_{t-1}^1\theta_{t-1}}{A_{TOT}}\right)$ accounts for the fact that if the existing invaded area is already large and close to the total available production area (A_{TOT}), it is less likely that any new invasions would add to the invaded area. Hence the size of the invasion is weighted by the proportion of available unaffected production area.

The last term in the equation represents expression (17) when adapted to the current situation. It is the new area that becomes invaded due to the spread of the existing population. The spread multiplier s_t ($s_t \geq 1$) is the equivalent of the reproductive rate R in expression (17). The size of the current population (N_t in expression 17) is represented by the total area invaded A_t multiplied by the level of winter survival θ_t which together represent the area that is capable of beginning to increase. The spread is limited by the total available production area (A_{TOT}) which is the equivalent of the carrying capacity K in expression (17). The spread is also limited by the fact that only a given proportion of the population (θ_t) survives the winter and is able to spread. Figure 12 below illustrates spread in Scenario 1 with a spread multiplier of 1.8 and different levels of winter survival (with θ_t = 0.2, 0.4, 0.6, 0.8, 1.0), assuming an invasion of 400 hectares every three years.

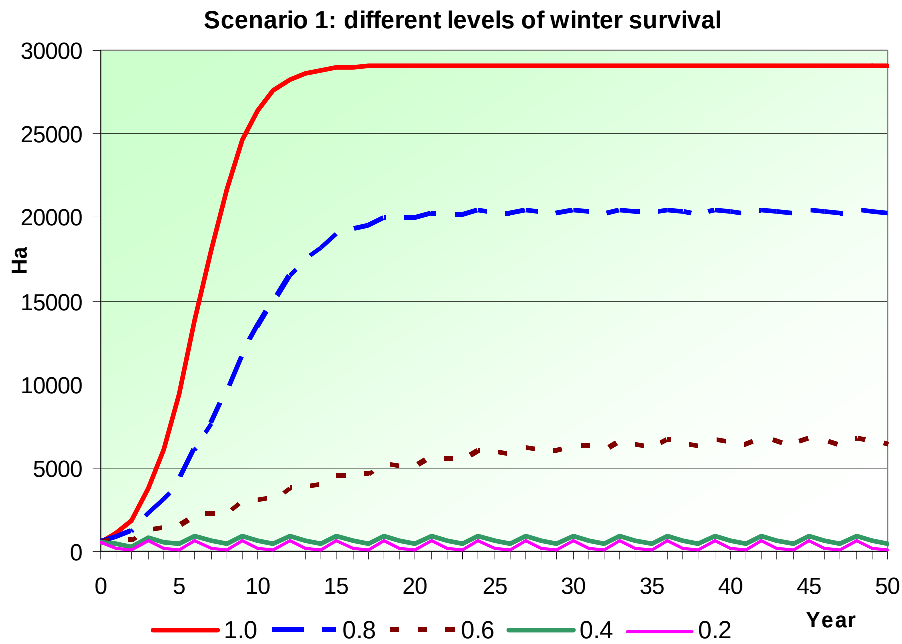

Figure 12. Spread in Scenario 1 with different levels of winter survival.

Scenario 2 is based on linear spread, with a given area added to the existing invaded area each year (for some justification for this form of spread, see Hastings 1996). The difference equation for the development of the infected area in Scenario 2 is as follows.

$$A_t^2 = \gamma_t s_{INITt} A_{INITt}\left(1-\frac{A_{t-1}^2\theta_{t-1}}{A_{TOT}}\right) + \left(A_{t-1}^2 + a_{t-1}\right)\theta_{t-1} \quad (19)$$

s.t. $A_t^2 \leq A_{TOT}$

and if $A_{t-1}^2 = 0$ then $a_{t-1} = 0$

The first term is similar to the first term in the case of Scenario 1, but the second term now comprises of linear spread, measured in hectares. Hence the additional area is simply the invaded area in the previous year plus the area of linear spread a_t, both multiplied by the rate of winter survival. Finally, the whole expression is subject to the invaded area not becoming larger than the total production area. This condition was not required in Scenario 1, because the specification of the spread function (18) already acts as a maximum area constraint. In addition, if the invaded area in the previous year is zero, then naturally also the magnitude of linear spread will be zero.

The two spread scenarios with the basic starting values used later in the analysis are presented in Figure 13 in a deterministic manner. In the figure it is assumed that there is an invasion only in the first year and that the entire population survives the winter (θ_t = 1.0). The figure is thus only for purposes of illustrating the spread functions.

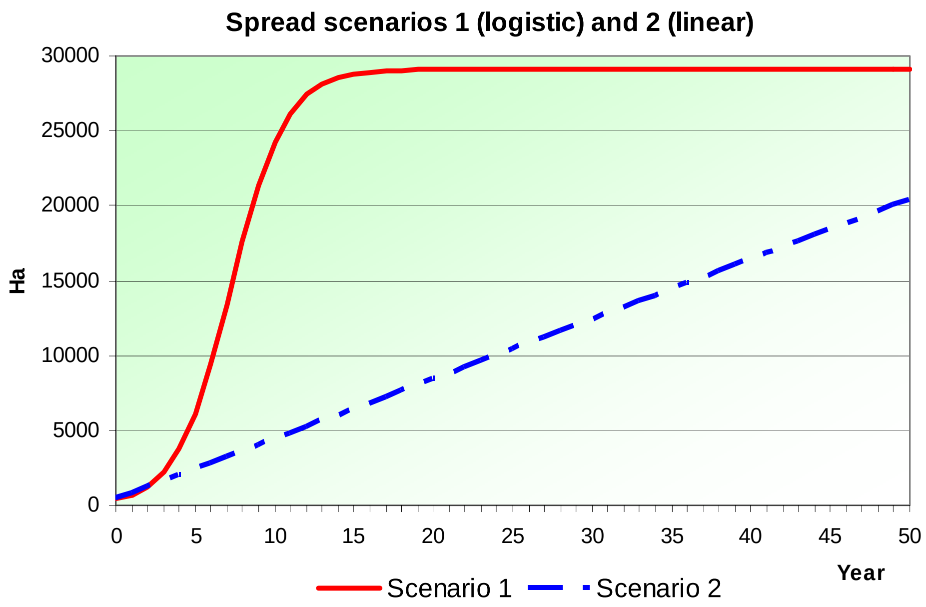

Figure 13. Spread scenarios in reactive control.

Finally, in the special case (*SC*) of no winter survival, the area invaded is

$$A_t^{SC} = \gamma_t s_{INIT\,t} A_{INITt} \tag{20}$$

The expression simply comprises of the first term of expressions (18) and (19), excluding the restraint on the invasion magnitude, which is not needed since there is no winter survival.

Now that the principle of estimating the invasion area is clear, let us consider how the changes in producer and consumer surplus are estimated.

4.3.1 Change in producer surplus

The producer objective function is of the following form (the time subscript *t* has been dropped from this section for clarity, subscript *i* denotes the hectare in question):

$$\max\ \pi_i = p_S q_i - c_i \tag{21}$$

In a standard fashion, the producer aims at maximising profits π_i, which consist of per hectare quantity produced of the agricultural product q_i multiplied by the invasion state dependent per unit producer price p_S. From this the per hectare production costs c_i are subtracted.

The production function incorporates a damage function and is of the following form

$$q_i = q_i(x_i)[1 - D(N_i)] \quad (22)$$

The quantity produced q_i depends on per hectare quantity of non-control inputs x_i (fertilisers, machinery, land). The properties of $q_i(x_i)$ have no practical relevance for the model as long as they remain unaffected by the presence of the pest. This is fairly realistic, so we deal here with an unspecified form $q_i = q_i(x_i)$.

The percentage damage caused by the invasive pest (D, with $0 \leq D \leq 1$) depends on post-control amount of pest individuals present on the i^{th} hectare (N_i). The properties of $D(N_i)$ are assumed to be $\partial D / \partial N_i > 0$ and $\partial^2 D / \partial N_i^2 = 0$. The shape of the damage function naturally depends on the pest dynamics and the interaction between the pest and the produced plant species. Yet, it is not unreasonable to assume that the larger the pest population, the larger the damage done. However, the sign of the second derivative is not quite so clear. Here we assume that the damage done is proportional to the number of pest individuals, i.e. that the damage increases at a constant rate. In the empirical section this is further simplified to a single (stochastic) number indicating the damage caused.

The damage done can be limited by controlling the number of pest individuals. The number of post-control individuals N_i depends on the number of pest individuals invading the i^{th} hectare (N_{0i}) and on the number of pest individuals eradicated by the producer φ_i. N_{0i} depends on exogenous factors such as temperature, proximity of permanent populations and so forth, but also on various farm attributes, including location, farm size, neighbouring areas, etc. However, the producer has basically no short term influence over them. The number of post-control individuals is thus determined by

$$N_i = N_{0i} - \varphi_i \quad (23)$$

The number of pest individuals removed by the producer follows

$$\varphi_i = \eta z_i \quad (24)$$

The number of pest individuals removed φ_i is the product of a parameter measuring the effectiveness of reactive control inputs (η) and the per hectare quantity of reactive control inputs such as pesticides (z_i). The amount of control applied is a producer decision variable. The decision in practice is affected by the cost of control, its effectiveness and on the pre-control number of pest individuals in the production area.

As for the cost side, the private cost function consists of the quantity of non-control inputs (x_i) multiplied by their unit price (p_x) plus the quantity of control inputs (z_i) multiplied by their unit price (p_z). Note that any production subsidies are ignored.

$$c_i = p_x x_i + p_z z_i \quad (25)$$

Thus far the producer objective function has only been subjected to one possible policy – that of reactive control. Let us now supplement the producer objective function by the other available policy, i.e. investment by the society on pre-emptive control.[29] The aim of the protection system is to reduce the number of pest individuals present in the region – in the successful case all the way down to zero.

[29] Remember that in the empirical analysis we assume that these two policies cannot be taking place at the same time. Hence, the implications discussed in the text related to this issue remain an analytical point of interest.

Thus N_{0i} is dependent on the level of protection as measured by aggregate funds invested in it C (with $C = C_F + C_V$):

$$N_{0i} = N_{0i}(C) \tag{26}$$

Compiling all the above information into a single expression, the producer objective is to

$$\max_{x_i, z_i} \pi_i = p_S q_i(x_i)[1 - D(N_i)] - (p_x x_i + p_z z_i) \tag{27}$$
$$\text{s.t. } N_i = N_{0i}(C) - \eta z_i$$

Let us now take a closer look at the properties of this producer objective function. In what follows profit maximisation takes place in the usual fashion, by differentiating the objective function with respect to the control variables (x_i, z_i) and equating the derivatives to zero for the maximum. Thus for the control variables the optimality requires:

$$p_S \frac{\partial q_i}{\partial x_i}[1 - D(\cdot)] = p_x \tag{28}$$

and

$$p_S q_i \frac{\partial D}{\partial N_i} \eta = p_z \tag{29}$$

In expression (28) the left-hand side (LHS) represents the marginal benefits of applying one more unit of input x, i.e. the marginal value product of input x. It includes two components. The first is the potential marginal benefit received by the producer if there are no pests present [$D(\cdot) = 0$]. The second component is the reduction in the potential marginal benefit due to presence of the pest.

Consider that $D(\cdot) = 0$. In this case the second term $[1 - D(\cdot)]$ becomes equal to one and the condition is the standard economic criterion. If $0 < D(\cdot) \leq 1$, the marginal value of the pest damage is subtracted from the potential marginal benefits. This is because of our earlier assumption that the damage done is proportional to the yield per hectare. Now, if the quantity of input x is increased, it is expected that the quantity produced per hectare (q) also increases, but as this also increases the amount of damage, the marginal damage has to be subtracted. The right-hand side (RHS) represents the marginal costs. The term p_x follows from the unit price which in a competitive market is equal to the unit price of one more unit of the input.

In expression (29), the RHS again represents the marginal cost of control, which in a competitive market for control measures is equal to the unit price of the control method. The LHS is the marginal benefit of reactive control. It is equal to the value of the additional quantity produced because of decreased damage. As before, $p_S q_i$ determines the potential value of the quantity that would be produced in absence of the pest, and $\partial D / \partial N_i$ measures the change in damage percentage induced by a one unit change in pest numbers N_i. This is multiplied by η, a measure of how many units of N_i are removed per unit of z_i. Combining these gives the marginal benefit of control in terms of reduced damage.

For the maximum profit the derivatives of both x_i and z_i are equated to zero and thus to each other, which after some rearranging yields:

$$p_S \left(\frac{\partial q_i}{\partial x_i}[1 - D(\cdot)] - q_i \eta \frac{\partial D}{\partial N_i} \right) = p_x - p_z \tag{30}$$

It is now easy to see the economic profit maximisation condition: the value of marginal product of *x* less the value of marginal product of *z* equals the marginal cost of *x* less the marginal cost of *z*. Alternatively,

$$p_S\left(\frac{\partial q_i}{\partial x_i}[1-D(\cdot)]-q_i\eta\frac{\partial D}{\partial N_i}\right)-(p_x-p_z)=0 \tag{31}$$

which is the basic profit maximisation condition. Now, consider an indirect profit function $\pi^*=\pi^*(x^*,z^*)$ where the control variables are set at their optimal levels x^* and z^* as discussed above. The impact of a change in the initial invasion magnitude N_{0i} (i.e. the impact of the invasion) on producer's maximum profits can now be seen:

$$\frac{\partial \pi_i^*}{\partial N_{0i}}=-p_S q_i\frac{\partial D}{\partial N_i} \tag{32}$$

The expression measures the marginal value of damages caused by an increase in N_{0i} (the term $\partial N_i / \partial N_{0i}$ is equal to unity and is not shown). Expression (32) is unambiguously negative, implying that so is the impact of the pest on the producer's profits. However, this conclusion holds only for as long as the producer price is assumed to remain constant.

The price of the agricultural product can be thought to be dependent on the aggregate damage done by the pest and the aggregate amount of additional inputs required. In other words, the invasion reduces supply and thereby increases the prices in two ways: directly by causing damage to the production process and indirectly by increasing the production costs. In the model these effects are approximated by N_{0i}. Thus, in the objective function, let $p_S = p_S(N_{0i})$. Then the impact of N_{0i} on producer's profits is:

$$\frac{\partial \pi_i^*}{\partial N_{0i}}=q_i\left\{\frac{\partial p_S}{\partial N_{0i}}(1-D(\cdot))-p_S\frac{\partial D}{\partial N_i}\right\} \tag{33}$$

The difference between expressions (32) and (33) is thus solely the term $q_i(\partial p_S / \partial N_{0i})$ $[1-D(\cdot)]$. The sign of this term depends on whether the price increases or decreases. As it is reasonable to assume that the price does not decrease, it can be concluded that the sign of the term is positive. The impact of the invasion on producer profits now includes a positive term (the price increase) and the negative term discussed earlier. Hence the overall impact of the invasion depends on the relative magnitudes of the damage done by the pest and costs of its control, compared to the increased income due to the price change.

As a point of curiosity, the impact of protection on producer profits can now also be seen when we let $p_S=p_S(N_{0i}(C))$. Expression (34) indicates the impact of costs of protection *C*.

$$\frac{\partial \pi_i^*}{\partial C}=q_i\frac{\partial p_S}{\partial N_{0i}}\frac{\partial N_{0i}}{\partial C}(1-D(\cdot))-p_S(\cdot)q_i\frac{\partial D}{\partial N_i}\frac{\partial N_{0i}}{\partial C} \tag{34}$$

The first term in the expression is negative: it denotes the fact that increased protection (*C*) by the society reduces pest induced price increases, and hence lessens potential increases in producer profits. The second term (which is subtracted from the first) is also negative: it denotes the positive impact of protection on producers through reduced damages. Hence the aggregate impact of protection on producers is unambiguous, as there is a theoretical possibility that increasing N_{0i} could raise prices and hence revenue by more than what the associated crop losses are, making producers better off. As social intervention reduces N_{0i}, the outcome is not clear.

Having discussed the properties of the producer objective function, let us return to the expected change in producer surplus. The annual impact of an invasion can now be estimated as the difference between aggregate producer profits in the case when no production hectares are invaded Π_t^{NOINV} and aggregate producer profits when an area A_t of production hectares are invaded Π_t^{INV}. Reintroducing the time subscript, we get an expression for estimating the annual change in producer surplus.

$$\Delta PS_t = \Pi_t^{NOINV} - \Pi_t^{INV} \tag{35}$$

$$\Delta PS_t = \sum_{i=1}^{A_{TOT}} \left[p_B q_{it}(x_{it}) - p_x x_{it} \right] - \sum_{i=1}^{A_{TOT}-A_t} \left[p_t q_{it}(x_{it}) - p_x x_{it} \right] - \sum_{i=A_{TOT}-A_t}^{A_{TOT}} \left[p_t q_{it}(x_{it})(1-D_{it}) - \left(p_x x_{it} + p_z z_{it} \right) \right] \tag{36}$$

Π_t^{NOINV} is derived from expression (27) when the pest is not present (N_i and z_i are equal to zero). This yields the first term in (36). Π_t^{INV} is derived from expression (27) when the pest is present in some areas (N_i and z_i are greater than zero). This comprises of two terms. The first one is the aggregate profit in areas where the pest is not present, but which nonetheless receives the elevated price (middle term in 36). The second term is the aggregate profit in the areas in which the pest is present, and which suffers the damages and increased production costs, but also receives the elevated price (last term in expression 36). These together give the annual change in aggregate producer surplus.

4.3.2 Change in consumer surplus

Having analysed producer behaviour and the impact of policies on producers, let us turn to the other component in reactive control cost: the expected change in consumer surplus. Since we assume constant returns to scale, the produced quantity is $q_t A_{TOT}$. Hence the annual change in consumer surplus (ΔCS_t) is estimated by:

$$\Delta CS_t = \Delta p_t q_t \left[\left(A_{TOT} - D_t A_t \right) + \left(\frac{D_t A_t}{2} \right) \right] \tag{37}$$

The term Δp_t in the expression refers to the change in price of the agricultural product triggered by the invasion. The expression is illustrated in Figure 14.

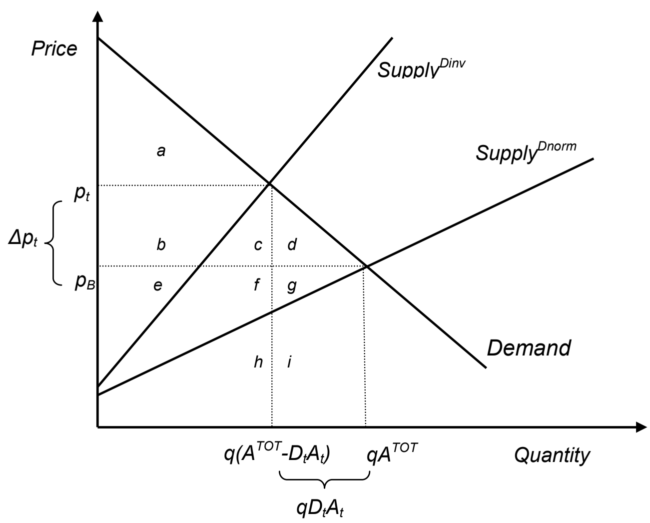

Figure 14. Elastic demand and elastic supply with and without the pest invasion.

The dometic supply (demand) curve depicts the quantity supplied (demanded) at each price level of the agricultural product. Invasion induces a leftward shift in the supply curve: at each price level less is supplied as production costs have increased and crop damages have occurred. As a result consumer surplus is reduced from area $a + b + c + d$ to just a. Supply change thus results in the consumers losing $b + c + d$ in consumer surplus. Expression (37) corresponds to this area in Figure 14, indicating also that we assume the demand curve to be linear over the (relatively small) price range considered. This is not too restrictive an assumption for as long as the price changes and changes in supply are not very big. Note also that we assume that there are no exports or imports.[30]

The price change used in expression (37) and illustrated in Figure 14 can be calculated by

$$\Delta p_t = -p_B \varepsilon D_t \frac{A_t}{A_{TOT}} \tag{38}$$

We assume that there is an historical base price p_B, which is subsequently modified by the magnitude of the invasion A_t / A_{TOT} and the damages incurred D_t, which together measure by how much supply is reduced in percentage terms. This measure is then multiplied by the yield effect on price ε, which determines by how much the price changes given a change in aggregate supply.

4.3.3 Aggregate reactive control costs and policy choice criteria

We have now looked at the impact of the invasion (a biological phenomenon) and society's actions (a policy phenomenon) on individual producers and consumers. It is time to consider the aggregate impact and policy choice. The importance of aggregation was discussed in Section 3.1.5. It is now evident that the model presented here is easy to aggregate to a social level and hence can be directly used in empirical policy analysis. When we add the annual change in producer surplus (expression 36) to the annual change in consumer surplus (expression 37) and sum the impacts over T years, we get an expression for estimating the aggregate reactive control costs.

$$E(TC_2) = \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum_{i=1}^{A_{TOT}} \left[p_B q_{it}(x_{it}) - p_x x_{it} \right] - \sum_{i=1}^{A_{TOT}-A_t} \left[p_t q_{it}(x_{it}) - p_x x_{it} \right] - \\ \sum_{i=A_{TOT}-A_t}^{A_{TOT}} \left[p_t q_{it}(x_{it})(1-D_{it}) - \left(p_x x_{it} + p_z z_{it} \right) \right] + \Delta p_t q_t \left[\left(A_{TOT} - D_t A_t \right) + \left(\frac{D_t A_t}{2} \right) \right] \end{array} \right\} (1+r)^{-(t-1)} \tag{39}$$

This is a more detailed version of expression (16) and will be applied in empirical analysis in Chapter 5. We have now built up functions for estimating the costs of both policy alternatives (expressions 14 and 39).

Adopting the objective of unconstrained cost minimisation, the problem of the risk neutral and welfare maximising society is to choose $\min\{E(TC_1), E(TC_2)\}$, in other words $\min\{(14),(39)\}$. However, having chosen this objective, it is good to bear in mind that this is an analysis of a single invasive species only. The fact that one of the policies is optimal in this analysis in no way implies that limited government budget is worth spending on this particular species and not some other species. With this caveat in mind, it is time to move on to the empirical analysis.

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[30] It might be worthwhile including some modification factor to account for exports and imports, since in the latter stages of reactive control when the pest has spread to most of the country, these impacts may be significant. The modification could be a simple restriction determining that price is not allowed to increase above some predetermined level. Issues related to international trade were discussed earlier briefly in Section 3.1.3.

5. THE EMPIRICAL ANALYSIS

We have now discussed the physical and economic impacts of IAS and the institutional setting in which they are considered. We also reviewed economic models that discuss the issue from either standard agricultural or from the invasive alien species point of view, and presented an analytical model to study the policy problem. It is now time to undertake an empirical analysis of the policies discussed. The case study deals with the Colorado potato beetle and potato production in Finland.

We will first discuss the costs that are included in the analysis and give a qualitative discussion of impacts that are excluded from the analysis. We also present the cost structure of the analysis. We will then present the data available, including the trends and the stochastic variables used in the analysis. Then, the basic analysis is undertaken. First, to validate the model the results of an ex-post analysis over the period 1998−2004 are discussed. Second, the results of an ex-ante analysis over the period of 50 years are presented. These basic results are followed by a sensitivity analysis and an analysis of to whom the policy costs accrue intertemporally and intratemporally. Before proceeding, let us for clarity define what is meant when the words policy, scenario and trend are used in the analysis.

DEFINITION 8 – POLICY STRATEGY, SCENARIO AND TREND	
Policy strategy	Refers to the policy that the decision maker chooses, in this study this means either pre-emptive control (protected zone) or reactive control (no protected zone).
Scenario	Refers to pest spread in the case of reactive control. In this study there are two scenarios: logistic spread scenario (Scenario 1) and linear spread scenario (Scenario 2).
Trend	Refers to change in external conditions. In this study there are three linear trends (local change, regional change and pest characteristics change). Trends are studied at three different levels: off, slow and rapid.

5.1 Policy costs

An invasion by the CPB would have impacts on various parties in Finland. Those affected include producers, manufacturers, exporters, importers, consumers and taxpayers. Producers and manufacturers (industry) are affected by increasing production costs, reduced yields and possible price changes. Exporters and importers are affected by the domestically produced potato price and quantity changes, legislative restrictions on imports and exports and changes in reputation status of the country that may affect exports. For instance, should Finland lose its protected zone, potato could no longer be exported to other protected zones. Importers on the other hand could start importing potato from anywhere if the protected zone was renounced.[31] Finally, consumers are affected by the potato price and quantity changes and taxpayers by the burden of having to pay for the actions undertaken by the society to deal with the pest. Hence several groups are affected regardless of whichever policy is eventually chosen.

The economic implications materialise through changes in consumer and producer surplus. In the empirical part we ignore imports and exports and furthermore deal only with 'producers' and 'consumers' of potato. Potato is such a basic good that taxpayers and consumers can for all practical purposes be equated. Finally, it is good to note, as has already been mentioned before, that it is possible to design various types of transfer mechanisms to make sure that the right agents (however that is defined) pay for the costs. Hence, the discussion on affected parties and to whom the costs accrue is conditional on what type of costs we choose each group to face.

Costs caused by IAS were earlier divided into four categories. Let us now present the costs that the CPB could cause in Finland according to this categorisation, as well as to explain why the impacts in certain categories are left out of the analysis. The costs that are included in the analysis are discussed here only briefly, since they are extensively discussed in the data section.

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[31] Naturally any restrictions applying to other pests or diseases would still remain in force and restrict imports.

Control costs

Control costs are included in the analysis. In both policy options, control costs are encountered. The effectiveness and cost of control differ in the two policies. In the case of the protected zone, the society can co-ordinate control and aim at eradication of the pest. It can also manage the development of pesticide resistance to some extent through co-ordination. In the case of reactive control, individual producers undertake control to the extent determined by their private objective functions. In the empirical case this is reduced to a single figure for simplicity.

Production costs

Production costs in the case of potato are included in the analysis. The beetle targets primarily potato in Finland and potato is also produced almost throughout the country. Theoretically also tomato production could be threatened. Tomato is produced on about 120 hectares in Finland, with the annual production being around 36 million kilograms. The mean price in 2004 was 1.16 euro per kilogram. The value of the tomato crop is thus about 42 million euro annually (Niemi and Ahlstedt 2005).

Tomato production takes place primarily in Ostrobothnia and Närpiö, and to some extent in the south-western parts of the country. These are not the areas that would initially be at risk from the CPB invasion. Further, Finnish tomato is produced in glasshouses, and thus the beetle would have some difficulty in finding the tomato plants. However, if a large part of the country was invaded by the CPB, it might be possible that also tomato crop would be at risk. Despite this possibility, possible tomato production losses are not included in the analysis.

Secondary market effects

Certain domestic market effects are included in the analysis. The Finnish potato markets are not fully integrated to the European markets in that changes in domestic supply do impact on the price the consumers pay. Hence an invasion that reduces domestic supply and increases domestic production costs may have also consumer effects.

International market effects on the other hand are not included in the quantitative analysis, but are qualitatively discussed here in order to have a complete assessment of possible impacts. Finland as a member of the European Union is committed to unrestricted trade within the union, as well as to any regulations set out in the various agreements enforced by the World Trade Organization. However, the fairly distant and isolated location of Finland combined with a small population size makes it only a marginal trader in many commodities. The value of food imports to Finland in 2004 was 2.3 billion euro, which is about 11% of the estimated money flow in the food sector (Niemi and Ahlstedt 2005). Part of the imported commodities consists of those primary products that cannot be produced in Finland or that are produced in insufficient quantities, but some proportion is also being imported due to the increased integration of the European markets. Food exports from Finland on the other hands had a value of 910 million euro in 2004, of which exports to Russia accounted for about 20% (Niemi and Ahlstedt 2005).

As for potato, the quantity and value of exports from and imports to Finland in the period 1995−2003 are shown in Figure 15.[32] Figure 16 (after FAOSTAT) plots the annual Finnish domestic potato production and imports as a percentage of quantity produced. It is fairly evident, by comparing the data in Figure 15 to domestic production quantities in Figure 16, that international trade in potato is a fairly small business in Finland.

[32] The data are from FAOSTAT. The original data on the value of trade (in dollars) were converted to euros using average annual exchange rates, which were calculated from monthly rates provided by the PACIFIC Exchange Rate Service (http://pacific.commerce.ubc.ca/xr/).

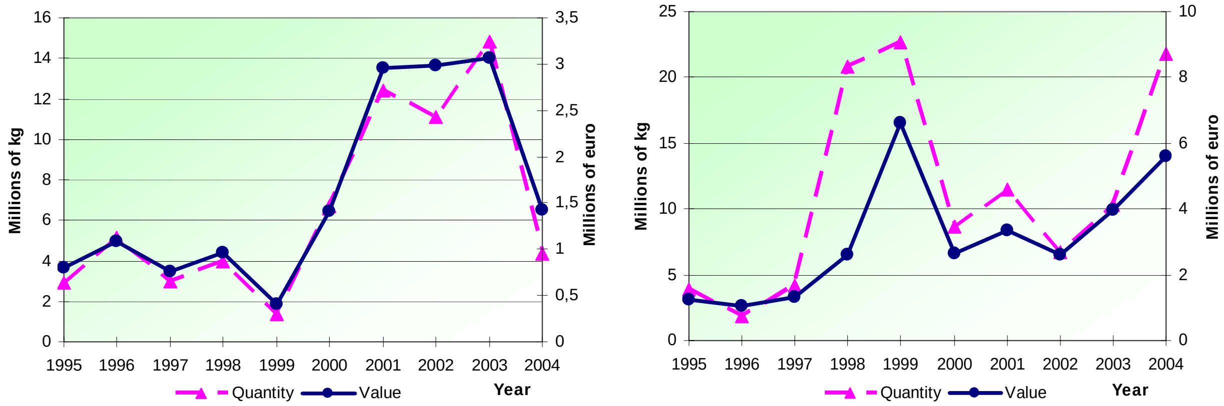

Figure 15. Quantity and value of Finnish potato exports (left) and imports (right) in 1995–2003.

Exports in 2003 were worth about three million euro. There was an increase in exports from the level of 1995–1999 to a new level in 2001–2003 and a subsequent drop back in 2004. It is worth noting that the exports are still only a fraction of domestic production in terms of both quantity and value.

On average, imports of potato are greater than exports, but imports are still fairly insignificant when compared to domestic production. They have not exceeded 4% of domestic production in any year in the period 1995–2003. However, there is some inter-annual fluctuation in imported quantities and bad domestic yields seem to be to some extent substituted by imports. For instance the poor yield in 1998 is clearly visible in the import graph. It seems to have caused about five-fold increase in imported quantity from 1997 to 1999. This quantity remains high also in the year following the bad yield, which is a trend that can be seen also when a longer time-series is analysed. This is natural as consumption of this year's crop will take place both this year and the next.

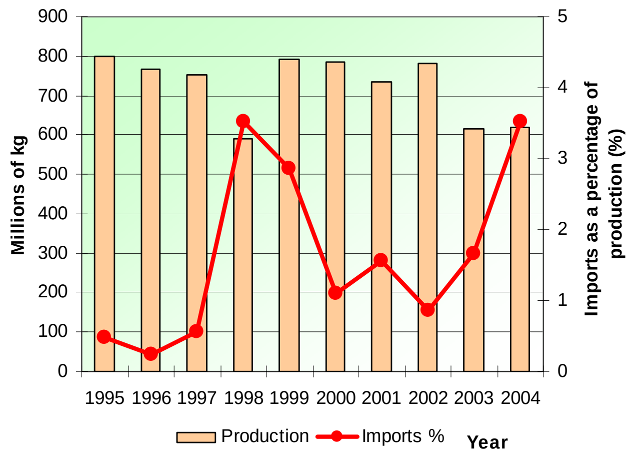

Figure 16. Production of potato in Finland and imports as a percentage of production in 1995–2003.

Looking at the issue from a producer organisation point of view, one could argue that imports are such a small share of consumed potato in Finland that there is no point in risking the domestic production by not regulating international trade with respect to plant pests. In other words, since imports always pose a risk of exotic pest invasions, there is little point to take that risk since the potential benefits would not be substantial: imports are so low that consumer prices would be little affected.

Furthermore, given the relatively small import quantity, also regulation (e.g. inspections) is much easier to carry out efficiently. Hence the current policy of regulated imports only from pest-free areas seems justified when looked from this perspective. However, causalities are not entirely clear here. The low import quantity may be – at least partially – precisely because of the protection system, which increases the import price of potato, as was discussed earlier.

If the protection system was removed, the import prices might decrease and consumers could substitute imported potato for domestic potato. However, one reason for the low volume of trade is that the transport distances are fairly long, and potato is a relatively cheap good that requires quite a lot of space in transport. Hence the pure distance increases the transport costs such that large-scale trade with Central Europe may become unprofitable.

On the other hand, on basis of the value of Finnish potato trade it can be argued that if the protection system is not profitable in terms of providing least-cost protection against the CPB, there is not much point in maintaining it for purposes of export protection. The extent to which imports could substitute for domestic potato and the effects of the protected zone for potato exports thus determine the trade implications of the current protected zone policy. In our opinion, in this particular case these impacts may play a role, but are unlikely to be substantial. Hence they are at least at this stage excluded from the analysis.

Health, environmental and cultural costs

Health, environmental and cultural costs are excluded from the quantitative analysis. Instead, they are qualitatively discussed here for completeness.

The beetle does not spread any zoonotic diseases, i.e. diseases that can infect humans. Main health impacts are likely to arise from the increased use of chemical control substances in the potato fields invaded by the beetle. If these substances are used in accordance with the existing legal requirements and regulations, there should be no health impacts from this source to the general public. The farmers who do the spraying may suffer from increased health problems if the safety guidelines are not properly followed.

In year 2000, Finns acquired 0.499 μg of chemical control substances per day from vegetables, fruits and cereals (National Food Agency 2001). The intake has been reduced by about 9-30% since 1992. The majority (91%) of residues were from imported foods, while the principal domestic sources were wheat, oat and strawberries. Compared to acceptable daily intake levels (ADI), the intake of individual control substances was at most 1.1% of the ADI value (National Food Agency 2001). It seems that even with increased control substance usage the health impacts are likely to remain minor. In addition, estimating the health impacts of increased insecticide application might prove a daunting task. For these reasons, health impacts are ignored in the quantitative assessment.

As for environmental costs, the CPB occupies a fairly empty niche in the agricultural ecosystem. The fact that it has no natural predators and parasites in Europe (or at least not in Finland), together with its diet that is restricted on Solanacae, imply that there will be no or very little ecosystem effects. The beetle has been suspected to spread some potato diseases, including *Ralstonia solanacearum* and *Clavibacter michiganensis sepedonicus* (EPPO 2005). However, as these also target the potato, there is no reason to consider them as an environmental cost as such.

Hence, as with the health impacts, the main environmental impacts are likely to arise from the increased use of insecticides to control the beetle. Chemical control substance use overall in Finland is one of Europe's lowest, with less than 0.6 kg of active substance used per hectare in 2004 (Niemi and Ahlstedt 2005). This figure is minute when compared to use in many other European countries, for instance in Belgium the figure was 12.5 kg per hectare in 1996 (MAF 2003c). In 2001, the sales of control substances in Finland were 0.44% and the sales of insecticides 0.13% of the EU15 sales (Eurostat). In 2003, altogether 1,680 tonnes of chemical control substances were sold in Finland, of which 58 tonnes were agricultural insecticides (Savela and Hynninen 2004; Eurostat). Hence about 3.4% of the total amount sold were agricultural insecticides.

Between 4% and 30% of control substances are lost through evaporation and leaching (Schepel 1996). In rainy and cold summers it is possible that up to 80% of the amount applied may be lost (SYKE 1998). This is because the cold weather slows down the breakdown of the products, and rain increases the amount of leaching. This effect is somewhat compensated by the fact that in cold and wet conditions the CPB feeding and development rates slow down, and hence smaller amounts of control are needed. Nonetheless, if we apply the figure 4-30% to insecticides sold in year 2003, between 2.3 and 17.3 tonnes of insecticides are currently lost in Finland annually through evaporation and leaching.

These leaching substances eventually end up in lakes and seas affecting the aquatic ecosystems. The effects would be seen in the Baltic Sea, and particularly in the Gulf of Finland. If the CPB spread to the main potato production areas in Ostrobothnia, also the Gulf of Bothnia would be affected. These water bodies are already affected by pesticides and excessive nutrient loads, and recognised as one of the most significant environmental problem facing Finland.

Organisms that have in the past suffered from pesticides include for instance the Baltic herring (*Clupea harengus membras*), grey seal (*Halicoerus grypus*), ringed seal (*Pusa hispida*) and the white-tailed sea eagle (*Haliaeetus albicilla*). However, many of the agricultural pesticides that were involved in endangering them (especially DDT) are nowadays illegal and the situation of the species has been improving (Haahti and Kangas 2003; Verta et al. 2004). Other organisms that potentially suffer from pesticides are bees and other pollinating insects. They do not necessarily die because of pesticides, but the sub-lethal effects can shorten their life-span and cause behavioural changes (Schepel 1996). The impacts can be reduced by applying the control substances in a right manner, for instance at times when they are least likely to affect pollinating insects.

As with health impacts, it is relatively difficult to estimate how much harm the additional amount of insecticides (to control the CPB) may do to the environment. The actual amount of insecticides currently used in Finland is very low, about 0.02 kg of insecticides per hectare when distributed over the entire agricultural area. Specifically in potato production the use of insecticides is currently almost non-existent in Finland. The only insecticide used generally is paraffin oil, which is used in seed potato production in order to prevent certain diseases spread by aphids (Jussi Tuomisto, MTT Economic Research, verbal communication). For comparison, in the US about 3-5 kg of insecticides per hectare have been used to control the CPB (Ferro et al. 1983).

It is thus possible that the current usage of insecticides increases perhaps substantially in the event of a CPB invasion. However, it is difficult to predict how the future application of chemical control substances might change, and even if this was known, it would be difficult to estimate the ensuing environmental impacts and monetary costs of the additional pesticides. For these reasons, this cost category is excluded from the quantitative analysis. However, it is worth bearing in mind that primarily the reactive control strategy (and to a lesser extent pre-emptive control) carries this additional cost which is excluded from the quantitative analysis.

Finally, other types of costs, including cultural impacts, are ignored. Such may occur if a large scale invasion affects for instance habitual production of potato, but any such impacts can be considered to be minor. Thus the impacts included in the quantitative assessment include control and production costs as well as the domestic market effects of those costs.

5.2 Cost structure in simulation

In MATLAB simulation analysis the expressions derived for pre-emptive and reactive control costs in the Chapter 4 are applied. For pre-emptive control, expression (14) takes the following form in the simulation analysis.

$$E(TC_1) = \sum_{t=1}^{T} \left(\frac{F + V_1 I_t + (V_{2t} + V_3) A_t}{(1+r)^{t-1}} \right) \quad (40)$$

In this expression the total costs depend on the fixed costs F as well on three types of variable costs. These are the variable costs per inspection visit V_1, variable costs per eradicated hectare V_2 (control substances) and the variable costs per eradicated hectare V_3 (work and compensation payments).

The difference equation for the development of the total area invaded is

$$A_t = \gamma_t A_{INITt} + \omega_{t-1} w_{t-1} \theta_{t-1} A_{t-1} \tag{41}$$

This is the same as expression (15) in the theoretical analysis. We assume that the area invaded and the area eradicated are identical. This is required by the protected zone legislation, but in principle if the protected zone was given up, a national policy could be built such that the area eradicated is some function of the area invaded. This option is not examined in this study.

The area invaded / eradicated A_t depends on the probability of the invasion γ_t ($0 \leq \gamma_t \leq 1$) in any one year multiplied by the invasion magnitude (i.e. the size of the invasion coming from outside the system) in the present year (A_{INITt}). The area also depends on the invaded area of the protection system that is being carried over from the previous year $\omega_{t-1}\ w_{t-1}\ \theta_{t-1}\ A_{t-1}$ due to failure of the protection system.

The probability of invasion γ_t is modelled in the simulation such that in any given year there either is an invasion or there is not. The probability then affects the *frequency* of invasions. For instance, if the probability is 0.33, there is *on average* an invasion every third year.

Inspection visits are estimated such that they simply depend multiplicatively on the area controlled through the inspection visit multiplier g (with $g \geq 1$). This relationship has been established on empirical grounds. Naturally, there is nothing to stop from treating this as a choice variable.[33]

$$I_t = gA_t \tag{42}$$

Altogether, the cost of pre-emptive control is thus affected by the invasion magnitude, the frequency of invasion years, and the extent of a possible failure in the previous year's protection. The invasion frequency has an impact in two ways: first, by dictating whether there is an invasion or not in a particular year (direct effect), and second, by the fact that there may be remnants of previous invasions still existing in the network (indirect effect). The cost of the protection system thus varies in time depending on how often and to what extent preventative actions are needed.

As for reactive control costs, in MATLAB simulation, expression (36) is approximated by

$$\Delta PS_t = A_{TOT}(p_B q - p_x x) - (A_{TOT} - A_t)(p_t q - p_x x) - A_t\left[p_t q(1-D_t) - (p_x x + p_z z_t)\right] \tag{43}$$

In other words, change in producer surplus is the difference between what the aggregate profit would have been in the absence of the pest and what the aggregate profit is in the presence of it. This can be rearranged and simplified into two effects. The first effect is the damage and additional control costs inflicted on those producers whose farm is invaded.

$$(qp_B D_t + p_z z_t)A_t \tag{44}$$

The second effect is the subsequent price increase enjoyed by all producers in the market, regardless of whether they have been subject to the invasion or not. Note that expression (45) is negative (i.e. it is

[33] Inspection visits as a choice variable would seem to be more truthful than the empirically derived relationship used in this study. However, this would require more data on the relationship of inspection rate and found infestations. For simplicity, it is here this assumed that the rate of inspection is optimal, and as shown in expression (42).

actually a benefit, provided that the price change is positive), because it measures the additional profit due to the increased price.

$$-q\Delta p_t\left[(A_{TOT}-A_t)+A_t(1-D_t)\right] \tag{45}$$

[34]

The change in consumer surplus in the simulation can be found directly by applying expression (37). Hence, the aggregate costs of reactive control (expression 39) in the simulation becomes as follows.

$$E(TC_2)=\sum_{t=1}^{T}\left(q\frac{\left[(p_BD_t+p_zz_t)A_t\right]-\Delta p_t\left[(A_{TOT}-A_t)+A_t(1-D_t)\right]+\Delta p_t\left[(A_{TOT}-D_tA_t)+(D_tA_t/2)\right]}{(1+r)^{t-1}}\right) \tag{46}$$

Producer surplus change consists of damages and control costs incurred (first term in the numerator) and the additional income due to invasion induced price increase (second term). The loss of consumer surplus is due to the price increase (third term). All the costs are discounted at a discount rate *r* and summed over years 1 to *T*. Note that some of the terms in expression (46) actually cancel out. We have maintained the division between consumer and producer effects in the simulation analysis in order to analyse to whom the policy costs accrue.

To summarise, the cost categories included in the quantitative analysis are presented in Table 7.

PROTECTED ZONE (PRE-EMPTIVE CONTROL)		***NO PROTECTED ZONE (REACTIVE CONTROL)***	
Fixed	**Variable**	**Fixed**	**Variable**
Authority's fixed costs - inspection visits to fixed inspection points, postage, telephone, advertising, etc.	*Authority's variable costs:* - costs dependent on inspections - costs dependent on the area controlled and eradicated - compensation payments	*No expenses*	*Changes in producer surplus* - production losses - control costs - invasion induced price changes *Changes in consumer surplus* - invasion induced price changes

Table 7. Costs of pre-emptive and reactive control.

5.3 Model variables and uncertainty

This section goes through the variables used in the analysis and presents the values used. Before going further, it is necessary to note that there exists a large amount of uncertainty around the issue. Existing uncertainty can be categorised into three broad categories according to Heal and Kriström (2002), namely scientific, impact and policy uncertainty. We highlight here the relationship of the CPB case study to uncertainty.

First, we are uncertain of the invasion process and its pre-determinants in the points of origin in Russia. Certain weather patterns, including particular wind corridors, can be related to invasions, but the exact relationships of the various components are unknown. This can be seen as *scientific uncertainty*, which arises when a certain physical relationship is not known (Heal and Kriström 2002).

[34] Expressions (44) and (45) are expressed in these particular forms due to the intuitive interpretation that they provide. They are derived as follows. Starting with expression (43), expanding the function and deleting terms that cancel out gives $A_{TOT}p_Bq-A_{TOT}p_tq+A_tp_tqD_t+A_tp_zz_t$. Expressing ($p_t$ – p_B) in the first term as Δp_t gives $-\Delta p_tqA_{TOT}+A_tp_tqD_t+A_tp_zz_t$. Expressing p_t in the middle term as (p_B + Δp_t) yields $-\Delta p_tqA_{TOT}+A_tp_BqD_t+A_t\Delta p_tqD_t+A_tp_zz_t$. Expressing A_{TOT} in the first term as $(A_{TOT}-A_t)+A_t$ gives $-\Delta p_tq(A_{TOT}-A_t)-\Delta p_tqA_t+A_tp_BqD_t+A_t\Delta p_tqD_t+A_tp_zz_t$. Finally, rearranging and grouping the terms yields $-q\Delta p_t\left[(A_{TOT}-A_t)+A_t(1-D_t)\right]+(qp_BD_t+p_zz_t)A_t$ which is equivalent to expressions (44) and (45).

Secondly, it is unknown how the continued invasions would affect the production patterns in Finland. Production may be regionally rearranged and new more tolerant plant varieties may be introduced. In the shorter term, also the impact of the beetle on potato yield is somewhat uncertain depending for instance on timing of the invasion, weather conditions and producer counter-measures. These can be seen as *impact uncertainty*, where the impacts of natural phenomena on the various components of human societies are uncertain, even if the physical science behind them is known (Heal and Kriström 2002).

Finally, there is a third type of uncertainty, which can be categorised as *policy uncertainty* (Heal and Kriström 2002). It is related to questions such as: What type of policy should we undertake, and what are the conditions that determine the optimal policy? Does the optimal choice change over time and are there irreversibilities involved? In such questions, we may know the physical structure of problems, and how those affect the human societies, but we are still uncertain about the impacts of our own corrective actions. For instance, there is uncertainty related to which policies are needed to address the problems, how those policies impact on the issue in question and what are the costs of undertaking the policy. The simulation analysis attempts to answer some of these questions. However, it is naturally restricted by how we choose to tackle scientific and impact uncertainty.

To account for uncertainty, invasions are modelled as temporally random events and stochasticity in key variables is built into the analysis. In addition, an extensive sensitivity analysis is carried out. Below, as each variable is presented, if the variable is stochastic also a probability density function (PDF) will be provided. For computational reasons the PDFs presented are based on 50,000 iterations, not the full 300,000 that are used in the analysis. Despite this they present the distribution with sufficient accuracy.

The stochastic variables in the analysis are assumed to be independent of each other – there are no interdependencies. This corresponds fairly closely to reality. For instance, invasion pressure (magnitude) is determined mainly by the environmental, climatic and production conditions behind the border, which is independent of for instance the level of crop damage in Finland, because the external conditions are different. Similarly, the level of winter survival depends on winter conditions and only to a minor extent on previous summer's conditions that determine for instance crop damage.

5.3.1 Costs of pre-emptive control

The invasion magnitudes (farms inspected, inspection visits and the number of infestations discovered) as well as the actual costs incurred in maintaining the CPB protected zone in Finland in years 1998−2004 were obtained from KTTK (Plant Production Inspection Centre, the relevant authority) and are reported in Table 8. The star in the table in year 2002 denotes a partial estimate.

Year	1998	1999	2000	2001	2002	2003	2004
Farms inspected	400	140	200	200	800	500	238
Inspection visits	500	270	200	240	1485	773	309
Infestations	149	1	0	2	324	6	29
Total cost (euro)	N/A	78,712	19,005	45,747	576,371*	279,181	29,659
Compensation (cases)	38	11	8	2	85	130	N/A
Compensation (euro)	9,340	3,110	3,100	1,850	25,264	31,090	N/A

Table 8. Beetle observations, inspection visits and costs incurred in the protected zone 1998−2004.

Table 8 thus provides the available dataset for estimating the costs of the protection system. Fixed costs of the protected zone (*F*) used in the assessment are calculated from costs incurred in years 1999 (1 infestation), 2000 (0 infestations) and 2001 (2 infestations). The compensation payments (a variable cost) are subtracted from these costs. The calculation is conducted such that in the weighted average year 2000 with zero infestations is given double the weight of the other two years.

1999: 78,712e - 3,110e = 75,602e	weight 1	
2000: 19,005e - 3,100e = 15,905e	weight 2	→ **mean 37,827e**
2001: 45,747e - 1,850e = 43,897e	weight 1	

There are 60-70 fixed inspection sites (required by the protected zone status) that are visited 1-3 times a year. Hence in the fixed costs we include 200 inspection visits per year as well as other fixed costs (advertising, postage, telephone, etc.).

As for the variable costs of protection (V_1, V_{2t}, V_3), a simple model was built to estimate the inspection cost per visit, control substance cost per hectare and eradication cost (including compensation payment) per hectare. These were empirically derived from the data in Table 8. We do not have direct data on the hectares invaded, since KTTK has not recorded them in any way. Thus an assumption had to be made that an infested plot is the size of one hectare. This assumption is difficult to either support or deny on basis of available data, but discussions with experts confirm that an average potato plot size of one hectare is not an unreasonable assumption. Thus the number of infestations is equated with the number of hectares invaded. The estimated costs are as follows.[35]

Inspection cost	256 euro / visit
Control substance cost	20 euro / hectare infested
Eradication cost (incl. compensation)	610 euro / hectare infested

In addition, we include the possibility that the protection system may fail in any particular year. In this case the beetles survive eradication, and the area they have invaded will be added to the invasion area in the next year. In practice this will be modelled as a product of two variables. The first is the event of protection failure, which is either true or untrue – it either happens or it does not. If it has happened, then it will happen on a given percentage of the area invaded in that year. In the present analysis, the failure probability that we use is 0.30, meaning that every year there is a 30% chance that some beetles will be left unobserved. If there is a failure, then we assume that it will be on 20% of the invaded area. Thus, protection fails annually on average on 6% of the invaded area.

In addition, a trend (discussed in detail in Section 5.4) which will increase both of these parameters over time is included in the analysis. This trend is not a separate trend as such, but is included in all other trends that are analysed. This is because increasing winter survival, increasing invasion magnitude and increasing pesticide resistance (the three trends analysed) all imply that maintaining the protection system will become more difficult, which is then captured in our analysis through increasing failure probability and area.[36]

5.3.2 Costs of reactive control

If the beetle is not eradicated as a part of the protection policy, and the producers have to apply control, there will be reactive control costs. We assume that these consist of the cost of the chemical control substances used and of the cost of applying them. Alternative CPB control strategies (see Section 2.5.1) are not considered in this analysis.

The chemical control substance costs ($p_z z_{it}$) have been estimated to be on average about \$300/ha in Michigan in 1991 (Grafius 1997). However, they varied over the range \$35-\$412/ha, depending on the level of pesticide resistance. On Long Island the costs increased with increasing resistance to about \$300-\$700/ha (Raman and Radcliffe 1992). We are not aware of any cost estimates being readily available for Europe.

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[35] Note that any one of the figures may not be correct as such, but together they produce fairly reliable estimates of the costs incurred in the period 1998-2004.

[36] Increasing winter survival increases the effective failure probability of the protection system, because relatively more of those who survive protection also survive the winter. Increasing invasion magnitude increases the effective failure probability because more beetles invading means that there is an increasing probability that some of them remain undetected. Increasing pesticide resistance increases the effective failure probability because fewer beetles are killed by the pre-emptive control actions.

In this analysis we apply a non-stochastic figure of 100 euro per hectare. The figure is lower than the costs in the US due to, for instance, lower level of pesticide resistance in northern Europe. On the other hand, the figure is higher than the cost of 20 euro per hectare used in estimating the costs of the protection system. This is for two reasons. First, the protection system cost does not include work input (which is included in eradication cost category). Second, the government agency may have better bargaining power than individual private producers in obtaining the control substances.

However, we undertake a sensitivity analysis around this value in order to find out its impact on the results. Further, a trend (discussed in Section 5.4) is built into the cost of chemical control to account for increasing pesticide resistance. To anticipate the results, it seems that the impact of this variable on the aggregate policy choice is minor.

5.3.3 Production losses

Crop damages (D_t) are modelled as a percentage reduction in the yield. This is a simplified yield-loss model, linking the pest individuals to the magnitude of yield loss. With sufficient ecological data it would be possible to incorporate a more complex yield-loss model into the study. Lacking such data, we adopt a simple proportional damage function.

Within the area the beetle is projected to invade, the statistical mean yield is thus reduced by a given percentage. In the literature estimates for the crop damages include the estimate in Michigan, where losses were on average about 12% of the yield, except in badly hit areas where losses of 21% were encountered (Grafius 1997). Europe is lacking the natural enemies of the beetle, and hence the losses in Europe could in principle be higher. On the other hand, beetle feeding is temperature dependent as discussed earlier, and hence this factor in theory reduces the losses in Finland. In badly infested areas of Russia the losses have been reported to be 20-70% of the yield (Parkkonen 2002). In some EPPO countries yield losses of up to 50% have been encountered (EPPO 2005).

The estimate should be based on the damages that incur when we have adapted (in the short term) to the presence of the beetle.[37] In the cost-benefit analysis carried out in England (Mumford et al. 2000) it was assumed that fully controlled the beetle would impose no damages whatsoever, which we do not find likely. We thus use a mean of 10% of the potato crop for damages by the beetle, and allow this to vary stochastically according to the PDF presented in Figure 17. The mean damage is 0.10, the maximum is 0.40 and the minimum is zero. In at least 5% of the iterations the crop damage is zero, and in 5% of the iterations it is greater than 0.22. The distribution is truncated such that values less than zero are assigned the value zero. This results in the hump close to zero value in the PDF.

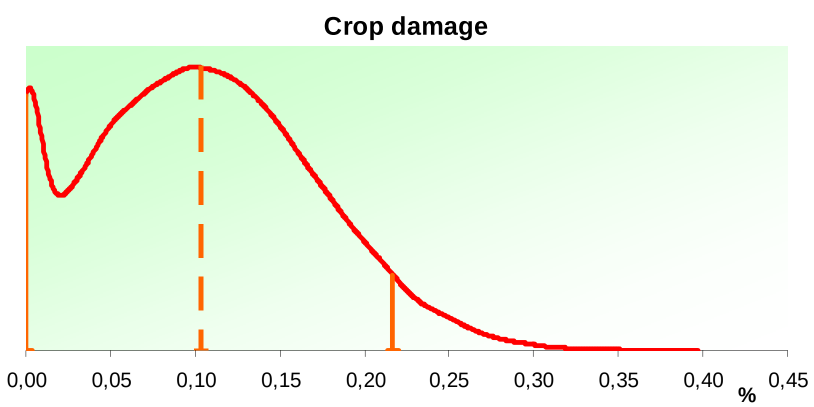

Figure 17. Probability density function of the crop damage.

[37] Note that long-term adaptation, for instance switch to more tolerant potato cultivars and biotechnology, has not been taken into account in the analysis.

5.3.4 Invasion magnitude and probability

Invasions are modelled as a product of two variables. The first is the invasion event, which is either true or untrue – in effect either one or zero. There is a given probability (γ_t) associated with this. We use the figure 0.33, i.e. that there will be an invasion on average once every three years, broadly consistent with the existing invasion data. The variable is simulated such that in any given year a random number y ($0 \leq y \leq 1$) is drawn from a uniform distribution, and if this is smaller than the specified probability, the event is on. This variable is also allowed to increase with a trend, as discussed in Section 5.4.

If the invasion is true, i.e. that it happens, it will be of a given size. The size, or magnitude, of the invasion (A_{INITt}) is a stochastic variable. We use a mean of 400 ha for the variable, which is roughly based on the estimated invasion magnitude in year 2002. This magnitude is important in two respects. First, in calculation of the cost of the protection system, it is the area in which the authorities need to undertake eradication and pay compensation. Second, in calculating the costs of reactive control, it is the area on which the beetle produces crop losses, has to be controlled and begins its spread from. The PDF of the invasion magnitude, which is also allowed to increase with a trend, is presented in Figure 18. The mean is 400 hectares, the maximum is 935 hectares and the minimum is zero. In 5% of the iterations the size is below about 170 hectares and in 5% it is above about 630 hectares.

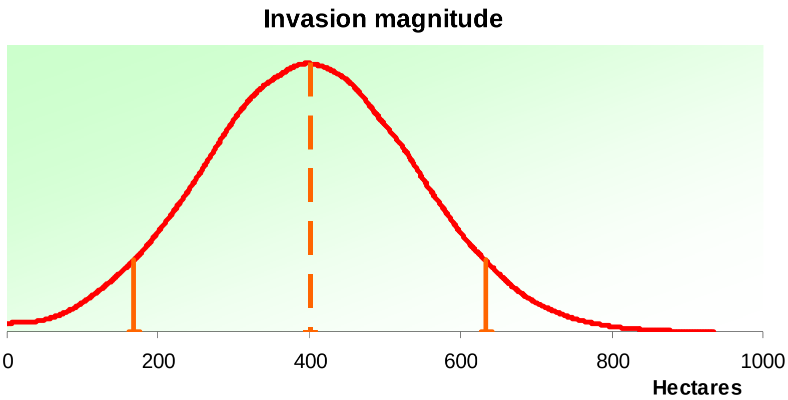

Figure 18. Probability density function of the invasion magnitude.

Additionally, the invasion magnitude determines the number of inspection visits (I_t), as discussed in Section 5.2. Inspection visits are assumed to take place such that their number is g times the invasion magnitude (expression 42). The value of g that we use in the analysis is 4, which is broadly based on the KTTK data (Table 8) on the number of infestations and inspection visits, once the 200 inspection visits considered as a fixed cost element are subtracted. This is simply a functional relationship, which we need in order to estimate the costs, and thus it does not imply causality either way.

5.3.5 Winter survival

Winter survival (θ_t) affects the spread of the beetle in reactive control, where the protection system is abandoned and coexistence with the beetle becomes reality. It also affects the survival of the population under the protection system when protection has failed in some area. The analysis assumes that in these instances some proportion of the beetle population (or rather, of the area invaded) survives the winter and adds to the invasion area in the following year.

In the Ukraine survival during hibernation was on average 70% (EPPO 2005). We do not have any hard data on which to base this variable in Finnish conditions, and hence an educated guess is needed. The analysis here uses a value of 30% for the basic level of winter survival. Figure 19 shows the PDF of the winter survival variable used in the analysis. The mean is 0.30, the maximum value is 0.87 and the minimum value is zero. In 5% of the iterations the value is below 0.07 and in 5% of the iterations it is above 0.53.

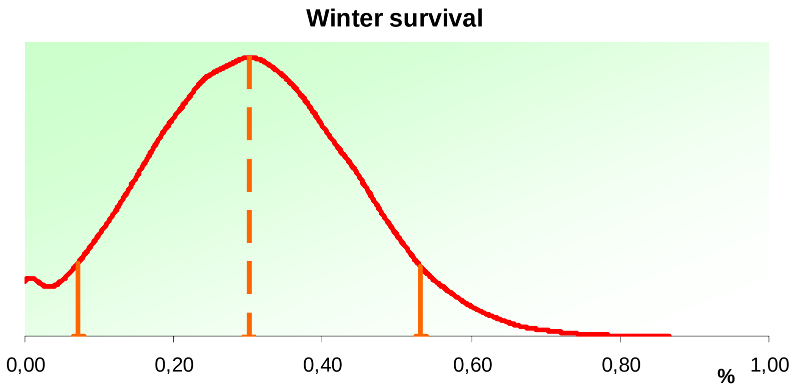

Figure 19. Probability density function of the winter survival.

To anticipate the results, it turns out that this variable is extremely important, and perhaps one for which reducing the uncertainty regarding its true value would be extremely valuable. An extensive sensitivity analysis is conducted for this variable to account for the uncertainty involved. In addition, a trend is built into the variable to account for the fact that winter survival is likely to increase over time due to climatic changes (Jylhä et al. 2004; Knight and Wimshurst 2005; Walker and Steffen 1997).

5.3.6 Spread variables

In addition to new invasions and the winter survival of the existing populations, the spread of the beetle determines the extent to which it will be present in the country in the event of giving up the protection system. These variables are only related to reactive control. In the case of pre-emptive control, it is assumed that the co-ordinated protection actions can curb any further spread.

If authority driven protection is not undertaken (i.e. in reactive control), we assume that there will be some spread already in the first summer, determined by the initial year spread multiplier (s_{INITt}). In other words, the controlled area is always somewhat smaller under co-ordinated authority driven protected zone than under control based on actions of individual producers. In the latter case, the area controlled in the initial invasion year is s_{INITt} times the initial invasion magnitude, i.e. on average s_{INITt} x 400 ha (recall expressions 18 and 19).

In the analysis the mean of s_{INITt} is taken to be 1.5. What this means is that if the initial invasion size is 400 ha, then under reactive control the area invaded during the first summer will be 600 ha, while under pre-emptive control it will be 400 ha. The distribution of s_{INITt} is restricted such that it cannot take values less than 1.00. The PDF is presented in Figure 20. The mean value is 1.5, the maximum is 2.5 and the minimum value is one. In 5% of the iterations the value is below 1.13 and in 5% of the iterations it is above 1.87.

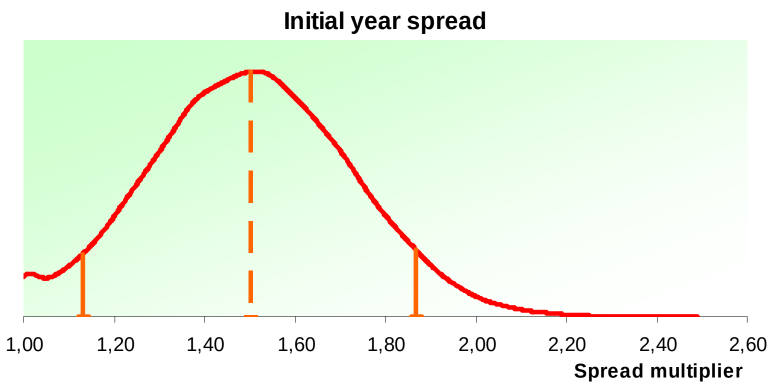

Figure 20. Probability density function of the initial spread multiplier.

In the first of our two reactive control scenarios, the spread of the beetle is logistic, as presented earlier in expression (18). The mean of the spread multiplier (s_t) is taken to be 1.8 in the analysis. This means that if all the beetles survive the winter, and there are no new invasions, then the invaded area becomes 1.8-fold every year.[38] The distribution of the variable is restricted such that values of s_t less than 1.00 are not allowed, as presented in Figure 21. The variance of the variable is assumed to be fairly large. The mean value is 1.83, the maximum is 4.41 and the minimum value is one. In at least 5% of the iterations the value is one, and in 5% of the iterations it is above 2.84.

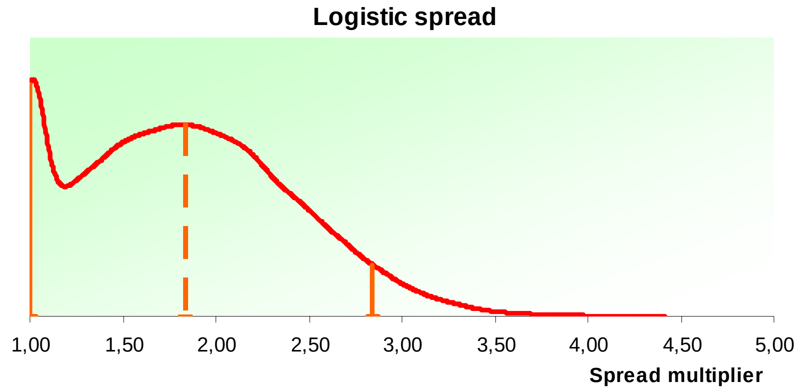

Figure 21. Probability density function of the spread multiplier.

Our second spread scenario assumes linear spread. This means that the beetle will invade a given area every year, regardless of the area it currently occupies (recall expression 19). This spread area (a_t) is assumed in the analysis to be on average the same size as the original invasion, i.e. 400 ha. This is, however modified by two factors. First, the spread area is stochastic. Its PDF is presented in Figure 22. The mean is 400 hectares, the maximum is 860 hectares and the minimum is zero. In 5% of the iterations the size is below 235 hectares and in 5% of the iterations it is above 564 hectares.

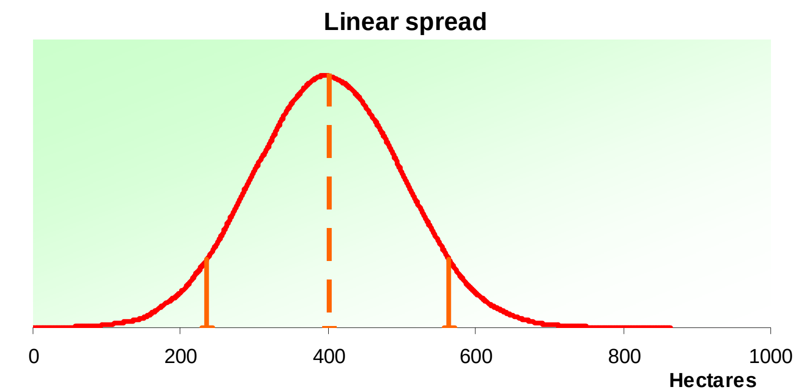

Figure 22. Probability density function of the linear spread area.

In addition to stochasticity, the linear spread area is affected by stochastic winter survival. In other words, if the linear spread area is 400 ha, and the level of winter survival is 0.3, the true spread area will only be 120 ha. This is visible also from expression (19).

5.3.7 Production, prices and discounting

The production area of potato, the mean yield per hectare and the producer price of potato in Finland in years 1995–2004 are shown in Table 9 (after TIKE 2006; FAOSTAT).

[38] However, remember that in a logistic spread equation spread is slower in the early and in the late stages of the spread.

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Production (ha)	36,100	34,800	33,200	32,800	32,300	32,200	30,000	29,800	28,700	29,300
Mean yield (kg/ha)	22,110	22,000	22,710	18,630	24,490	24,460	24,400	26,210	21,540	22,700
Producer price (e/kg)	0.21	0.13	0.18	0.23	0.22	0.10	0.13	0.16	0.16	0.23

Table 9. Potato production area, mean yield and producer price in Finland 1995−2004.

The figures used in the simulation analysis are a total production area (A_{TOT}) of 29,100 ha and a mean yield (q) of 24,400 kg/ha. These figures correspond to an approximate average of recent years.[39] There was some consideration of including the trends of increasing yields per hectare and decreasing production area into the analysis. This was not done mainly because other long-term adaptation measures and the impacts of agricultural policies were not included either. Hence the idea is to look at the question as if the current policy environment and thus also production conditions remain unchanged. Including such effects would naturally be more realistic, but the pest impacts and the impacts of pest policies could in such a case be lost under the changes in the production environment.

In this study 0.20 e/kg is used as the base food potato producer price (p_B). As discussed earlier, it is assumed that there are invasion induced price increases and hence consumer effects. Yield effect on price (ε) of -2 is used, meaning that a 10% reduction in domestic supply results in a 20% increase in the price. The shock is assumed to stay for the duration of that year (Jalonoja and Pietola 2001).

We assume that the price change is fully transferred to consumers. The model calculates the producer effects from the change in producer price, and consumer effects from the change in consumer price. Thus, although the two prices need not be the same, the change has to be equal in absolute terms. Thus, it is assumed that e.g. 0.05e increase in producer price leads to 0.05e increase in consumer price. Producer prices are generally more volatile than retail prices (Jalonoja and Pietola 2001 citing Young II et al. 1997), and hence there may be some justification for this assumption. Again, it is worth bearing in mind that this assumption affects merely to whom the costs accrue – not the cost efficiency of policy alternatives.

In problems that deal with change the time horizon is often long or very long, implying the importance of the discount rate (r). The discount rate measures the current value of costs and benefits that take place in the future. The British treasury recommends using a discount rate of 3.5% in public projects with timeframe less than 30 years. Before 2003 the recommended rate was 6%, but this included factors such as optimism bias[40] that are now separated from the discount rate (Great Britain H.M. Treasury 2003). We are not aware of the Finnish Ministry of Finance issuing any recommended discount rates for public projects.

Weitzman (2001) reports of a survey of 2,160 economists, who were asked which discount rate should be used in problems related to global warming. The mean of their answers was 4 percent and the standard deviation 3 percent. On basis of the answers received, Weitzman (2001) calculated marginal discount rates for long-term projects and for the medium future (26-75 years forward) arrived at a marginal discount rate of 2%. Lacking recommendations from Finnish authorities, we adopt a constant discount rate of 2%.[41] We also undertake sensitivity analysis of the discount rate using the values of 4% and 0%. For a discussion on discounting long-term projects and policies, see for instance Karp (2005), Gollier (2002) and Howarth (1996).

It is not obvious how the timespan of the analysis (T) should be chosen. In some sense the analysis could be conducted to eternity, in which case it would in practice be the discount rate that determines the length of the analysed period. However, changes in the policy environment are likely to be sizable

[39] The fact that these figures and not some other figures are used has to do with the history of this research.
[40] Optimism bias refers to the fact that the costs of public projects are often underestimated. Accounting for this was earlier incorporated in the recommended discount rate.
[41] This is not directly derived from Weitzman (2001), since he discusses marginal discount rates. According to his line of argument, although an individual correspondent believes in a constant discount rate, the wide range of the responses means that the effective social discount rate declines over time. We abstract from the declining discount rate in this study.

and hence a shorter term evaluation is also warranted. We have chosen a timeframe of 50 years, primarily to give some time for the analysed changes to materialise. A differently chosen timeframe would not, however, in this case affect the conclusions in any major way – unless a very short timescale (say, less than ten years) is chosen.

5.4 Local change

Traditionally Finland's situation concerning invasive pests has been fairly favourable, partly due to the isolated geographical location. However, changes affecting crop production seem relatively significant in the near future.

First, Finland's membership in the European Union has opened borders and increased trade and movement of both goods and people. The expansion of the Union to ten new member states in 2004 and further expansion in the future, possibly all the way to Turkey, enhance the effect. Although pests such as the CPB may be carried by stormy winds, other invasion pathways include transport with tourists and traded goods. In Finland the invasion pressure from this source has increased with for instance the increased Russian roundwood imports.

Secondly, potential warming of temperatures may be changing environmental conditions in Finland. Temperature changes are larger close to polar areas and growing conditions both to plants and to their pests may be rapidly changing with the warming temperatures. The CPB seems to suffer somewhat from cold winters and from cold and short summers. However, with the changing weather, the threat from both increasing invasion pressure and permanent establishment of the CPB in Finland increase (Jylhä et al. 2004; Knight and Wimshurst 2005; Walker and Steffen 1997). The potential of the CPB to extend its range to Finland has been shown by genetic (Boman et al. 2006a) as well as climatologic analysis (Baker et al. 1998; Jeffree and Jeffree 1996).

Finally, agricultural practices and modifications in those practices in surrounding countries may also increase the invasion pressure. Large-scale use of pesticides in Russia and Poland initiate and speed up development of resistance to common pesticides. Also structural changes in Russia have caused large number of private people to start subsistence potato production on small domestic plots, which is also likely to affect the pests' living conditions.

Resulting from all this, the CPB invasion and establishment pressure is increasing in Finland. A further component in the analysis is thus local change. This materialises in the analysis through changes in the mean variable values over time. Three specific trends are studied, and all trends are analysed at three different levels: i) no change; ii) slow change; and iii) rapid change.

Trend 1: Domestic climatic change (population winter survival)
Through climatic change and changes in the beetle's winter tolerance it is likely that the winter survival of the beetle population is getting better. In the simulation the change materialises through increases in the percentage share of those who survive the winter. The winter survival variable is created for each time period according to the following equation, which creates a linear trend.

$$\theta_t = \theta\left(1 + (t-1)\theta_{trend}\right) \tag{47}$$

θ represents the baseline mean winter survival, and θ_{trend} is a trend variable which takes different values depending on the strength of the trend (no, slow or rapid). Note that expression (47) (as all trend equations that follow) shows the deterministic development of the variable. However, in stochastic analysis this represents *the mean* around which variation is allowed in a stochastic manner. The variance remains unaffected, however. We assume that, in slow change, winter survival increases in 50 years from 30% to about 45%. In rapid change, the change is from 30% to about 60%.

We also assume that the protection system failure probability and area failing both increase, due to increasing invasion and establishment pressure. ω is the baseline failure probability of protection and ω_{trend} is the trend variable. Similarly, w is the baseline mean failure area of protection and w_{trend} the associated trend variable.

$$\omega_t = \omega(1 + (t-1)\omega_{trend}) \tag{48}$$

and

$$w_t = w(1 + (t-1)w_{trend}) \tag{49}$$

Trend 2: Regional change (invasion pressure)

Due to regional climatic change, increased trade, modified production practices and advancement of the permanent beetle population towards north it is to be expected that invasions will become more frequent in the future. In the simulations, the probability of invasion as well as the average size of the invasion increase over time as follows.

$$\gamma_t = \gamma(1 + (t-1)\gamma_{trend}) \tag{50}$$

and

$$A_{INITt} = A_{INIT}(1 + (t-1)A_{INIT\,trend}) \tag{51}$$

γ is the baseline invasion probability and A_{INIT} the baseline mean initial invaded area. γ_{trend} and $A_{INITtrend}$ represent the trend variables. We assume that in 50 years the average size of an invasion increases from about 400 ha to about 600 ha in slow change and to about 800 ha in rapid change. The annual invasion probability increases from about 33% to about 50% in slow change and to about 65% in rapid change. In addition, expressions (48) and (49) are included in this trend.

Trend 3: Increasing pesticide resistance

The beetle is capable of quickly developing resistance towards different pesticides. Thus the effectiveness of pesticides decreases and the costs increase over time. In the analysis the impact of increasing pesticide resistance functions through increasing costs of reactive control as well as of the chemical control substance component of the variable costs of the protection system as follows.

$$V_{2t} = V_2(1 + (t-1)V_{2trend}) \tag{52}$$

and

$$p_z z_t = p_z z(1 + (t-1)\, p_z z_{trend}) \tag{53}$$

V_2 is the baseline variable cost of protection and $p_z z$ the baseline reactive control cost. V_{2trend} and $p_z z_{trend}$ represent the trend variables. We assume that the variable costs of protection increase from 20 e/ha to about 40 e/ha in slow change and to about 50 e/ha in rapid change. In reactive control, the costs increase from 100 e/ha to about 200 e/ha in slow change and to about 250 e/ha in rapid change. In addition, expressions (48) and (49) are included in this trend.

5.5 Summary of the data

The data and information used in the analysis have now been introduced. The two tables below summarise the data. The total cost estimates used in the analysis are as presented in Table 10 and the parameter and variable values used in the analysis are summarised in Table 11.

Cost	Estimate (e)	Source and notes
Pre-emptive fixed costs (inspection, misc costs, etc.)	37,827 e	Plant Production Inspection Centre (KTTK). Misc costs include costs of data processing, laboratory, postage, telephone, etc. Based on costs in 1999–2001.
Pre-emptive variable costs:		
i) inspection	256 e / visit	KTTK. Based on costs of invasions in 1999−2004.
ii) control substances	20 e / ha	KTTK. Based on costs of invasions in 1999−2004.
iii) eradication	610 e / ha	KTTK. Based on costs of invasions in 1999−2004.
Reactive control costs:		
i) production losses	10% of yield in infected areas	Elsewhere crop losses of 15-20% have been reported. We use a lower figure due to temperature dependent feeding rates and low level of resistance.
ii) reactive control costs	100 e / ha	Estimate, includes costs of control substances and labour costs.
iii) domestic market effects	estimated	It is assumed that there are invasion induced price increases and consumer effects. Yield effect on price of -2 is used (Jalonoja and Pietola 2001).
iv) international market effects	assumed zero	Finnish potato trade is presently only small scale activity.
v) health, environmental and cultural costs	assumed zero	If control substances are used in accordance with regulations there will be no health implications. The CPB invades an empty niche and there are no direct ecosystem impacts. Environmental impacts of control substances are not accounted for here. Beetle could threaten habitual potato farming, but such impacts are likely to be minor.

Table 10. Cost estimates used in the analysis.

Symbol	Parameters and Variables	(Mean) Value	Variance (if any)
A_{INITt}	Invasion magnitude (from outside) (ha)	400	20000
$A_{INITtrend}$	Trend variable in invasion magnitude (slow/rapid)	0.01/0.02	0
a_t	Spread area in linear spread (ha)	400	10000
A_t	Annual infected area (ha)	varies	> 0
A_{TOT}	Total production area (ha)	29,100	0
D_t	Crop damage caused by the pest (%), $0 \leq D_t \leq 1$	0.10	0.005
F	Fixed costs of pre-emptive control (e)	37,827	0
g	Inspection area multiplier	4	0
I_t	Annual variable inspection visits (visits)	$g\,A_t$	> 0
p_B	Pre-invasion (base) producer price (e)	0.20	0
p_t	Modified potato producer price (e)	$p + \Delta p_t$	> 0
p_{zt}	Control costs per hectare in reactive control (e)	100	0
p_{ztrend}	Trend variable in p_{zt} (slow/rapid)	0.02/0.04	0
q	Base production quantity per hectare (kg)	24,400	0
r	Discount rate (%), $0 \leq r \leq 1$	0.02	0
s_{INITt}	Spread multiplier in the first year	1.5	0.05
s_t	Spread multiplier in nonlinear spread	1.8	0.4
T	Terminal time period	50	0
V_1	Variable costs, bought services per visit (e)	256	0
V_2	Variable costs, control substances per hectare (e)	20	0
V_{2trend}	Trend variable in V_2 (slow/rapid)	0.10/0.20	0
V_3	Variable costs, eradication costs and compensation per hectare (e)	610	0
w_t	Failure area of pre-emptive control (%), $0 \leq w_t \leq 1$	0.20	0
w_{trend}	Trend variable in failure area	0.05	0
γ_t	Invasion probability (%), $0 \leq \gamma_t \leq 1$	0.33	0
γ_{trend}	Trend variable in invasion probability (slow/rapid)	0.01/0.02	0
Δp_t	Invasion induced price increase (e)	$-D\,p_B\,\varepsilon\,A_t\,/\,A_{TOT}$	> 0
ε	Yield effect on price	-2	0
θ_t	Proportion of population that survives winter (%), $0 \leq \theta_t \leq 1$	0.30	0.02
θ_{trend}	Trend variable in winter survival (slow/rapid)	0.01/0.02	0
ω_t	Failure probability of pre-emptive control (%), $0 \leq \omega_t \leq 1$	0.30	0
ω_{trend}	Trend variable in failure probability	0.05	0

Table 11. Parameter and variable values used in the quantitative empirical analysis.

5.6 Ex-post cost-benefit analysis

To validate the model calculations of protection costs, we first calculated the estimated costs for the period 1998−2004 using the equations and invasion data presented in section 5.3.1. We then compared the estimated results to the true costs incurred in that period, as reported in Table 8. The results of this comparison are shown in Table 12.

	1998	1999	2000	2001	2002	2003	2004	Total 1999-2004
True cost (e)	N/A	78,712	19,005	45,747	576,371	279,181	29,659	1,028,675
Model result (e)	208,497	66,617	38,940	49,327	571,597	220,279	93,029	1,039,790

Table 12. True costs versus projected costs of the protected zone 1998−2004.

The model results are fairly close to the actual results, although there are discrepancies in individual years (especially in year 2004). This is understandable due to data being available only for limited number of years, as well as due to the fact that the compensation payments can be spread out to the invasion year plus the next two years. Hence the magnitude of the invasion in this year affects the costs in this year as well as in the next two years. This cannot be taken into account in the model, since we do not have information on which year's invasion compensations are being paid. Thus in the model all compensation payments are taken to be for that year's invasion. Given the extent of uncertainty related to the issue and the relatively satisfactory estimates of the costs on average, we are fairly satisfied with the model and the overall estimation of protection costs that it produces.

Further, also primarily for model validation purposes, an ex-post analysis of the CPB protection system in 1998−2004 was carried out. In other words, the actual protection costs were compared to costs that could have ensued had we abandoned protection system in 1998. Thus the true invasion magnitudes were taken as given, and spread was then assumed to take place according to the two scenarios described earlier. The projected spread in the two scenarios and the case with no winter survival (corresponding to the true observations) are presented in Figure 23.

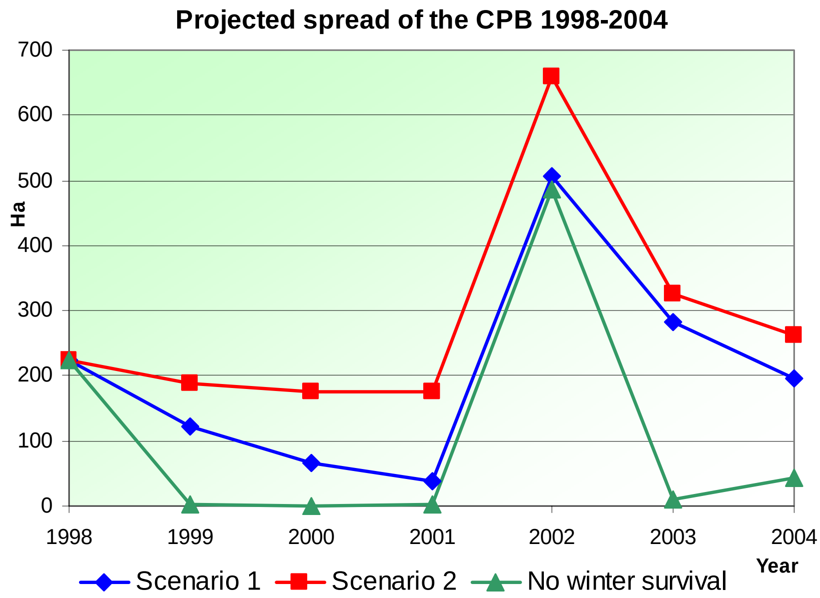

Figure 23. Projected spread of the Colorado potato beetle 1998−2004.

The data on true invasion magnitudes (infestation and additional visits) and the results of the ex-post analysis by year are presented in Table 13. Additional visits row refers to the number of actual inspection visits less the 200 visits that have been assumed to be included in fixed costs of the protection system. Initial invaded area is, as discussed before, assumed to be equal to the number of plots infested (i.e. average invaded plot size is one hectare).

Year	1998	1999	2000	2001	2002	2003	2004
Additional visits (visits)	300	70	0	40	1,285	573	109
Infestations (plots)	149	1	0	2	324	6	29
Initial invaded area (ha)	149	1	0	2	324	6	29
Projected invaded area (ha)							
- Scenario 1	223.5	122.0	65.8	38.5	506.8	281.5	195.2
- Scenario 2	223.5	188.6	176.6	176.0	658.8	326.6	261.5
- No winter survival	223.5	1.5	0.0	3.0	486	9.0	43.5
True protection cost (e)	N/A	78,712	19,005	45,747	576,371	279,181	29,659
Projected protection cost (e)	208,497	66,617	38,940	49,327	571,597	220,279	93,029
Projected reactive control cost (e)							
- Scenario 1	131,502	71,742	38,696	22,647	298,423	165,671	114,825
- Scenario 2	131,502	110,927	103,873	103,522	388,097	192,242	153,872
- No winter survival	131,502	882	0	1,764	288,164	5,292	25,581
BCR: True protection cost							
- Scenario 1	-	0.91	2.04	0.50	0.52	0.59	3.87
- Scenario 2	-	1.41	5.47	2.26	0.67	0.69	5.19
- No winter survival	-	0.01	0.00	0.04	0.50	0.02	0.86
BCR: Projected protection cost							
- Scenario 1	0.63	1.08	0.78	0.46	0.52	0.75	1.23
- Scenario 2	0.63	1.67	2.67	2.10	0.68	0.87	1.65
- No winter survival	0.63	0.01	0.00	0.04	0.50	0.02	0.27

Table 13. Ex-post analysis data and results by year 1998–2004.

The first observation is that Scenario 2 gives higher benefit-cost ratios (BCRs)[42] than Scenario 1. This is because at the early stages of spread, the linear spread model produces higher rates of spread than the logistic model. Hence also the benefit of protection (the avoided spread) is higher. Second, whether we use the real protection costs or the projected protection costs to calculate the BCRs, the results are qualitatively similar. Only under Scenario 1 in years 1999 and 2000 the BCR is either above or below one, depending on whether projected or true protection costs are used. Third, in the case of no winter survival, protection in any individual year is more expensive than giving it up (the BCR is always less than one).

However, looking at the results of individual years serves primarily a validation purpose, not the purpose of analysing which policy is economically sensible. This is because the benefits of protection (the avoided spread) mainly materialise in the coming years. Instead of individual years we can look at the whole 7-year period, as presented in Table 14. The column titled 'true protection costs' displays the protection costs and the BCRs when the real-life protection costs have been used. The true protection cost is calculated by taking the true costs for the period 1999−2004, and for year 1998 – for which data are lacking – the projected cost is added. The column titled 'projected protection costs' displays the costs and the BCRs when the protection costs produced by our model are used.

Results for the period 1998−2004		True protection costs	Projected protection costs
Total protection cost (e)		1,237,172	1,248,287
Projected reactive control costs (e)	- Scenario 1	843,505	843,505
	- Scenario 2	1,184,033	1,184,033
	- No winter survival	451,185	451,185
BCRs	- Scenario 1	0.68	0.68
	- Scenario 2	0.96	0.95
	- No winter survival	0.36	0.36

Table 14. Ex-post analysis results for the period 1998–2004.

The first observation is that over this period it does not matter whether we use the projected protection costs or the true protection costs to compute the BCRs. The outcomes in both cases are very close to each other. The second observation is that even so, the BCR is in all cases less than one. In other words, the protection system has not been economically sensible over the period 1998-2004.

42 Benefit-cost ratios for pre-emptive control are produced by dividing the benefits of the protection system (i.e. avoided reactive control costs) by the costs of the protection system. It denotes by how much one of the policies is cheaper or more expensive than the other. Any ratio below one implies that protection is more expensive than reactive control.

However, to produce results with more validity, we should look not just over the seven years, but further into the future in order to judge whether the protection system is a sound policy over a longer period of time. The main lesson from the ex-post analysis when looked from the perspective of this entire study is that in this type of cases it is not sufficient to look at the costs over only a short period of time. Hence, we need to start simulating possible future scenarios.

5.7 Ex-ante simulation analysis

5.7.1 Basic results

The planning horizon in the ex-ante simulation is 50 years, during which time invasion events take place randomly. As mentioned, the length of the analysed period is chosen to demonstrate the impact of changes, giving them sufficient time to materialise. The analysis is conducted for 300,000 iterations in order to have a sufficient representation of various stochastic variable combinations. The main results are presented such that the three trends are simultaneously all off, all slow or all rapid. The impact of individual trends is discussed later in the section on sensitivity.

To illustrate the spread scenarios that drive the results, Figure 24 represents the mean annual invaded areas in Scenarios 1 and 2 under the three different levels of change.

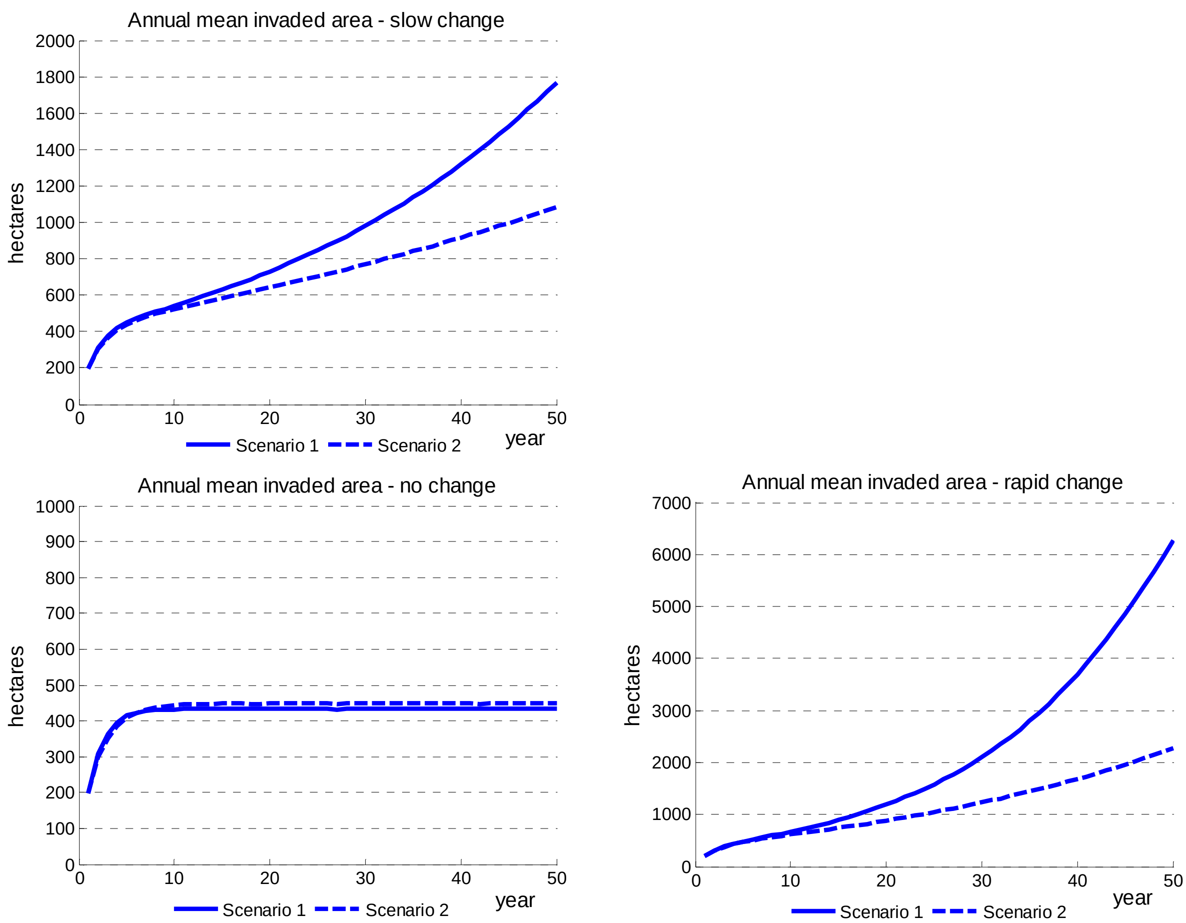

Figure 24. Mean annual invaded areas under different levels of change.

As can be seen, the invaded areas on average are not very big. This is due to the assumed level of 30% winter survival (i.e. 70% winter mortality). In fact, under no change the area invaded remains on average at around the level of the current invasion years. Under rapid change, on average roughly 25% (Scenario 1) and 7% (Scenario 2) of the entire production area is invaded after 50 years. Under the base case of slow change, on average about 6% (Scenario 1) and 3% (Scenario 2) of the production area is invaded after 50 years. However, it is worth remembering that these represent the means of the iterations, and much higher and lower areas are achieved within individual iterations.

We will first discuss the number of cases preferring each policy, followed by a discussion on the mean, minimum and maximum costs involved. The section also introduces the different ways to present the results, which will subsequently be used later on in the analysis. Following the basic results, we shall discuss benefit-cost ratios before moving to sensitivity analysis. We finish the chapter by discussing to whom the costs accrue intertemporally and intratemporally.

The number of least-cost cases

Table 15 depicts the number of iterations (cases) in which one of the policies imposes lower costs than the other. For instance, under Scenario 1 and in the case of all trends set at ‘slow’, in 93.6% of the 300,000 iterations pre-emptive control imposes lower costs than reactive control. In other words, on average in 93.6% of different realisations of future, pre-emptive control is the least-cost policy choice.

Cases %	Scenario	Pre-emptive control	Reactive control
No trend	Scenario 1	37.5%	62.5%
	Scenario 2	47.3%	52.7%
Slow trend	Scenario 1	93.6%	6.4%
	Scenario 2	67.6%	32.4%
Rapid trend	Scenario 1	100.0%	0.0%
	Scenario 2	93.1%	6.9%

Table 15. Proportion of iterations in which the policy imposes lower costs than the other policy.

When all trends are off, reactive control is the least-cost policy choice in the majority of cases (62.5% under Scenario 1 and 52.7% under Scenario 2). Similarly, when all trends are either slow or rapid, pre-emptive control is the least-cost policy choice in the majority of cases (93.6% and 100.0% under Scenario 1 and 67.6% and 93.1% under Scenario 2). The trends thus enhance the profitability of protection. Whenever there is some anticipated change, pre-emptive control is the cost minimising strategy in 68-100% of the cases. This result can also be looked from the other perspective. If we assume that there will be no changes in the future, or that the pests die for certain over the winter (results not shown in the table), it seems that it might be economically sensible to abandon the protection system. Under such assumptions reactive control would be the least-cost policy choice in 53-63% of the possible realisations of future.

Mean, median, minimum and maximum costs

Looking at the mere number of cases would suffice if society was truly risk neutral and there was no uncertainty regarding the distribution of the model variables. As this is not so, the results above have to be supplemented by looking at the mean, median, minimum and maximum costs of the strategies, as depicted in Table 16.

Costs		Pre-emptive control	Reactive control	
			Scenario 1	Scenario 2
No trend	Mean (e)	8,338,400	8,043,300	8,264,900
	Median (e)	8,284,200	7,868,200	8,184,800
	Min (e)	2,229,900	856,890	1,390,300
	Max (e)	16,379,000	25,420,000	16,837,000
Slow trend	Mean (e)	13,053,000	17,258,000	13,712,000
	Median (e)	13,011,000	16,809,000	13,616,000
	Min (e)	4,182,300	3,327,300	3,600,100
	Max (e)	23,344,000	57,168,000	25,536,000
Rapid trend	Mean (e)	18,919,000	39,976,000	21,968,000
	Median (e)	18,903,000	38,679,000	21,851,000
	Min (e)	5,970,400	11,056,000	9,372,300
	Max (e)	32,116,000	120,750,000	37,745,000

Table 16. The discounted present value costs under each policy, scenario and trend.

The table displays the present value costs of the policies under pre-emptive control, under the two spread scenarios of reactive control and under the special case of reactive control in which there is no winter survival of the beetle. The costs are discounted at a rate of two percent. In all the cases the mean and median costs are very close to each other, indicating that the distribution of the costs is fairly symmetric. The differences in mean cost estimates under pre-emptive control and the two scenarios of reactive control are not very large in the context of no change (8.3, 8.0 and 8.3 million euro, respectively) and to some extent under slow change (13.1, 17.3 and 13.7 million euro). In the case of rapid change, however, the differences become larger (18.9, 40.0 and 22.0 million euro). The mean costs are depicted in Figure 25.

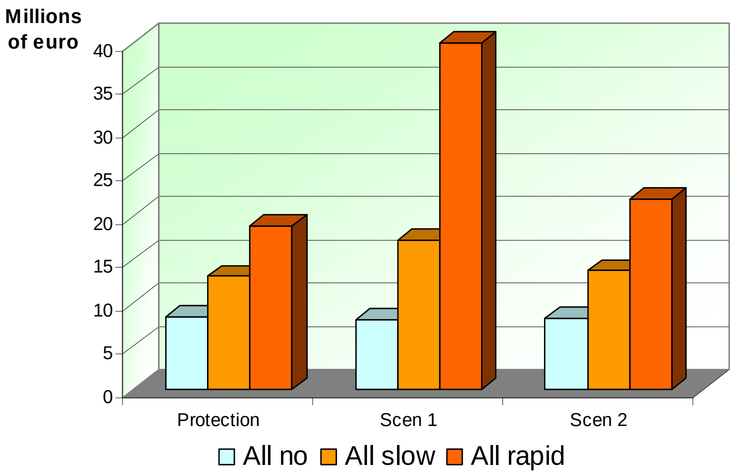

Figure 25. Mean present value costs of protection and reactive control (two scenarios).

The trends unambiguously increase the mean, minimum and maximum costs of both policies, but increase the costs of reactive control relatively more. This is also evident from looking at the number of iterations in which pre-emptive control is cheaper in Table 15. There we already noticed that pre-emptive control basically becomes more preferred the more change there is. This is because with the increasing trends the pest is able to spread to larger areas, survive the winters better and becomes more expensive to control, increasing the costs also in the subsequent periods and hence resulting in relatively larger costs of reactive control.

As for the variability of the cost estimates, it is remarkable how the present value costs vary from the minimum cost of Scenario 1 under no change of less than 900,000 euro (or less than 400,000 euro in the case of no winter survival as discussed later) to the maximum cost of Scenario 1 under rapid change of nearly 121 million euro over the 50 year period. The highest possible estimate is thus over 140 times greater than the lowest estimate. This would be unfortunate if we had no way of knowing which state is likely to materialise.

However, it is possible to look at the distribution of costs and make subjective evaluations as to how that impacts on policy considerations. Figure 26 through to Figure 28 depict the probability density functions of net benefits of protection under the two scenarios and different levels of change. Net benefits of protection are derived simply by subtracting the cost of pre-emptive control from the cost of reactive control in each iteration. Values below zero then indicate that on those occasions net benefits of protection are negative and the protection system is more expensive than giving it up.

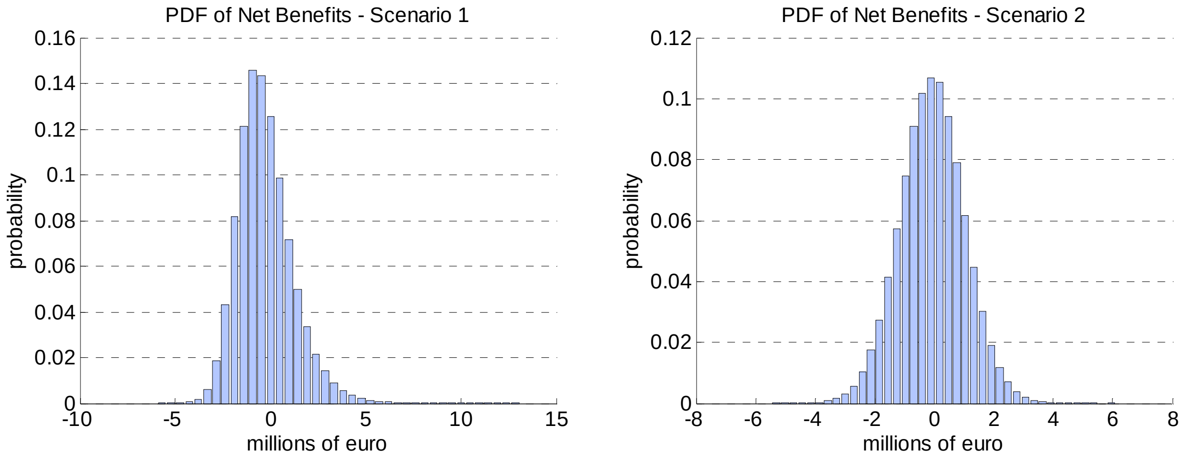

Figure 26. Distribution of net benefits of protection under no change in Scenario 1 and Scenario 2.

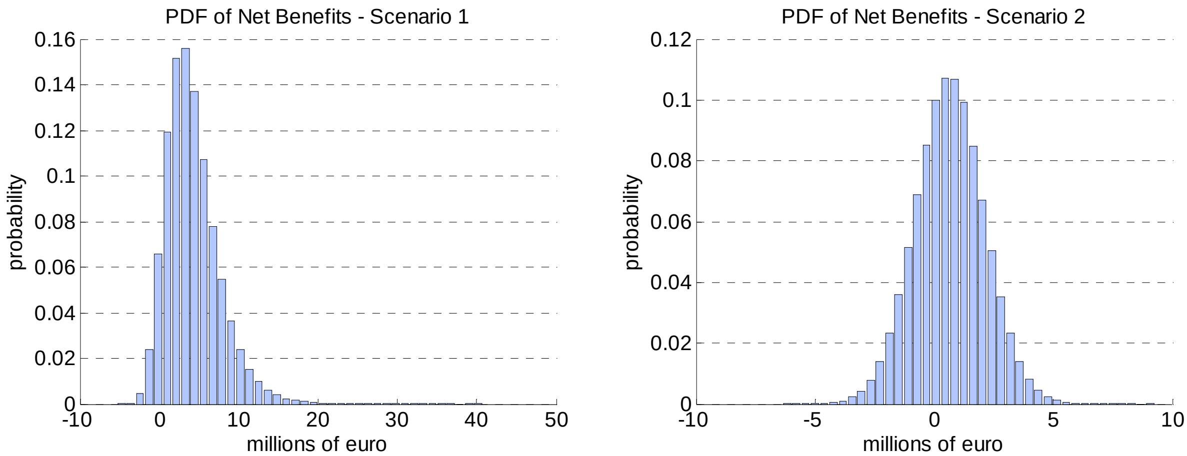

Figure 27. Distribution of net benefits of protection under slow change in Scenario 1 and Scenario 2.

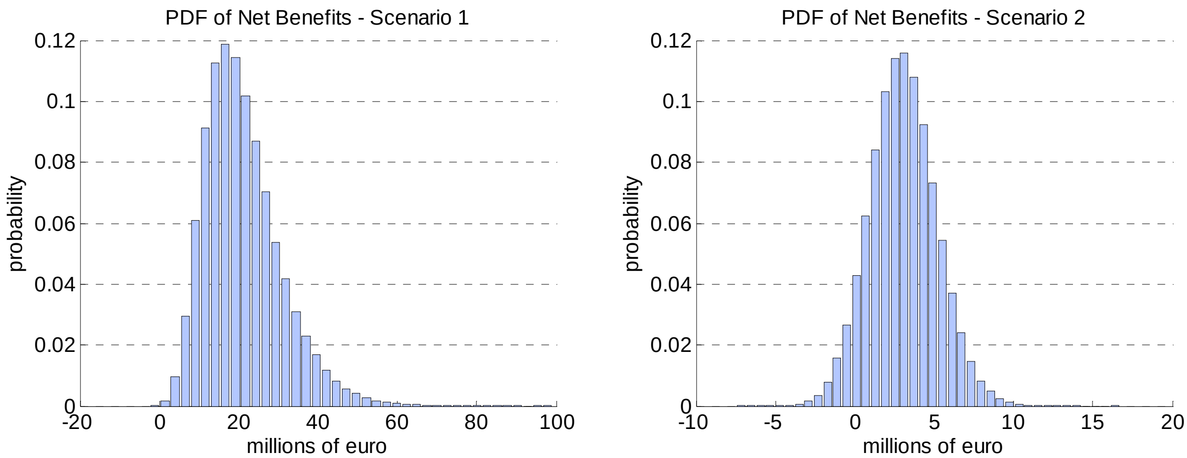

Figure 28. Distribution of net benefits of protection under rapid change in Scenario 1 and Scenario 2.

The distribution of net benefits under Scenario 1 is much more clearly to the right of the zero than Scenario 2. This means that the net benefits of protection are more often positive under Scenario 1 than under Scenario 2. Further, note that there is a fairly long tail to the right under Scenario 1, indicating that the maximum net benefits of protection (avoided costs) can be relatively large under Scenario 1. On the other hand, in Scenario 2 the net benefits are fairly evenly distributed on either side of zero, with relatively low (positive or negative) net benefits involved.

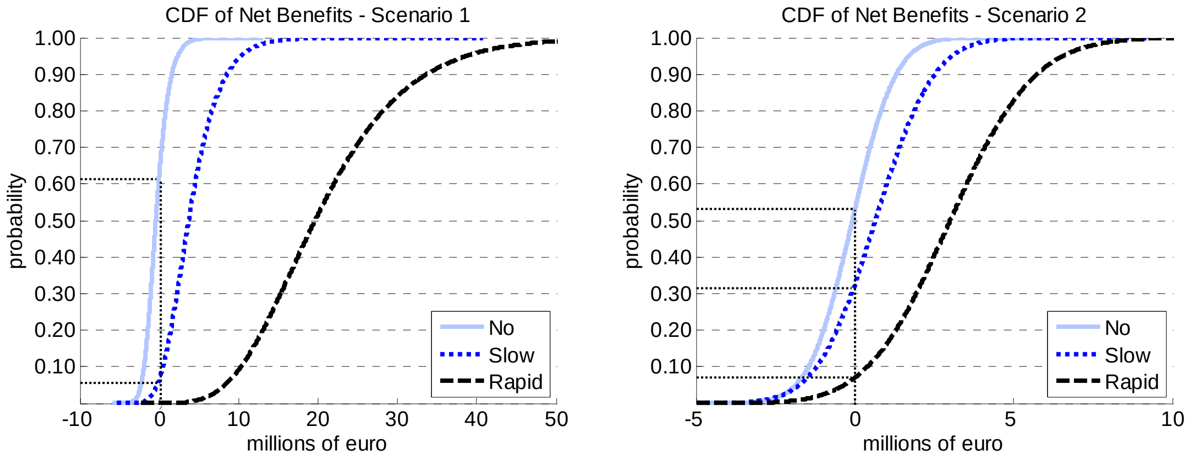

Figure 29. Cumulative distribution of net benefits of protection in Scenario 1 and Scenario 2.

Plotting the cumulative density functions (CDFs) instead of the probability density functions reveals interesting further information. Figure 29 plots the CDF of the net benefits of protection under different levels of change in Scenario 1 (panel on the left) and Scenario 2 (panel on the right).

The points marked with dashed lines represent the probabilities at which the net benefits of the protection system are positive (greater than zero) under the two scenarios when subjected to different levels of change. These levels are the same as the percentages/probabilities reported in Table 15. The additional value of representing the net benefit distributions this way is to be able to take into account the level of risk we are willing to accept. For instance, we can see that under Scenario 1 there is a 62% probability that the net benefits of protection are negative (no change), less than ca. 5 million euro (slow change) or less than ca. 23 million euro (rapid change). Similar assessment can be done for all probabilities and the associated net benefits.

The results can also be looked at through the maximum costs. Figure 30 depicts the maximum costs associated with the two policies. It is clearly visible from the diagram that the maximum costs under rapid change in Scenario 1 can be much higher than the maximum costs associated with pre-emptive control. Hence, if we are fairly certain that Scenario 1 is the more adequate description of the likely spread of the CPB, then should we choose to abandon protection, the risk from doing so would be very high indeed. However, if we consider Scenario 2 to be a more truthful description (or if we think that there will be no change in the future), there is not so much difference in the maximum risk associated with the two policy options.

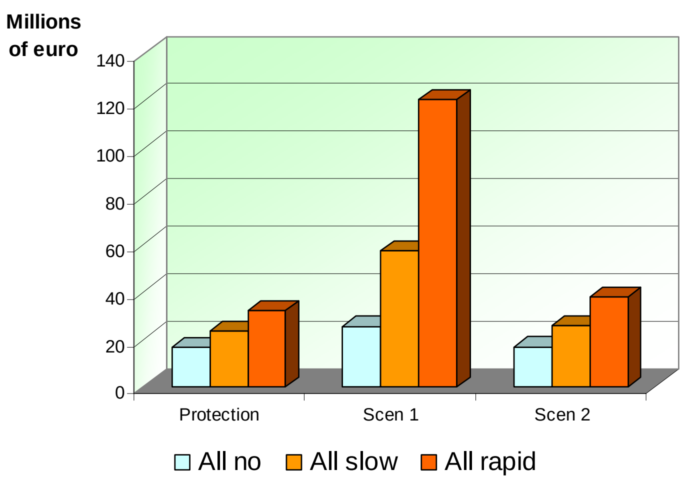

Figure 30. Maximum present value costs of protection and reactive control (two scenarios).

Benefit-cost ratios

Another way to look at the results is to compute the benefit-cost ratios (BCRs).[43] Here the figures presented are benefit-cost ratios for pre-emptive control. As mentioned briefly earlier, the ratio is produced by dividing the benefits of the protection system (i.e. the avoided reactive control costs) by the costs of the protection system. The BCR denotes *by how much* one of the policies is cheaper or more expensive than the other. For instance, the mean ratio of 1.32:1 for slow change under Scenario 1 means that giving up pre-emptive control would on average be 1.32 times more expensive than continuing with it. Any ratio below one implies that protection is more expensive than reactive control. The BCRs are presented for each scenario and trend in Table 17.

BCRs		Scenario 1	Scenario 2
NO CHANGE	Mean	0.96	1.00
	Minimum	0.30	0.39
	Maximum	2.40	1.90
SLOW CHANGE	Mean	1.32	1.06
	Minimum	0.54	0.57
	Maximum	3.77	1.75
RAPID CHANGE	Mean	2.12	1.17
	Minimum	0.86	0.67
	Maximum	7.04	1.90

Table 17. The benefit-cost ratios of each strategy and scenario.

The minimum BCRs are systematically – regardless of the Scenario and the level of change – below one. Hence protection cannot be automatically regarded as a least cost strategy in all possible states of the world. On the other hand, the maximum BCRs are systematically greater than one, and hence by a similar argument reactive control cannot be regarded as a least cost strategy. The mean BCRs are presented in Figure 31.

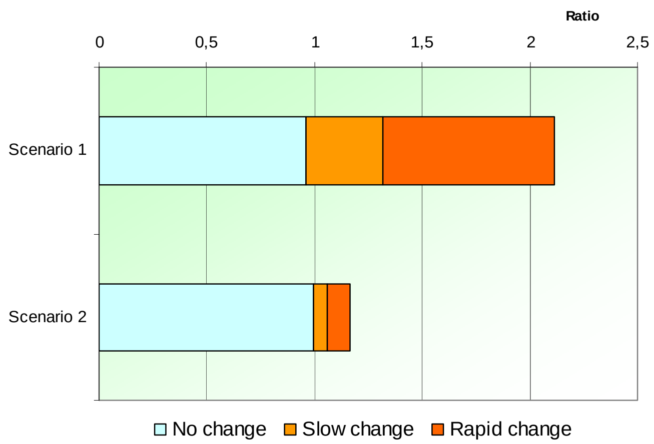

Figure 31. Mean benefit-cost ratios of the two scenarios at different levels of change.

As can be seen from Figure 31 and Table 17, interpretation of results is further complicated by the fact that the mean BCRs are at a range of 0.96:1 to 2.12:1, depending on the Scenario and the level of change. Hence the mean BCRs are fairly close to one and on either side of it, indicating that the variable values that have been used are such that it cannot be established for certain which policy is the least-cost policy choice.

However, again it can be clearly seen that the trends strengthen the viability of the protection system. The more we expect the climate and the pest to change, the more likely the investment in the protection system is the least-cost policy. The mean BCRs can also be compared to the BCR of 7.5 that was estimated by Mumford et al. (2000) for the British CPB protected zone.

In the current study, at the extreme the protection system is about three times more expensive than reactive control (BCR of 0.30:1 under Scenario 1 with no change). At the other extreme reactive

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43 This section presents largely the same information as the previous section, but perhaps in a more illustrative form.

control is about seven times more expensive than protection (BCR of 7.04:1 under Scenario 1 with rapid change). The maximum BCRs for the policies are presented also in Figure 32. These results again raise the same arguments as those already mentioned when the maximum costs of the policies were discussed. Somewhat more interesting is the fact the BCR under Scenario 2 is hardly affected by the level of change, implying that the spread of the beetle is not promoted by change as much under Scenario 2 as is the case under Scenario 1, or that the cost increases in both protection and reactive control are roughly equal in relative terms and hence do not impact on the BCR.

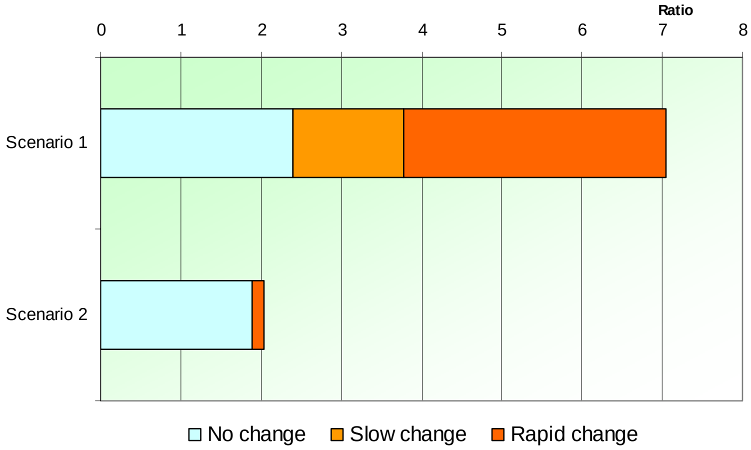

Figure 32. Maximum benefit-cost ratios of the two scenarios at different levels of change.

5.7.2 Sensitivity and uncertainty analysis

We have now discussed the basic results of the quantitative analysis. As discussed earlier, uncertainty is often a key factor in issues related to IAS. This case is no exception. To account for uncertainty, the results of a sensitivity analysis are now reported. A standard sensitivity analysis with low/high values was carried out as indicated in Table 18.

Target variable	Symbol	Value(s) analysed relative to base
Initial year spread multiplier	s_{INITt}	±10% / ±20%
Spread rate	s_t	±10% / ±20%
Crop damage	D_t	±10% / ±20% / ±50%
Winter survival	θ_t	±10% / ±20% / [0.1; 1.0]
Aggregate fixed costs of pre-emptive control	F	±50%
Aggregate variable costs of pre-emptive control	V_1, V_{2t}, V_3	±50%
Initial invasion magnitude	A_{INITt}	±50%
Linear spread parameter	a_t	±50%
Cost of reactive control	p_{zt}	±50% / +100%
Invasion probability	γ_t	±50% / +100%
Discount rate	r	±100%
Yield effect on price	ε	-100%

Table 18. Sensitivity analysis.

The key variables analysed are now discussed separately one by one. In the analyses that follow, all trends are simultaneously set at slow change.

<u>Winter survival</u>

Figure 33 represents the impact of different levels of winter survival on the mean BCRs. Allowing, for instance, 100% winter survival implies that the mean BCR is about 30:1 under Scenario 1 and about 14:1 under Scenario 2, suggesting very high costs for giving up the protection system.

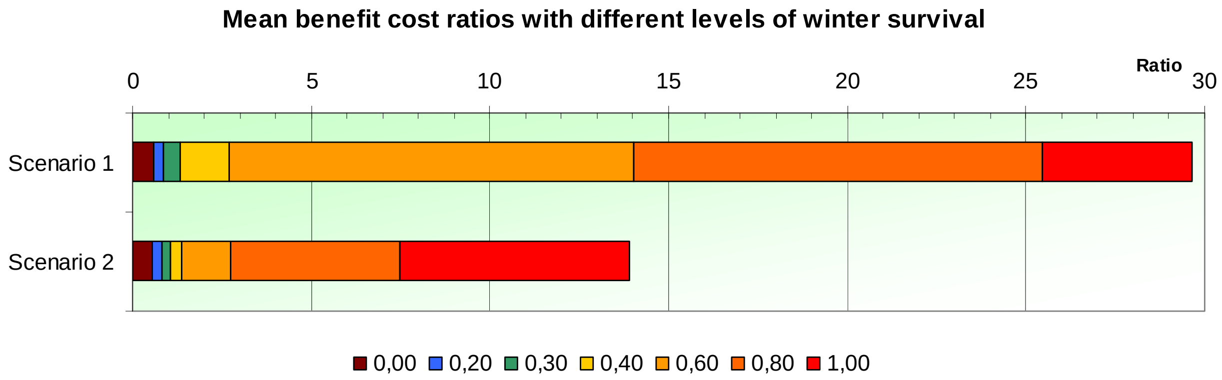

Figure 33. Mean benefit-cost ratios with different levels of winter survival.

Whereas before the mean BCRs were close to one, it is now evident that if the level of winter survival is even moderately greater than assumed (say, 40% instead of 30%), the mean results are no longer ambiguous. At 40% winter survival the mean BCR is greater than one under both Scenarios, implying that protection is an economically viable choice. If the level is moderately lower (say, 20%), the mean BCRs under both Scenarios are less than one, implying that protection is more expensive than reactive control. Furthermore, slightly greater changes in the survival level (assume, say, 60% survival) take the mean BCR to 14:1 under Scenario 1 and to about 3:1 under Scenario 2. Hence the importance of this variable is immense, and the implications of the analysis are very much dependent on the value of winter survival that is chosen.

The level of winter survival naturally affects not only the BCRs but also the mean and maximum costs of the policies. Figure 34 presents the mean (left hand side panel) and maximum (right hand side panel) policy costs under different levels of winter survival.

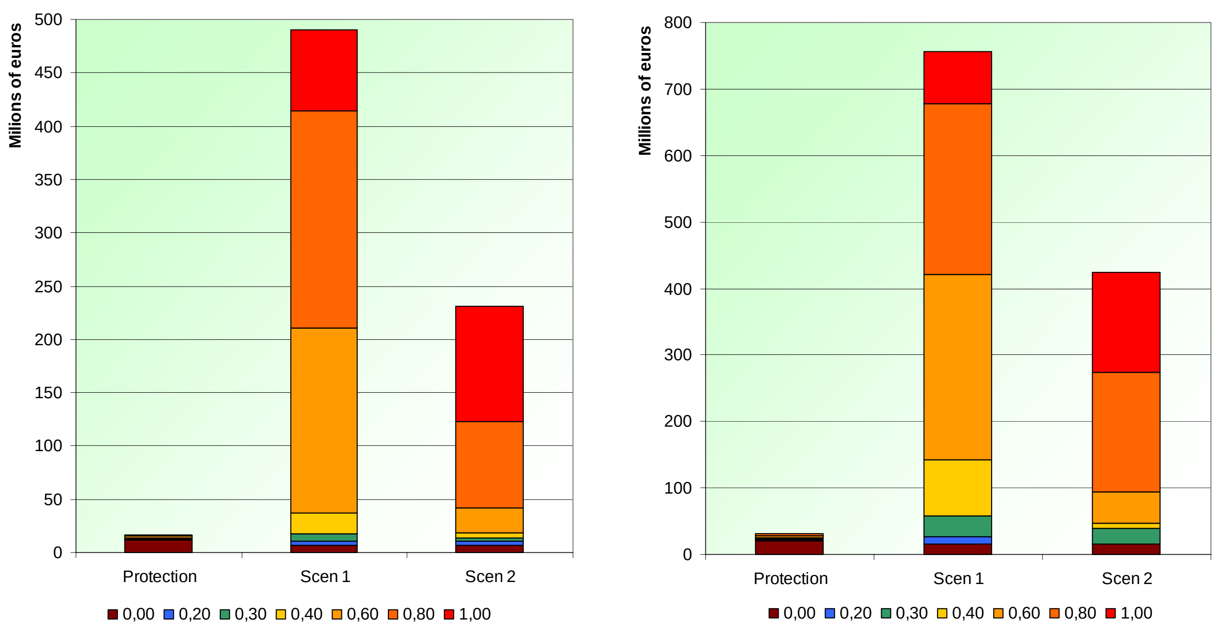

Figure 34. Mean (LHS) and maximum policy (RHS) costs with different levels of winter survival.

Remember that the present value mean costs under slow change were about 13-17 million euro, and the maximum costs about 23-57 million euro. The mean costs with higher levels of winter survival can become substantially greater than these values. For instance, assuming perfect (100%) winter survival, the mean present value cost of reactive control would be about 490 million euro under Scenario 1 and about 231 million euro under Scenario 2. The cost of protection would remain at about 17 million euro.

A similar phenomenon can be seen happening with the present value maximum costs, which under 100% winter survival would be about 755 million euro under Scenario 1 and about 411 million euro under Scenario 2. Note that the increase in maximum costs under Scenario 1 when the level of winter survival increases from 80% to 100% is not very big. This is due to the fact that already with 80% survival level the species can rapidly spread to the whole production area, and significant further damages are simply not possible.

Because winter survival turned out to be the most important single variable affecting the results, we undertook the analysis also under the assumption that there is no winter survival. This analysis acts as a worst case scenario for pre-emptive control – after all, if the beetles die *for certain* every winter, is there any justification in investing resources in eradicating them every summer. The results, presented in Table 19, in fact suggest that there is not. The aggregate costs are unambiguously lower with reactive control than with pre-emptive control and apart from a single iteration, also the BCRs are all below one.

Costs		**Pre-emptive control**	**Reactive control Scenarios 1 and 2**	**Min / Mean / Max BCR**
No trend	Mean (e)	8,213,700	3,825,700	0.10 / 0.46 / 0.82
	Min (e)	2,194,400	364,680	
	Max (e)	16,100,000	9,724,600	
Slow trend	Mean (e)	11,565,000	7,449,100	0.33 / 0.64 / 1.02
	Min (e)	3,547,500	1,659,400	
	Max (e)	20,834,000	16,235,000	
Rapid trend	Mean (e)	15,795,000	8,926,300	0.29 / 0.56 / 0.87
	Min (e)	4,841,800	2,649,100	
	Max (e)	26,468,000	16,868,000	

Table 19. The discounted present value costs and benefit-cost ratios in the case of no winter survival.

Crop damage

Figure 35 presents the impact of different levels of crop damage on mean BCRs. The baseline crop damage is 10% of the crop, and the figure presents the mean BCRs when that damage level is reduced and increased by 10%, 20% and 50%. In other words, it is at a range 0.05-0.15.

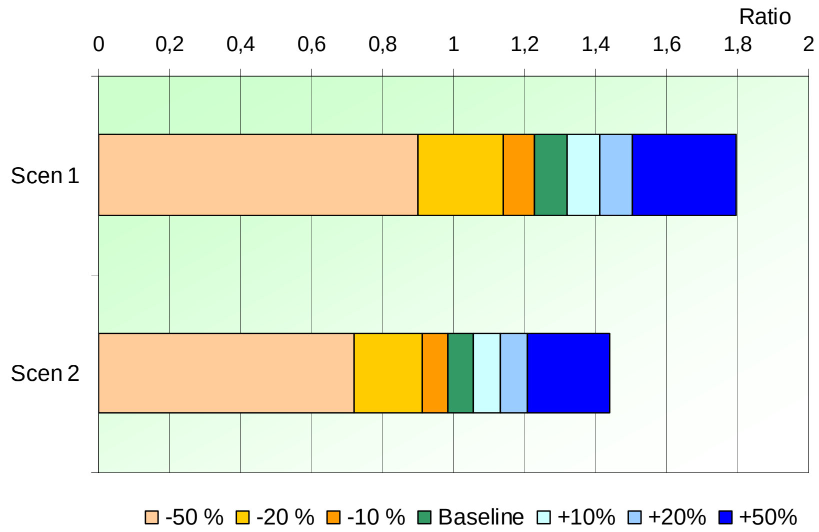

Figure 35. Mean benefit-cost ratios with different levels of crop damage by the beetle.

The first observation is that the results are not as drastic as with winter survival. Of course, winter survival was analysed for all possible levels, and here the maximum change is 50% of the original value. However, as is natural, greater level of damages increases the profitability of protection. On the other hand, a 50% reduction in damages (thus assuming 5% yield reduction due to the CPB) would take the mean BCR below one under both scenarios. Hence, if we can be certain that the beetle only results in

5% of crop damages (and all other variables are as assumed), then it would be economically sensible to abandon the protection system.

Invasion probability

Figure 36 presents the impact of different levels of invasion probability on the mean costs (left hand side panel) and the mean BCRs (right hand side panel).

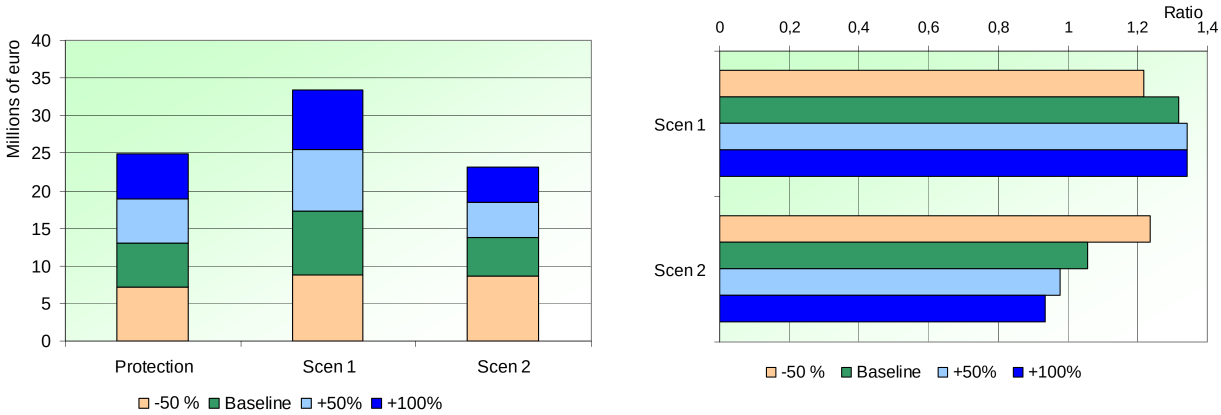

Figure 36. Mean costs and benefit-cost ratios with different levels of invasion probability.

Overall the impact on the mean BCRs is again relatively minor, largely due to the fact that more frequent invasions increase the costs of both pre-emptive and reactive control. The BCR of Scenario 1 is affected in a positive manner, because in this case the more frequent invasions also mean that the beetle is able to spread more, hence resulting in greater costs. The impact on the BCR of Scenario 2, however, is negative in the sense that the higher the invasion probability, the less economically viable protection becomes. This is likely to be due to the fact that in this case, the spread is slower and the impact on protection costs is thus greater than the impact on reactive control costs.

The impact of invasion probability on present value mean costs of the policies is in fact fairly sizable and approximately proportionate to the change in the invasion probability. Note also that even a 50% reduction in invasion probability (meaning that there would be an invasion on average every six years) still results in a BCR of about 1.2:1 under both scenarios. Hence the fact that invasions come very seldom is not automatically a valid argument for abandoning protection.

Spread multiplier

Figure 37 presents the impact of different levels of logistic spread multiplier on the mean BCRs.

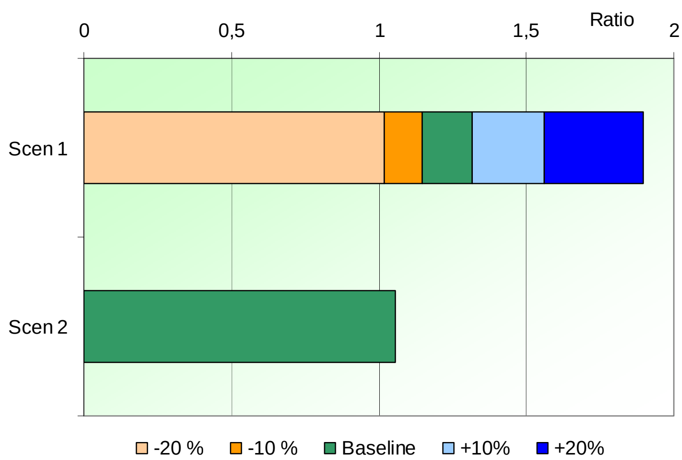

Figure 37. Mean benefit-cost ratios with different levels of logistic spread multiplier.

It is evident that even fairly small changes (10%) in the logistic spread rate can have a relatively large impact on the mean BCR in Scenario 1. Note that Scenario 2 is unaffected by changes in logistic spread, as it assumes linear spread. A 20% increase in the logistic spread rate already increases the BCR under Scenario 1 such that it is close to 2:1.

Given that the eventual spread of the beetle is affected to a large extent by winter survival and (logistic) spread multiplier, and that both of these have now been found to be very important from the policy analysis point of view, it is worth asking to what extent we can rely on the current estimates of the variable values. The answer is, frankly, we do not know. We have very little, if any, data available on the levels of winter survival or spread rate in Finland for the beetle, and hence there is a great deal of uncertainty involved. The best approach in this case is probably to present the results with a range of outcomes and let the decision on how much risk we are willing to accept be made by those who decide on the policy in the first place.

Reactive control cost

Figure 38 presents the impact of different levels of reactive control cost on mean present value costs and mean BCRs. Note that the smallest unit of change is 50% in this case. Note also that the cost of pre-emptive control is naturally unaffected.

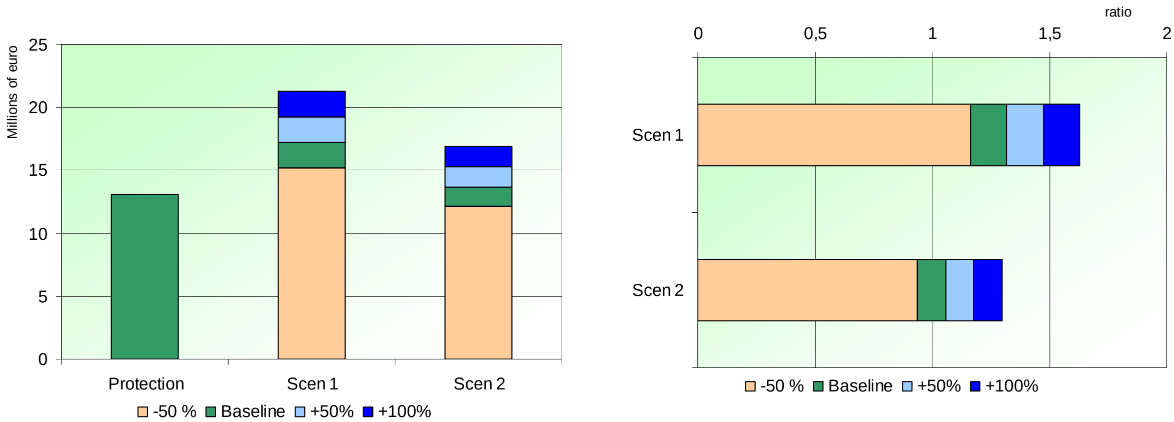

Figure 38. Mean costs and benefit-cost ratios with different levels of reactive control costs.

As can be seen from the figures, the resulting changes in either present value mean costs or mean BCRs are fairly insignificant, even when reactive control cost is increased by 100%. This is primarily due to reactive control cost representing fairly small proportion of total policy costs. Thus whether the reactive control cost is 50 euro per hectare or 200 euro per hectare has little relevance from the policy perspective.

Having said that, it can be noted that a 50% reduction in reactive control cost reduces the mean BCR under Scenario 2 such that its value becomes less than one and reactive control becomes on average profitable under Scenario 2.

Fixed protection costs

Figure 39 presents the impact of a 50% change in the fixed costs of protection on mean present value costs and mean BCRs. Naturally the costs of reactive control under both Scenarios remain unchanged.

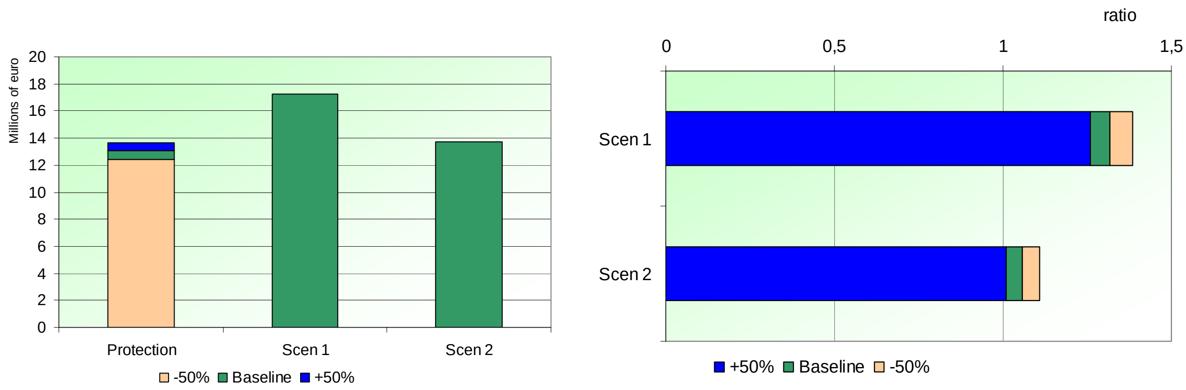

Figure 39. Mean costs and benefit-cost ratios with different levels of fixed protection costs.

As can be seen, the impact of fixed protection costs on both the mean present value costs and the mean BCRs is practically insignificant. This is largely due to the fact that fixed costs do after all present only a very small fraction of the total costs.

The implication is that even if the 38,000 euro or so that is annually spent on maintaining the protection system is in some sense a significant amount of money, it makes no practical relevance for the profitability of the protection system. It is the other types of costs involved that are much more significant. It also implies that by saving on the fixed costs it is not possible to change the optimal policy. Naturally the fixed costs should be efficiently used, but from the policy choice point of view they have little relevance.

Variable protection costs

Figure 40 presents the impact of a 50% change in the variable costs of protection on mean present value costs and mean BCRs. Again, the costs of reactive control under both Scenarios remain naturally unchanged.

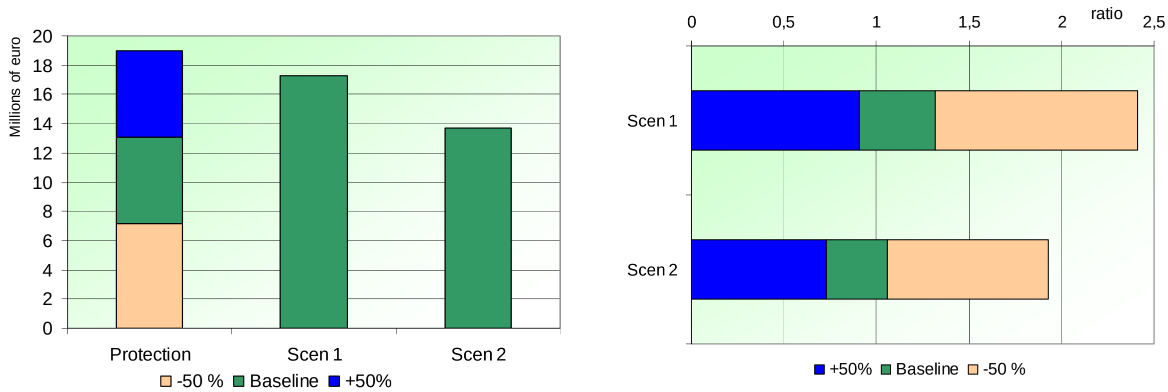

Figure 40. Mean costs and benefit-cost ratios with different levels of variable protection costs.

Although the change itself is also fairly large (50%), it is interesting to note that the mean BCRs are altered quite significantly with the change. For instance, both scenarios produce mean BCRs higher than 1.9:1 when the variable costs are increased by 50%, whereas both give ratios of less than 1:1 when the variable costs are decreased by 50%.

The impact of variable protection costs on the present value mean costs of the policies is proportionate to the change in the costs, but the impact on the mean BCRs is clearly greater. Together with the results of the previous section on fixed costs, this implies clearly that it is the variable costs of the protection system rather than the fixed costs that are important from the point of view of economic viability of the policies.

Overall sensitivity of the variables

The sensitivity analysis was conducted for a wide range of values and only the main results were discussed above. For instance the sensitivity analysis of the linear spread rate and the initial year spread multiplier were not presented due to the fact that they were found to be insignificant. Other fairly insignificant variables include the reactive control cost and the fixed costs of the protection system. The variables that were found to be significant include winter survival, logistic spread rate and the variable cost of protection. The impacts of the seven variables discussed above are presented in Table 20.

	Damage	Winter survival	Invasion probability	Spread	Reactive control cost	Protection, fixed cost	Protection, variable cost
Mean cost							
Protection	0.00	0.13-0.15	0.91	0.00	0.00	0.09	0.91
Scenario 1	0.64-0.72	1.32-2.57	0.94-0.98	1.13-2.18	0.23	0.00	0.00
Scenario 2	0.64-0.72	0.80-1.00	0.69-0.73	0.00	0.23	0.00	0.00
BCR							
Scenario 1	0.64-0.72	1.22-2.37	0.02-0.16	1.13-2.19	0.23	-0.09-0.10	-0.62-1.65
Scenario 2	0.64-0.72	0.69-0.84	-0.12-0.34	0.00	0.23	-0.09-0.10	-0.62-1.65

Table 20. The sensitivity analysis 'elasticity' values.

The figures in Table 20 are a type of elasticities, indicating by how much the mean present value costs and the mean BCRs change given a change in the column variable. For instance, a figure of 1.32 means that a one per cent increase in winter survival will increase the mean present value costs by 1.32%. A figure greater than one hence implies that change in the column variable changes the mean costs or the mean BCR in percentage terms by more than the change in the variable itself is. Thus the higher the figure is, the greater is its impact on the outcome. The range of values given for some variables is due to different elasticities arising from changes of different sizes in the column variable.

The table confirms the visual observation that winter survival is an important variable especially under Scenario 1, in terms of both mean costs (elasticity 1.32-2.57) and the mean BCR (elasticity 1.22-2.37). Similarly logistic spread rate is important (elasticity 1.13-2.19) for both costs and the BCR. The impact of variable costs of protection is large on the mean BCR (maximum elasticity of -1.65) but somewhat smaller on the mean costs (0.91). In the other end, the insignificant values include the reactive control cost (maximum elasticity of 0.23) and the fixed cost of protection (maximum elasticity of 0.10). For instance, a 10% increase in the fixed costs of protection changes the mean cost of protection policy by 0.9% and the mean BCR by a maximum of -1.0%.

5.7.3 Change through trends

In the basic results all the trends were simultaneously either off, slow or rapid. In the sensitivity section, all the trends were set at slow. In this section the trends are analysed separately, as presented in Table 21. The four categories of change are i) domestic change; ii) regional change; iii) local and regional change; and iv) development of pesticide resistance.

Name of the trend	**Trend 1 (winter survival)**	**Trend 2 (invasion pressure)**	**Trend 3 (pesticide resistance)**
No trends	no	no	no
All trends, slow (base)	slow	slow	slow
All trends, rapid	rapid	rapid	rapid
Domestic climatic change, slow	slow	no	no
Domestic climatic change, rapid	rapid	no	no
Regional change, slow	no	slow	no
Regional change, rapid	no	rapid	no
Regional and domestic climatic change, slow	slow	slow	no
Regional and domestic climatic change, rapid	rapid	rapid	no
Increasing pesticide resistance, slow	no	no	slow
Increasing pesticide resistance, rapid	no	no	rapid

Table 21. Simulation runs of the different trends.

The impacts of the different trends on the mean BCRs and the mean present value costs of the policies are presented in Figure 41 through Figure 44.

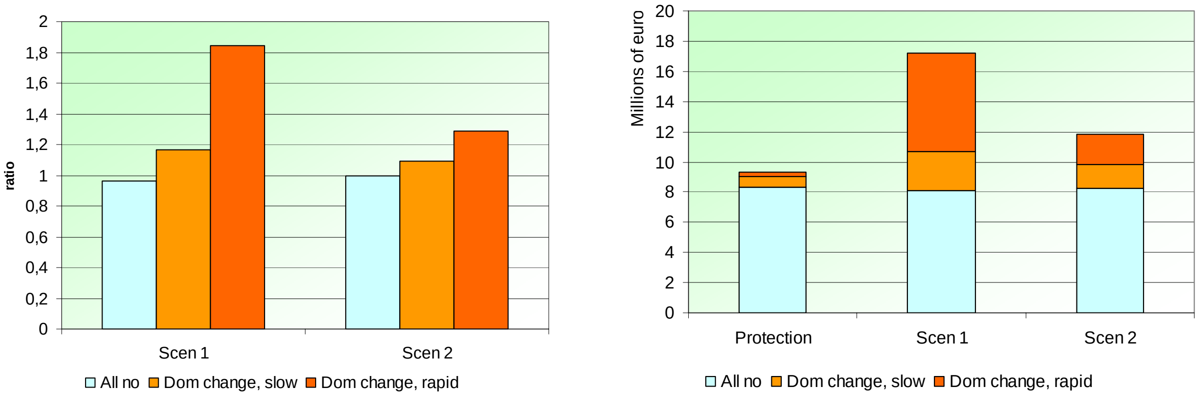

Figure 41. Mean benefit-cost ratios and mean present value costs with domestic change.

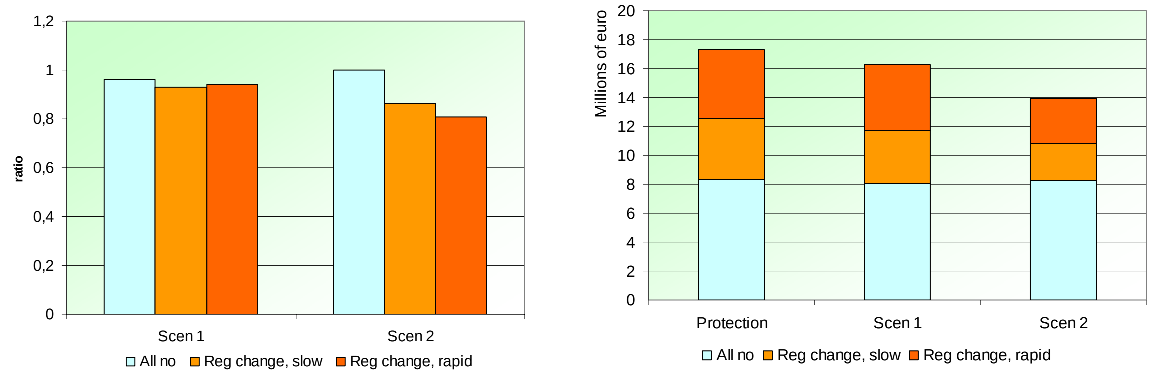

Figure 42. Mean benefit-cost ratios and mean present value costs with regional change.

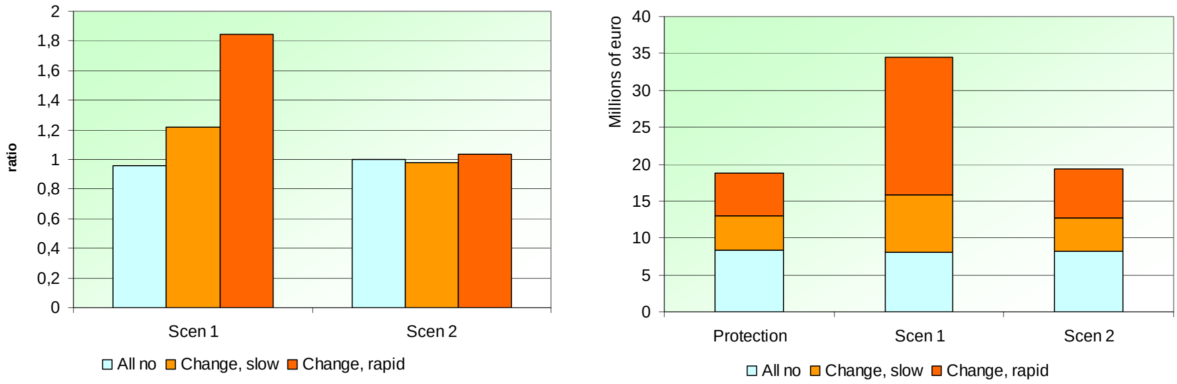

Figure 43. Mean benefit-cost ratios and mean present value costs with domestic and regional change.

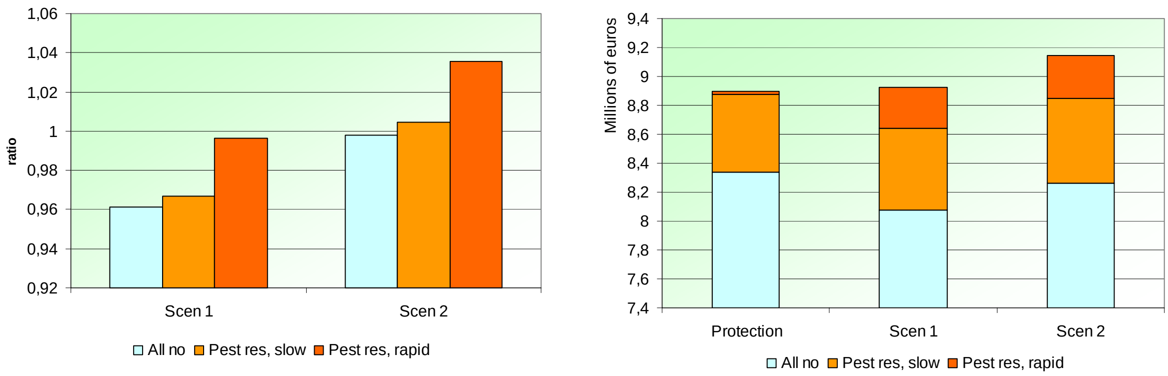

Figure 44. Mean benefit-cost ratios and mean present value costs with increasing pesticide resistance.

On basis of the above graphs, domestic change is the most important trend that has been specified here. It has a fairly substantial effect on the mean costs of reactive control as well as on the BCRs. This is consistent with the results of the standard sensitivity analysis, where it was found out that winter survival is the single most important variable, and it is that same variable that is increasing in domestic change but not in any other separate trend.

Regional change (the impact of increasing invasion probability and magnitude) plays a role in increasing the mean present value costs of both policies, but not so much on the relative profitability of different policies (BCRs). In fact, the BCR of protection is even decreased under Scenario 2 with regional change. This is likely to be due to the fact that at high frequencies of invasion, but in a situation where the pest has not had an opportunity to spread yet under reactive control (winter survival remains unaffected at the fairly low level of 30%), the variable costs of protection are higher than the reactive control costs. Hence the protection strategy becomes more expensive in this case.

The impact of domestic and regional change combined is similar to the impacts of domestic change, only that the magnitude of changes is somewhat increased because now also regional change takes place. In fact, under rapid change the mean costs and mean BCR are increased quite a lot compared to domestic change alone. This is because there are now two effects at play: there are more beetles coming in annually and more of them also survive the winter in proportional terms.

Increasing pesticide resistance is seen to play only a minor role, both in terms of impacts on BCRs as well as on the mean present value costs. This of course may simply be due to the fact that the trend has been specified to be too weak, but it is also plausible that the increase in control costs is relatively insignificant when compared to the other policy costs incurred. Again, this result is consistent with earlier finding that the reactive control cost is fairly insignificant and can be increased by 50% without any real influence on the results. Whether its value has been set too low in the analysis is a point of discussion.

Finally, it must be emphasised that the functional form and the magnitude of the trends analysed are not based on hard and solid science. The trends themselves are plausible and likely in the future, but the actual values they take are subject to much scientific uncertainty.

5.7.4 Intertemporal and intratemporal issues

It is finally worth spending a moment discussing the issue of to whom the policy costs accrue in the society. This section discusses both intertemporal and intratemporal costs.

Intertemporal issues include questions such as how costs are distributed among years, what is the impact of the discount rate, and whether we should be concerned about large initial investment at the present time or large costs later on. There are two types of so-called option value impacts with contradictory implications involved (Heal and Kriström 2002). First, by waiting and not acting now, we could get more information about the true impacts of local or regional changes, for instance that they might be smaller than initially expected. Thus we could formulate better policy later on, instead of currently having to invest in expensive prevention. Second, by acting now in a precautionary way and preserving the current conditions we may avoid the irreversibilities that are associated with change in the future, for instance if it is possible that impacts will be greater than initially expected (Heal and Kriström 2002).

Intertemporal costs can be analysed by looking at the annual costs of the policy alternatives, either discounted or not discounted. We show in Figure 45 the annual net benefits of protection (cost of reactive control less the cost of protection) discounted at 2% and given slow change.

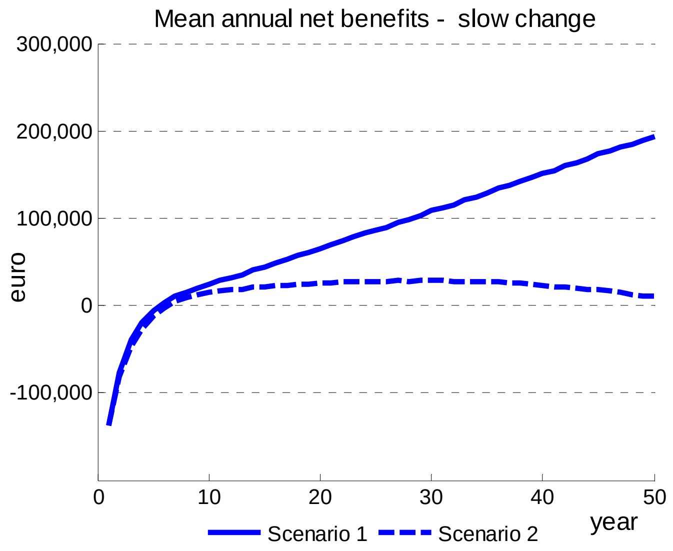

Figure 45. The annual net benefits of protection with slow change.

From the diagram it can be seen that the protected zone can be seen as an investment that may produce negative net benefits in the early years, but given change and the spread of the beetle the discounted net benefits may increase rapidly over time. This is because the benefit of protection, i.e. preventing the spread of the pest, is assumed to take place mainly in later years. This result also helps to put into perspective and confirm the results of the ex-post analysis, which seemed to suggest that the protected zone is not the least-cost policy choice if only the first few years are analysed.

However, the shape of the mean annual net benefit curve depends on out assumptions regarding change, as illustrated in Figure 46. In the event of no change, the net benefits barely become positive and continue hovering at around zero. This is not an inevitable characteristic of no change, but rather results from the fact that the mean invaded area (recall Figure 24) settles at only slightly above zero. This, in turn, is determined primarily by the level of winter survival and the magnitude of spread. Thus, again, the level of winter survival is important – should it be somewhat higher, also the no change area would begin to increase over time and so would the net benefits of protection. This is also consistent with the earlier finding that if there is no change, protection is barely the least-cost policy choice, with a BCR at around 1.00. Hence it is logical that the net benefits are around zero. In contrast, under rapid change the shape of the mean annual net benefit curves is similar to that under slow change, but the increase in the net benefits that ensue in the future is much greater. Under rapid change the larger net benefit of protection thus materialise towards the later years of the analysis.

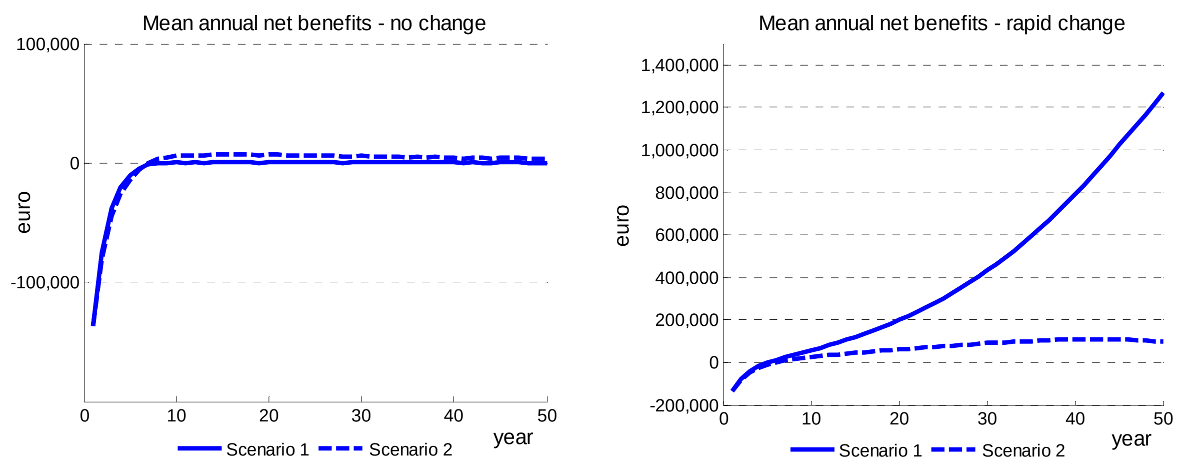

Figure 46. The annual net benefits of protection with no change and rapid change.

Another way to consider to whom the costs accrue intertemporally is to look at the impact of the discount rate on the results. Figure 47 depicts the impact of a ±100% change in the discount rate on the mean BCRs and the maximum present value costs of the policies.

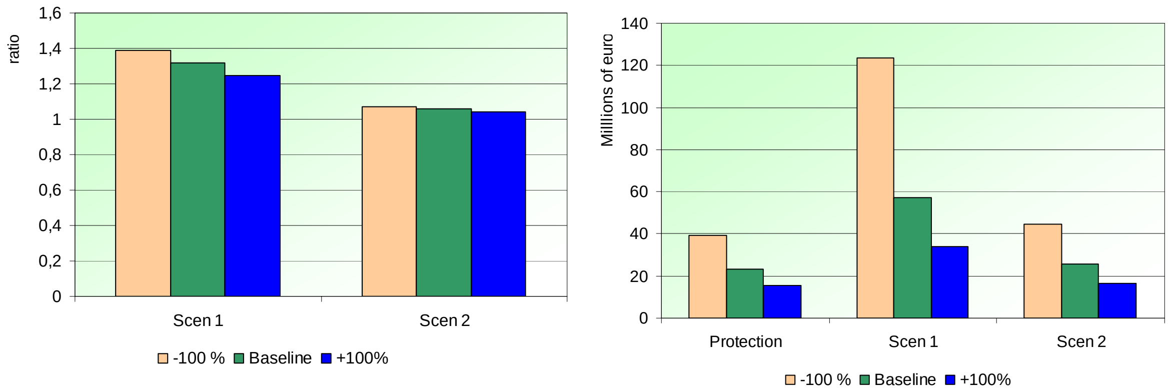

Figure 47. The impact of discount rate on mean benefit-cost ratios and maximum present value costs.

The mean BCRs remain relatively unaffected. This is primarily due to the fact that the discount rate affects the costs in both policies in a fairly equal manner. Of course, if there are large costs later on, then increasing the discount rate makes the present value of these costs smaller, hence favouring reactive control in the present case. This can be seen from the mean BCRs in that increases in the discount rate reduce the BCR – in effect making protection less profitable. The changes, however, are relatively minor.

The maximum present value costs are affected more than the BCRs, which is also expected. The present value maximum cost of Scenario 1 (with slow change) in the baseline case is about 57 million euro. With a 100% reduction in the discount rate (i.e. with no discounting) this cost is over 120 million euro. On the other hand, when discounted at 4%, it is less than 35 million euro. Over such long time scales discounting and the discount rate have a big impact on the policy costs, but at least in the current case have little impact on the BCRs. For this the future generations are probably thankful.

The strategy choice also has effects regarding to whom the costs accrue intratemporally. Possible invasion induced price increases unambiguously lead to losses in consumer surplus, and an invasion would also impact the composition of producers to whom the profits accrue, as discussed earlier in Section 3.1.3. In the case of reactive control, such effects depend on the area invaded (and hence crop losses) and on how the price responds to the invasion. The pre-emptive strategy too has to be funded by some means. If it is the taxpayers that end up paying the bill, they in essence are subsidising the producers.

Further division is between those producers that have been subjected to the invasion and those who have not. Those unaffected may even benefit from the presence of the pest, if the prices increase. However, this benefit may be short-sighted, as also the risk of invasion to these production areas naturally increases. It has to be noted, too, that we have assumed the consumers to carry the full costs of the protection system. It can naturally be the case that the producers have to contribute towards these costs in a way or another. To whom (producers versus consumers/taxpayers) the mean policy costs accrue is depicted in Figure 48.

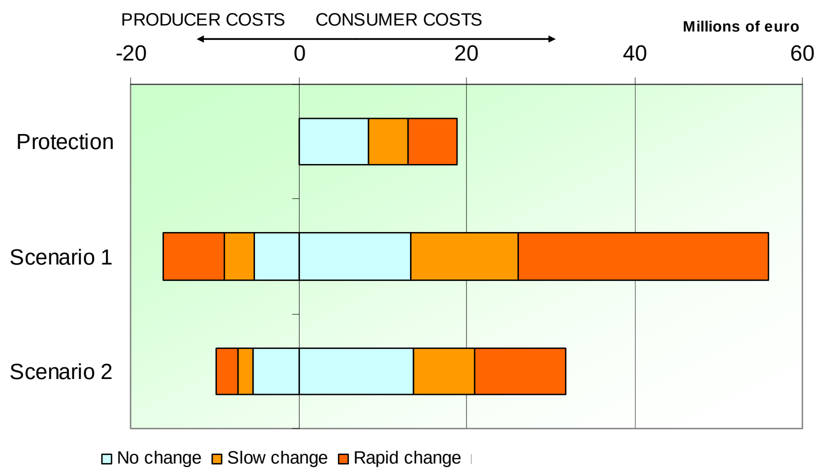

Figure 48. Who bears the policy costs intratemporally.

Figure 48 presents clearly that protection only results in consumer costs. The reactive control scenarios on the other hand result in both consumer costs and producer benefits (negative costs). These benefits accrue to producers on aggregate due to the price response. Of course, each individual producer may either benefit or suffer, depending on whether s/he has been subjected to the invasion and subsequent additional costs or not. In addition, the aggregate benefits of producers are in all cases smaller than the aggregate consumer costs and hence the overall impact is negative. The extent of benefits for the producers is naturally dependent on the price response that is assumed. It is fairly evident that the higher the price increase, the better off the producers on aggregate are under reactive control, whereas for the consumers the situation is the opposite.

The fact that one group on average may benefit from the harmful organism being present may seem odd at first sight, but is a fairly simple result that follows from the market conditions and the price increases. It is worth noting that it depends on two conditions in particular: there cannot be international competition that would prevent the price increase, and the market structure has to be such that consumers are willing to pay more for the goods. The result obtained here is not too unusual: for instance in the analysis of the classical swine fever in the Netherlands a similar result was obtained (Burrell and Mangen 2001; Mangen et al. 2002).

Price changes thus affect the parties to whom the costs and benefits accrue substantially, but they do not have overall policy effects. It should be stressed that whatever the price response, the aggregate policy costs remain unaffected. Hence the overall conclusions in this study are not affected by the assumption regarding the price response for as long as an equal weight is placed on both producers and consumers. We have assumed equal weights for both groups, but in reality the case may be that one of the groups is given more weight in decision making for instance due to stronger lobbying. If this is the case, then the aggregation of policy costs as carried out in this study is no longer appropriate, and the conclusions regarding the optimal policy do not hold. However, hopefully any transfers of income are assigned separately, not as a part of invasive pest policies. The conclusion nonetheless is that whether there is an invasion or not is not the only issue to take into account. It is also important to consider how the market environment responds to the shock and how any counter-measures are to be financed.

6. DISCUSSION

This final section presents some conclusions on basis of the discussion and analysis carried out in this study. The main results and policy implications of the study are discussed first. That is followed by discussion on certain special themes, including i) prevention versus adaptation; ii) issues beyond economic efficiency; and iii) uncertainty and irreversibility. The section concludes by making suggestions towards future research.

As has been seen, IAS are capable for causing significant economic impacts and their management is characterised by the public good properties involved. This thesis has discussed the economic impacts of IAS and the policies used in controlling their dispersal. The specific aim was to evaluate the economic desirability of continuing the CPB protected zone policy in Finland, explicitly accounting for uncertainty and local change in the policy analysis. The answers to the four specific aims posed in the introduction will be summarised below in Section 6.1. These aims were to:

i) review and evaluate the scale, type and magnitude of impacts IAS are capable of causing;
ii) specify the policy problem in IAS management and review how the institutional framework in Finland addresses the issue;
iii) review existing cost-benefit studies on agricultural IAS and determine the components that such studies should include;
iv) undertake an economic risk assessment of the Colorado potato beetle in Finland and evaluate the conditions under which it is optimal to prevent a species from establishing in this particular case.

6.1 The main findings of the study

<u>Topic 1: Scale, type and magnitude of impacts of invasive alien species</u>
Invasive alien species are a global phenomenon. They are found in most geographic locations, in most categories of living organisms and in most ecosystem types. They thus present a threat to biological diversity at all levels and have a negative impact on the goods and services provided by ecosystems (Vitousek et al. 1996). The potential costs caused by IAS are wide-ranging, but can be roughly divided into four categories: control costs, production losses, secondary market effects, and health, environmental, and cultural effects.

The magnitude of the invasion threat can be exemplified by the magnitude of actions in some potential pathways. In Finland, in 2004, non-domestic civil aircraft from abroad carried about nine million passengers and over 120,000 tonnes of cargo and mail, international trains between Russia and Finland carried 252,000 passengers and 15 million tonnes of cargo, harbours received directly from abroad 53 million tonnes of imported international cargo and over eight million passengers, and the internet provides global commercial possibilities for purchasing thousands of plant species and varieties (Finnish Civil Aviation Administration website; Finnish Maritime Administration website; McNeely 2001; VR-Group website). This anecdotal example from a relatively remote country illustrates the huge potential for species and diseases to be spread rapidly around the globe.

Individual studies have been conducted for a range of species under a range of conditions, accounting for a variety of different impacts and using different estimation techniques. Some of these studies in an agricultural setting were summarised in Table 5. The United States is still effectively the only country where a fairly thorough economic study on IAS damages has been conducted at the national level (Pimentel et al. 1999; 2005). The study includes control costs, production losses to animal and plant diseases and pests, and costs of certain human diseases, estimating the annual costs as about US$120 billion. Results from other countries where cost estimates exist for particular sectors or species types, including Australia, Canada, Germany and New Zealand, suggest a similar scope of the issue (Bertram, in Jay et al. 2003; Colautti et al. 2006; Martin 2003; Reinhardt et al. 2003). Aggregate cost estimates as such do not provide guidance on individual management questions, but are useful for pointing out the scale of the issue.

Topic 2: Policy problem in management and the institutional framework

IAS control is a public good of the 'weakest link' type (Perrings et al. 2002) or of the 'weaker link' type (Burnett 2005). It is a public good because it is both non-excludable in production and non-rival in consumption. It is non-excludable because once protection against an invading species is provided, any one member cannot be excluded from enjoying the benefits. If the pest is prevented from invading, nobody can be prevented from enjoying the protection service. Further, it is non-rival because any one member's consumption of protection does not reduce the amount of protection enjoyed by others. Because of these two properties it is difficult to charge a price from consumers of the protection service, and hence public goods are typically under-provided by the free market.

Moreover, protection against IAS is of the 'weakest link' type because its effectiveness depends on the weakest link in the protection chain. It does not matter how well other parts of the chain provide protection if the species gets into the country through the weakest control point. Instead of a weakest link issue, Burnett (2005) has described IAS protection as a weaker link public good. In this case the investment of those who invest more on protection is negatively affected by those who invest less, but those who invest more are still better protected against IAS than those who invest less (Burnett 2005).

Nonetheless, the public good property partly explains the need for the involvement of the state in protection. To manage a weakest (or weaker) link problem related to IAS, Perrings et al. (2002; 2000) suggest the following policy responses: i) an appropriate regulatory regime; ii) an appropriate set of property rights with supporting institutions; iii) a compensation mechanism; and iv) a structure of incentives and disincentives. Let us review how the legislation in force in Finland (as discussed in Section 2.3) performs given these four criteria.

1. An appropriate regulatory regime: The regulatory regime consists primarily of Council Directives 2000/29/EC and 92/43/EEC, Council Regulation 338/97, Act on the Protection of Plant Health, the Nature Conservation Act and their supporting institutions. The established authority dealing with plant health protection in Finland is the Plant Production Inspection Centre (KTTK). Its responsibilities and rights are set out in a fairly specific manner in the Act on the Protection of Plant Health, including the right – in face of an immediate threat – to act without a prior permission by the Ministry, as well as the right for executive assistance in policy implementation. Systems using a list of prohibited species (black list) often suffer from the major weakness of such lists being too rigid to be updated effectively. The fact that legislation allows the authorities to target also species outside these lists is a welcome improvement.

Provided that the weaknesses of using a black list system can be overcome to a satisfactory extent, the regime seems adequate for purposes of protecting health of productive plants. It also seems to function properly in Finland, at least in the potato sector (European Commission 2002). The recent actions against the CPB have in addition raised the knowledge capacity of the KTTK, and it seems that they are now better equipped also against other invasive plant pests.[44]

However, for protecting the health of natural ecosystems the system may not be sufficient. Council Directive 92/43/EEC allows prevention of an introduction as an option if the member states consider it necessary but does not require it in any way. The national Nature Conservation Act is more designed to deal with conservation of existing endangered species and habitats than with the threat posed by IAS. Moreover, it emphasises that there has to be cause or reasonable cause to suspect that a species may be harmful to native species. Plant introductions are still allowed in gardens and fields and for silvicultural purposes also outside these areas. Thus the implication is that nature can be protected provided that doing so does not compromise economic production possibilities. There is nothing intrinsically wrong with this principle, but the problem is that there is no system or resources for

[44] Hannu Kukkonen, Head of the Plant Protection Department at KTTK, verbal communication.

assessing whether such an introduction is economically viable when the possible impacts on ecosystem health are properly accounted for.

Another point to make is that although the powers and responsibilities for protecting the health of productive plants are clearly given to the KTTK under the Ministry of Agriculture and Forestry, the wider picture of IAS management and control is distributed in a vague manner among many different actors. These include, among other actors, the Ministry of Agriculture and Forestry, the Ministry of the Environment, the Ministry of the Interior (customs and border control), the Ministry for Foreign Affairs (foreign commerce) and the Ministry of Transport and Communications (control of airplanes, trains and ships). The result is that no single body is responsible for a coordinated response to manage all the invasive alien species in all the invasion pathways that there exists. The same argument applies to the wider issue of managing biosecurity in general.

2. An appropriate set of property rights with supporting institutions: If there existed property rights to pest-free production, the market might solve the IAS problem altogether. Given appropriate property rights the neighbours of a producer with IAS on his fields could in theory be given the right to sue for compensation if the species spread to their fields. There has been recent interest in for instance South Africa for applying such a property rights regime (Perrings et al. 2002).

Despite this, such property rights would be very difficult to implement under the conditions discussed in this study (e.g. spread primarily through winds rather than with commercial activity). One system that has been suggested for species that spread through clear pathways is a special invasion fund or compulsory insurance that the firms associated with the risky sector or pathway need to invest in. In case of an invasion, the ensuing eradication costs would be paid from the fund or the collected insurance payments. If the parties involved make investments that would reduce the risk of an invasion through their activities, part of their investment could be returned or their insurance payments reduced. The risks and probabilities involved may however be so unknown that private sector insurers may not be interested in setting up the system, implying that the state would still need to be actively involved in setting up the system.

Given the Finnish legislation with regard to productive plant health, there seems to be no immediate reason to implement such a system. In the case of the Colorado potato beetle that spreads mainly by natural means such a system would be, as mentioned, difficult to execute in practice. For species spreading primarily by means of tourism or trade the approach might be much more attractive.

3. A compensation mechanism: Compensation from those who gain from the activity that spreads an IAS to those who lose as a result of the introduction is not applicable to the current case. This has again to do with the spread medium discussed above. As for other types of compensation, the Act on the Protection of Plant Health allows compensation to be paid to producers for costs incurred in eradication procedures. Such compensation makes the system more effective in that more agents are involved and committed to eradication. However, it is also worth remembering the point made by Butler and Maher (1986), who argued that if compensation is paid to the victims of an externality, it should not be based on uncorrected marginal damages, as this would induce the victims to undertake too little control.

In the case of the Colorado potato beetle in Finland the state has covered the costs involved in counter-measures together with the value of the lost crop. Whether the system functions flawlessly in practice and all the losses are actually compensated for in a timely fashion is a matter that cannot be established on a theoretical basis. The compensation payments have so far been fairly small – a total of about 74,000e in the period 1998−2003, the vast majority of them incurring in 2002 and 2003. At the Community level, Council Directive 2000/29/EC allows also national compensation to be paid. However, the condition of spread through commerce prevents Finland from applying for funding for the expenses incurred in fighting the Colorado potato beetle. In addition, there is no system to compensate individual actors (or for that matter anybody else) for actions taken against IAS that are harmful to the environment – it is only agents growing productive plants that are compensated.

<u>4. A structure of incentives and disincentives</u>: The compensation mechanism discussed above is part of the incentive mechanism of the existing legislation. Another incentive that is executed is education. Compliance with law is promoted by informing the producers and the public about the threat presented by particular IAS and the benefits to different actors from co-operating with the appropriate authorities. Again, this applies mainly to pests of plant production.

On the disincentive side, there are penalties for not abiding by the regulations. First of all, the producers have an obligation to inform the authorities in case they find on their fields any of the quarantine pests that Finland has a protected zone for. Second, the eradication and other measures ordered by the Plant Production Inspection Centre need to be followed by individual producers. This again is strictly controlled only in the case of productive plants and their pests. Also the Nature Conservation Act carries penalties if it is breached, but the regulations are so loose for IAS that it may be doubted whether anyone will ever be held legally liable on their basis.

Thus, overall it seems that the European Union and the Finnish systems perform satisfactorily according to these four criteria. However, this is primarily the case for species that threaten economic systems directly, i.e. through the production process of for instance food or timber. Species that may be harmful to ecosystem dynamics and impact on the economic systems indirectly through various interlinkages are much less regulated and controlled by the existing legislation, even though their impact may be much greater than that of directly production damaging IAS. A small but hopeful move is the new Act on the Protection of Plant Health, where a pest is defined as a species that may impact on productive plants either directly or indirectly.[45]

Overall the case seems to be the same as in New Zealand (Jay et al. 2003)[46] and the United States, where according to a report by the Environmental Law Institute (Filbey et al. 2002):

> "[C]urrent federal law offers limited protection from this menacing problem. Multiple federal laws and programs address invasive species in a fragmented manner and primarily focus on the impacts to our natural resource-based industries, particularly agriculture; thus, they fail to adequately cover invasive species that cause widespread damage to our natural areas."

Tomminen (2000), of the Finnish Plant Production Inspection Centre, echoes this:

> "[T]he main objective of plant inspection is to prevent new harmful pests and diseases of plants in horticulture, agriculture and forestry from spreading into Finland … the problem, therefore, is approached almost purely from the economical and anthropocentric point of view. There is little attention paid to whether an accidentally or intentionally introduced new organism will replace a native one, for instance."

In conclusion, invasions by species that cause agri-, horti- or silvicultural damage – including the Colorado potato beetle – seem to be fairly well covered by the policy framework, whereas the case is not so for the species that cause mainly ecological damage. The case is all the more so now that the more powerful Act on the Protection of Plant Health has replaced the old Plant Protection Act. The future challenge lies in considering the whole issue of invasive alien species and diseases in a biosecurity framework. Within this framework, the issue would be managed in an integrated fashion from the point of view of multiple threats, multiple pathways, multiple parties involved and multiple methods and stages of control. In doing so, the potential negative impacts on international commerce need to be borne in mind. Transparency and scientific basis of the protective measures are important, and even then, as pointed out by Margolis et al. (2005), the information requirements to differentiate legitimate public good protection from disguised protection may be substantial. Therefore, many challenges lie ahead in planning a functioning institutional framework to deal with the issue.

[45] For species that have the potential to cause harm to human health a different set of regulation applies. This aspect is left out from the scope of this study. It is worthwhile noting, however, that also these species and diseases are integrally related to the larger biosecurity framework in which matters should be considered.

[46] However, at this point it has to be noted that the procedures in New Zealand are almost from another planet when compared to the Finnish regulation. Despite the much stricter procedures, the main weaknesses seem to be the same.

Topic 3: Economic studies on invasive alien species and their key components

In Section 3.4 several cost-benefit studies on invasive species were reviewed. Let us summarise some key points regarding these analyses of (agricultural) IAS. First of all, the policy alternatives evaluated are often simply undertaking some policy versus not undertaking it. The most common analysis seems to be between the current protective policy versus abandoning it. Wider policy options are generally either not available or not analysed. This is the case also in the analysis conducted in this study.

Second, it is often only the direct, easily monetised costs that are included in the quantitative analysis. Costs that are more difficult to analyse are often ignored altogether, even though in the cases where they are included they turn out to be extremely important. In this study, although we exclude some cost categories that are difficult to monetise, we discuss those impacts qualitatively and highlight the relative importance or non-importance of each.

Third, sensitivity analyses are mostly very inadequate, if conducted at all. As discussed before, this is surprising considering the magnitude of uncertainties involved. In this study we attempted to include some of the uncertainty involved through stochastic analysis and through a fairly extensive sensitivity analysis. Of course, undertaking such an analysis and interpreting the results takes some time and effort, but given the additional information that can be retrieved from a sensitivity analysis, we find it to be an integral part of any cost-benefit assessment.

Two further observations from published cost-benefit assessments deal with their authors and their applicability. It is possible to replicate IAS cost-benefit analyses elsewhere in the world. Of course, the particular local circumstances and availability of data need to be taken into account, and the study modified accordingly. Further, in the case of developing countries issues related to development need to be included in the assessment. However, the main point is that once a proper assessment has been undertaken, it may be used as a basis or valuable starting point for studies elsewhere. Finally, in many cases IAS cost-benefit studies are not written by economists or published in economic journals. It generally seems to be the case that ecologists and biologists are more interested in undertaking such studies than economists.[47]

Born et al. (2005) review economic evaluations of invasions. Their main conclusions on studies that they reviewed are as follows: i) studies mostly have methodological shortcomings; ii) assessments are mostly ex-post rather than ex-ante; iii) prevention is hardly reflected in the analyses; and iv) uncertainty is insufficiently addressed. They conclude that most studies "focus on ex-post evaluation, on control measures, on few countries, on agriculture, and on use values" (Born et al. 2005). Many of their points sound rather similar to the observations made above and elsewhere in this study, although the 23 studies they discuss are primarily different from the studies reviewed in this paper.

On basis of these considerations, we would suggest the following ten points to be taken into account when conducting economic policy evaluations of invasive alien species:

- i) Choose a minimum of two realistic policy options to evaluate.
- ii) Consider all the possible direct and indirect impacts, monetise the ones you can and take the others into account qualitatively.
- iii) Describe in detail which costs and whose costs are included in the analysis and how they are derived.
- iv) If possible, formalise the basis of your analysis.
- v) Undertake an ex-ante analysis to supplement an optional ex-post analysis.
- vi) Carry out a sufficient sensitivity and uncertainty analysis.
- vii) Consider how the impacts excluded from the quantitative analysis affect the results.
- viii) Discuss to whom the costs and benefits accrue in time and between different agents.
- ix) Make a (conditional) policy recommendation.
- x) Relate your findings to the wider framework of biosecurity measures.

[47] This is merely an observation, not a critique.

Topic 4: Economic risk assessment of Colorado potato beetle in Finland

The current study used a basic cost-benefit framework to assess the economic profitability of two alternative Colorado potato beetle management policies. The expected costs of prevention were compared to the expected costs that could ensue in an alternative policy strategy in which the species is allowed into the country. The primary focus was on ex-ante analysis and an ex-post assessment was conducted for purposes of model validation.

The Colorado potato beetle is a typical wide-spread plant pest and a nuisance in North America, Europe and to an increasing extent in Asia, affecting productivity of an important food crop. Hence it is of general interest worldwide. In terms of the European Union, the case is of specific interest as protected zones are an EU-wide instrument that has been designed for protecting plant production. In Finland the case is of interest because potato is a relatively important national food crop. Furthermore, the CPB provides a convenient case for studying the effects of invasions, uncertainty and local change in fairly manageable circumstances with some data on invasions available and relatively few externalities present. Given the life history characteristics of the CPB, there are five important factors to take into account from an economic point of view. First, the beetle has spread very rapidly across the continent, although its spread has slowed down as it has approached its ecological limits. Second, in propitious environmental conditions its population size can increase extremely rapidly. Third, it is capable of causing significant damage to potato plants. Fourth, cold summers and winters present an obstacle to its establishment, but it is assumed to be capable of establishing in at least some parts of Finland. Finally, lack of natural predators and ability to develop resistance to chemical control substances make the beetle difficult and expensive to control.

This study has concentrated primarily on direct costs and benefits of protection versus reactive control. The main lesson from the ex-post cost-benefit analysis is that it is not sufficient to look at the costs over only a short period of time. Protection against invasive pests is to a large extent an investment for the future – an investment that may produce potentially very high revenues in terms of avoided costs in the future. Short-sighted analysis of the past few years does not provide a truthful description of the economic performance of such systems.

The general results of the ex-ante cost-benefit analysis carried out in this study indicate that the current policy based on a protection system is economically viable, provided that there will be some future change and a non-insignificant level of winter survival of the pest population. These are the most important determinants of the economic profitability, together with the subsequent spread of the beetle population in Finland. For instance, even a 50% reduction in the invasion probability (implying an invasion on average every six years) still results in a benefit-cost ratio of about 1.2:1 under both spread Scenarios. Hence the fact that invasions come very seldom is not automatically a valid argument for abandoning protection. Similarly, the amount of fixed costs spent annually on maintaining the protection system makes no practical relevance for the profitability of the protection system. The other types of costs involved are much more significant. On the other hand, the impact of variable protection costs on the present value mean costs of the policies is proportionate to the change in the costs, but the impact on the mean benefit-cost ratios is clearly greater. Together these findings imply that it is the variable costs of the protection system rather than the fixed costs that are important from the policy profitability point of view.

Altogether, under the conditions and assumptions of this study, we can give up the CPB protection system if we are certain that there is no future change, winter survival of the pest population stays permanently below about 20% or potato crop losses will not exceed 5% of the yield under any circumstances. If we cannot be certain that one of these three conditions materialises, we should be cautious regarding the possibility of abandoning protection. This is because the risk associated with giving up protection is much larger than that associated with protection. At the extreme, the cost of giving up protection may be nearly thirty times greater than continuing with it. The cumulative distribution functions of net benefits of protection presented in Figure 29 can be used for determining the optimal policies given different levels of risk that we are willing to take.

It is also good to bear in mind the discussion on possible costs of the CPB that were not included in the quantitative assessment. On basis of these it can be concluded that because the health, environmental and cultural costs are all likely to be larger under the reactive control policy, the conclusions of the quantitative assessment remain unchanged in qualitative terms: in other words, because pre-emptive control is already the preferred policy from an economic point of view, excluding the health, environmental and cultural costs from the analysis does not change this conclusion. As for the secondary (international) market effects that were also excluded, it is difficult to say whether they would influence the results of the quantitative analysis in this particular case.

Finally, as the sensitivity analysis suggested that the winter survival, the logistic spread rate and the variable cost of protection are the most important variables in determining economic profitability, it is these variables that acquiring more accurate information regarding their true values would be most beneficial. However, regardless of the uncertainty involved, the aggregate results of the study undertaken suggest that the current policy of CPB exclusion should be continued.

6.2 Issues to consider

On prevention versus reactive control

A priori, at least five factors that affect the relative effectiveness of pre-emptive versus reactive control in the present case can be distinguished. First, the existing environmental conditions and their likely future development are important in determining how likely the species is to invade, establish and spread in all seasonal conditions. Second, the invasion pathways are important. If there are clear pathways for dispersal, preventative actions can be targeted at key sites. If, on the other hand, for instance the wind is the primary means of dispersal, prevention of establishment rather than entry becomes important.

Third, whether the species threatens the production environment or natural environment matters. For instance agricultural producers are used to regulations and relatively reliably undertake preventative measures as required. The case is different in natural ecosystems where such actors are difficult to identify, let alone mobilise. Also different legislation applies to the two environments. Fourth, the production structure matters. Professional producers can be expected to act according to regulations to protect their businesses, whereas habitual producers who produce only for enjoyment or possibly own consumption may be more difficult to educate and persuade to comply. Fifth, whether the actions are taken in a co-ordinated or decentralised manner affects their efficiency in reaching the desired targets. These five factors are likely to impact on pre-emptive and reactive control in an asymmetric fashion, and thus also affect the economic viability of the two policies.

The guiding principles of the Biodiversity Convention's Subsidiary Body on Scientific, Technical and Technological Advice emphasise that primary attention should be given to preventing IAS introductions (Perrault and Carroll Muffett 2001). In most economic assessments it has also been found to be the more cost-effective policy, although not without exceptions as discussed earlier in this study. Furthermore, there are trade-off situations in prevention in two respects. First, more resources spent on pre-emptive control means on one hand that protection becomes more preferable (as it becomes more effective), but on the other hand that it becomes less preferable (as it gets more expensive). Thus there is likely to be a point beyond which no more prevention should be provided. The second trade-off is that the more protection there is, the more better-off the society is in the sense that invasion and establishment are less likely, but the less well-off it is in the sense that international commerce and its benefits are restricted to a greater degree. Policies dealing with a public good issue such as the present one have to account for such trade-off problems.

With limited resources it is very difficult to make any system perfect even if we wanted to. Surkov et al. (2005) suggest that in the face of resource limitations it would be economically sensible to switch resources from inspecting more pathways to inspecting fewer, specific, pathways. In the current case this could be adapted to mean that resources should be switched to defining and concentrating on special high-risk areas. Even if the limited resources mean that the protection system might not succeed in keeping the pest out of the country, it could still reduce the impact of the invasion by for instance delaying it within the season such that the resulting damages are reduced.

In practice, reactive control may be preferred over pre-emptive control because of uncertainty. The relationship between resources invested in pre-emptive control and benefits thus acquired is very uncertain. It may be tempting to avoid such expenditures and focus on reactive control when needed, as reactive control actions often involve somewhat less uncertainty. Hence reactive control may appear as the less risky management strategy, even if it often is also the more expensive one (Finnoff et al. (2006), see also Shogren (2000) and Perrings (2005)).

The main point argued here is that it is the circumstances that make one strategy preferred over another – not that some strategy is automatically preferred in all circumstances. As argued by Smith et al. (1999), under certain circumstances the society could be better off concentrating on controlling and eradicating casual and naturalised species rather than trying to predict the pest status at the import stage. As was demonstrated in the case study analysis, it is not impossible to find plausible variable values that favour reactive control instead of protection in the case of CPB in Finland. Moreover, as argued by Sharov and Liebhold (1998) and Sharov (2004), policy switch from eradication to slowing the spread is in certain conditions an economically efficient choice.

It is also possible that the protection system is preferred even when reactive control appears to be the cost-minimising strategy. As mentioned earlier, Olson and Roy (2002) point out that if the discounted expected invasion growth rate is greater than one, it is optimal to eradicate small invasions even if the marginal costs of control are large relative to the marginal damages. This is because this way a rapid growth in costs in the future can be avoided. This once again highlights the fallacy of relying extensively on a limited ex-post analysis.

One policy strategy may be preferred over another despite the results of a quantitative cost-benefit analysis also when all the costs and benefits that matter are not included in the assessment. For instance, if environmental or health impacts are potentially sizable but difficult to monetise and hence excluded from the analysis, a policy decision opposite to the one favoured by the cost-benefit analysis may be taken. Similarly, one ‘benefit’ of the protection system that most probably would not be included in any assessment is the (unjustified) enhanced protection of domestic production from import competition. Nonetheless, such factors may still influence the policy making process. The key point here is that cost-benefit analysis is one tool that can be used to assess the economic viability of different policy alternatives. It is not an automated decision machine.

Beyond economic efficiency

The analysis undertaken in this study is primarily concerned with economic efficiency of the two alternative policies. Furthermore, the assessment concentrates on direct benefits, with some discussion on indirect effects and on to whom the costs and benefit accrue intertemporally and intratemporally. In a complete analysis indirect costs and benefits, effectiveness of institutions and social justice issues need more attention. For instance, there are likely to be differences between co-ordinated protection system where the state can plan the policy accurately and decentralised decision making by numerous independent farmers who have varying objective functions. The differences may materialise through indirect effects such as development of pesticide resistance in the target species or loss of export possibilities in other markets.

Regardless of the policy chosen, it can be argued that because of the public good properties the state should be involved at some level. The contribution may not necessarily be through direct financial support, but could be for instance through education, expert advice and research and development. This way the state can impact on the effectiveness of reactive control without getting actively involved itself. Society supported control can also be thought of as a means of distributing the economic impact of the pest from the producers to the society. This study has throughout dealt with unsupported reactive control.

Barbier and Shogren (2004) pointed out that it is unlikely that a decentralised economy produces the socially optimal level of self-protection by households against IAS. The analysis conducted in this study cannot completely differentiate whether it is the type of policy (pre-emptive control vs. reactive control) or the exact form of management (organised joint protection vs. decentralised farm level control) that is the key factor in favouring one policy strategy over another. However, in principle the timing of the policy (before or after the invasion) is independent of the execution (joint or decentralised). Hence the analysis conducted in this study is dependent on the exact policy environment as well as on the characteristics of the natural environment. Whether such effects need to be separated depends on the question we want to answer. In this study the aim has been to assess the economic viability of the two policy strategies as they exist and thus their constituents are in this sense irrelevant. Should we wish to study how to improve the technical or economic performance of those policies, we would need to consider the different constituents in more detail.

In a similar fashion, the question of to whom the costs and benefits accrue is in principle independent of the economic efficiency of the policies. After all, it is always possible to design various kinds of transfer mechanisms to compensate those who suffer or demand compensation from those who gain. In this study one type of market structure and payment mechanism has been used, but this in no way implies that it is the one that is the most economic or most equal or most socially acceptable mechanism. It is a task of the policy makers to decide not only which policy to choose but also who pay the costs of the policy and who get to take part in making the policy. Also when in time those costs incur and decisions are made is a matter of social justice.

A final point to make here in relation to social issues is about the weight given in cost-benefit calculations to different groups. In this study an equal weight is given to both producers and consumers/taxpayers. However, if we for some reason wanted to give a greater weight to one of the groups, economic efficiency would no longer be a separate issue from equity. Since under the current assumptions a market gain by one group is a market loss for the other group, the aggregate market effect is zero as long as the weight given to both groups is equal. If this were no longer so (for some reason), the equity issues would need to be considered much more thoroughly. However, we hope that any transfers of income are assigned separately from the phytosanitary policies.

Known unknowns and unknown unknowns

Jensen (2002) argues that protection is optimal if and only if the cost of the invasion is large enough. He adds that in his analysis this conclusion holds regardless of whether that cost is known for certain or only in distribution. This is one reason for why consideration of uncertainty and the dispersion of costs are important. The second reason is that issues related to IAS are inherently uncertain. What happens to IAS in new environments usually cannot be inferred by observing them in their natural habitats or under confined circumstances. Hence there are likely to be unknown elements surrounding any invasion. In addition to natural processes, there is uncertainty regarding the impacts of the invasion on human societies and about the effects of our own management actions.

It was pointed out earlier that despite this inherent uncertainty, analysis of uncertainty related to IAS is inadequate in many case studies that have been conducted. It has much more extensively been included in theoretical analysis of the issue, but these do not always translate easily into empirical assessments. However, inclusion of basic uncertainty in the analysis is not very difficult. Kann and Weyant (2000) suggest that consideration of uncertainty should include discussion on:

i) probability weighted net benefits of optimal policies (model outputs)
ii) optimal policies given uncertainty (optimal decisions)
iii) effects of risk on optimal policies (measure of dispersion)
iv) sensitivity of key parameters (value of input information)

These four points have all been addressed in the current fairly simplistic study, which more or less proves that they can be considered in most studies with relatively little effort. For instance, as pointed out by Eiswerth and van Kooten (2002), decision-making under uncertainty can be properly analysed even when hard data are missing, if the framework is complemented with experts providing verbal descriptors of the growth and damages caused by the invasive species in question.

If uncertainty is too severe to be studied in the conventional way (for instance if there are unknown unknowns), one can try for instance the hybrid info-gap model framework suggested by Moffitt et al. (2005) or the ignorance framework suggested by Horan et al. (2002). Nevertheless, some inclusion and assessment of uncertainty and ignorance related to the issue is clearly required in all empirical studies. There is no space to discuss the various methods available for handling risk and uncertainty in a cost-benefit analysis in this study. Instead, the interested reader is referred to consult for instance Kopp et al. (1997), Mumford et al. (2000), Nairn (1996) or Renn (2005).

The costs of an invasion by species threatening some anthropogenic production process are often easier to predict, quantify and monetise than costs incurred in an invasion by species that threaten for instance natural ecosystems. For these latter species it is difficult to compare the financial costs incurred in prevention with the often intangible costs avoided when a particular ecosystem is not invaded. The scale of the costs avoided may simply be unknown, but potentially very large. Further, in the production environment the species may often be feasibly controlled at least to an extent, whereas in natural ecosystems the case may not be so. Thus, in cases where unknown but potentially large impacts may occur it is worth considering whether a precautionary principle should be applied.

There are basically three reasons for using a precautionary approach. First, if the invasion and subsequent establishment are irreversible, acceptability of intentional introductions in the first place should be questioned (Smith et al. 1999) and a precautionary approach should be applied more generally. Second, under extreme ignorance precautionary approach may be warranted. Horan et al. (2002) point out that in ignorance framework the extreme low-probability outcomes are weighted more heavily than in the expected-utility framework, hence implying a precautionary approach. Third, even if there is some reversibility and reasonable knowledge of the distribution of costs, precautionary approach may still be justified if there is a small but positive probability that the ensuing costs are catastrophically large. Finally, it is worth recalling that the preamble of the Convention on Biological Diversity emphasises that "lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize" a threat of significant reduction or loss of biological diversity (CBD 1992).

6.3 Conclusions and suggestions for further study

This study assessed the economic viability of two alternative policy strategies under change and uncertainty. The main conclusion and policy recommendation from the study is that the current protected zone policy is economically sensible, unless we can be fairly certain that there will be no future change, the beetle cannot properly over-winter in Finland or that the beetle will not result in significant crop losses in Finland. In light of the current information, these qualifications do not seem likely and hence the current policy should be continued.

A possible alternative policy that could be assessed in later work is the use of a "local protected zone". In a local protected zone, instead of the entire invaded area the society only applies eradication in an area of its own choosing. Within this area, actions similar to those under the current protected zone are carried out, but in addition there remains a leftover area that is left for the individual private producers to take care of. Thus reactive control would be applied in this area. As before, reactive control does not aim at eradicating the pest, and hence it can continue spread within and from this area. This would be a type of "withdrawing the pest border" –approach, which may be worth considering in a case where the invasion pressure increases to such an extent that the state authorities have insufficient resources to deal with the issue.

Note that this approach would not fit within the classification of a protected zone, because in such a case Finland would be likely to lose the protected zone status and all the trade related restrictions in accordance with the rules of the Community legislation. However, such a spatial combination is a possible national policy strategy – an alternative to the current protection policy in circumstances under which the authorities no longer can cope with eradication.

In the course of the study, a need for more information has surfaced. In addition to standard costs and benefits discussed in this study and natural science data to resolve some scientific uncertainty, the following issues could be of interest from both scientific and policy decision-making viewpoints:

i) Who pays for the policies and when in time do the costs of different policies ensue?
ii) What are the impacts of possible nonlinearities in costs of pre-emptive control and reactive control on the optimal policy?
iii) What are the impacts of the different policies on international commerce in the form of restrictions, sanctions and reputation?
iv) What are the cost efficiencies of the actual available on-farm and state-level measures that could be adopted in order to adapt to the establishment of the CPB?
v) What are the implications from the fact that one of the policies (giving up protection) is irreversible, whereas the other one is not?
vi) What are the implications from the fact that there are both professional and habitual potato producers, whose objectives may differ from each other?
vii) What are the implications from the fact that the protected zone acts as a buffer zone protecting potentially also Sweden and Norway?
viii) If protection is given up at some point in the future, what is the optimal timing for such a switch?
ix) What are the implications and lessons learned from the case of the CPB for a more general assessment of invasive plant pest policy in Finland?
x) What is the role of the CPB protection policy in the wider framework of biosecurity measures given limited resources by the state?

It is probable that issues related to biosecurity, including invasions by IAS, continue to be a major factor threatening the production systems, ecological systems and human health in the modern societies. Understanding and taking into account in the policy-making process the scale and dimensions of the issue is therefore crucial. In addition, the performance of alternative (long-term) policy responses should be evaluated in order to ascertain that the societies are capable of dealing with the challenge. The ten points listed above are only a subset of questions that remain to be pondered – the current study has after all been limited to fairly specific circumstances. Much has been achieved in both ecological and economic research on IAS in the last decade or so. Much remains to be achieved.

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European and Mediterranean Plant Protection Organization	http://www.eppo.org
Eurostat	http://europa.eu.int/comm/eurostat/
EurLex	http://www.europa.eu.int/eur-lex/
FAOSTAT database	http://faostat.fao.org/
FinLex	http://www.finlex.fi/
Finnish Food Safety Authority	http:///www.evira.fi/
Finnish Maritime Administration	http://www.merenkulkulaitos.fi/
Finnish Meteorological Institute	http://www.fmi.fi/
Global Invasive Species Database	http://www.issg.org/database/
Global Invasive Species Programme	http://www.gisp.org/
Institute for Biological Invasions	http://invasions.bio.utk.edu/
Invaders Database System	http://invader.dbs.umt.edu/
Invasive Species Information Node	http://invasivespecies.nbii.gov/
North European and Baltic Network on Invasive Alien Species	http://www.nobanis.org/
PACIFIC Exchange Rate Service	http://pacific.commerce.ubc.ca/xr/
Plant Production Inspection Centre, Finland	http://www.kttk.fi/
Regional Biological Invasions Center	http://www.zin.ru/projects/invasions/
Swedish Clearing House Mechanism	http://www.biodiv.se/eng/intr-art/
VR-Group	http://www.vr.fi/
World Conservation Union Invasive Species Specialist Group	http://www.issg.org/
World Trade Organization	http://www.wto.org/

APPENDIX 1 – LEGISLATIVE TEXTS

A1.1 International legislation

A1.1.1 WTO Agreement on Sanitary and Phytosanitary Measures

Sanitary and phytosanitary measures are defined as[48]:

Any measure applied:
(a) to protect animal or plant life or health within the territory of the Member from risks arising from the entry, establishment or spread of pests, diseases, disease-carrying organisms or disease-causing organisms; …
(c) to protect human life or health within the territory of the Member from risks arising from diseases carried by animals, plants or products thereof, or from the entry, establishment or spread of pests; or
(d) to prevent or limit other damage within the territory of the Member from the entry, establishment or spread of pests.

Sanitary or phytosanitary measures include all relevant laws, decrees, regulations, requirements and procedures including, inter alia, end product criteria; processes and production methods; testing, inspection, certification and approval procedures; quarantine treatments including relevant requirements associated with the transport of animals or plants, or with the materials necessary for their survival during transport; provisions on relevant statistical methods, sampling procedures and methods of risk assessment; and packaging and labelling requirements directly related to food safety.

The basic idea behind the SPS agreement is that preventative measures are acceptable tools and can also be trade restricting, provided that the case can be scientifically proved, the measures are not discriminating between similar countries and the measures are not more trade-restricting than necessary. This basic idea is stated in the preamble to SPS agreement in that:

… no Member should be prevented from adopting or enforcing measures necessary to protect human, animal or plant life or health, subject to the requirement that these measures are not applied in a manner which would constitute a means of arbitrary or unjustifiable discrimination between Members where the same conditions prevail or a disguised restriction on international trade; …

This principle is stated in the actual agreement in Article 2 on Basic Rights and Obligations as:

1. Members have the right to take sanitary and phytosanitary measures necessary for the protection of human, animal or plant life or health, provided that such measures are not inconsistent with the provisions of this Agreement.
2. Members shall ensure that any sanitary or phytosanitary measure is applied only to the extent necessary to protect human, animal or plant life or health, is based on scientific principles and is not maintained without sufficient scientific evidence, except as provided for in paragraph 7 of Article 5.
3. Members shall ensure that their sanitary and phytosanitary measures do not arbitrarily or unjustifiably discriminate between Members where identical or similar conditions prevail …

Article 5 explains the concept of scientific evidence as well as clarifies (in paragraph 7) the exception pointed at above in Article 2:

1. Members shall ensure that their sanitary or phytosanitary measures are based on an assessment, as appropriate to the circumstances, of the risks to human, animal or plant life or health, taking into account risk assessment techniques developed by the relevant international organizations.
2. In the assessment of risks, Members shall take into account available scientific evidence; relevant processes and production methods; relevant inspection, sampling and testing methods; prevalence of specific diseases or pests; existence of pest- or disease-free areas; relevant ecological and environmental conditions; and quarantine or other treatment.
3. In assessing the risk to animal or plant life or health and determining the measure to be applied for achieving the appropriate level of sanitary or phytosanitary protection from such risk, Members shall take into account as relevant economic factors: the potential damage in terms of loss of production or sales in the event of the entry, establishment or spread of a pest or disease; the costs of control or eradication in the territory of the importing Member; and the relative cost-effectiveness of alternative approaches to limiting risks.
4. Members should, when determining the appropriate level of sanitary or phytosanitary protection, take into account the objective of minimizing negative trade effects.

…

6. … Members shall ensure that … measures are not more trade-restrictive than required to achieve their appropriate level of sanitary or phytosanitary protection, taking into account technical and economic feasibility.

[48] All the following excerpts from the SPS agreement are from WTO (1994).

7. In cases where relevant scientific evidence is insufficient, a Member may provisionally adopt sanitary or phytosanitary measures on the basis of available pertinent information … In such circumstances, Members shall seek to obtain the additional information necessary for a more objective assessment of risk and review the sanitary or phytosanitary measure accordingly within a reasonable period of time.

Risk assessment should be based on scientific evidence (par. 2), and the cost-effectiveness of alternative strategies to limiting risk (par. 3, 6) should be taken into account. The Article urges to take into account the objective of minimising negative trade effects (par. 4) when choosing the level of protection. If there is a measure that achieves the appropriate level of protection but is less trade-restricting than the current measure, then the current measure is seen as more trade-restrictive than required. Adopting a precautionary approach is unacceptable under SPS, unless adequate scientific evidence is available or research into the issue is initiated (par. 7). What constitutes sufficient scientific evidence for different Members is likely to vary, as is understanding of what is meant by 'a reasonable period of time' within which the precautionary measure should be reviewed.

The European Union protected zone system is justified on basis of Article 6:

1. Members shall ensure that their sanitary or phytosanitary measures are adapted to the sanitary or phytosanitary characteristics of the area … from which the product originated and to which the product is destined.
2. Members shall, in particular, recognize the concepts of pest- or disease-free areas and areas of low pest or disease prevalence. Determination of such areas shall be based on factors such as geography, ecosystems, epidemiological surveillance, and the effectiveness of sanitary or phytosanitary controls.
3. Exporting Members claiming that areas within their territories are pest- or disease-free areas or areas of low pest or disease prevalence shall provide the necessary evidence thereof in order to objectively demonstrate to the importing Member that such areas are, and are likely to remain, pest-or disease-free areas or areas of low pest or disease prevalence, respectively.

A1.1.2 United Nations Convention on Biological Diversity

The relevant part is Article 8 on In-situ Conservation, which simply states that (CBD 1992):

Each Contracting Party shall, as far as possible and as appropriate: …
(h) Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species

A1.2.1 Other International Agreements

The Bern Convention (Convention on the Conservation of European Wildlife and Natural Habitats) was adopted in 1979 and entered into force in 1982. The Convention has 45 contracting parties, including four African states. Its objective is to "conserve wild flora and fauna and their natural habitats; to promote co-operation between states; and to give particular emphasis to endangered and vulnerable species, including endangered and vulnerable migratory species". The relevant part regarding IAS in the Convention is Article 11, which states that (Bern Convention 1979):

Each Contracting Party undertakes:
- a to encourage the reintroduction of native species of wild flora and fauna …
- b to strictly control the introduction of non-native species.

In addition to the above agreements, there are several other international agreements that touch upon the issue of IAS in their own sectors. These agreements include the following (after the Swedish Clearing House Mechanism website).

Binding international conventions and agreements:

- Agreement on the Conservation of African-Eurasian Migratory Waterbirds, 1995.
- Cartegena protocol on Biosafety to the CBD, 2000.
- Parties to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), 1973.
- Convention on the Law of Non-navigational Uses of International Watercourses (ILC), 1994.
- Convention on Migratory Species of Wild animals (CMS, Bonn convention), 1979.
- International Plant Protection Convention (IPPC).
- International Watercourses Convention.
- The Jakarta Mandate on Marine and Coastal Biodiversity - Alien Species.
- Office International des Epizootes (OIE) - International Animal Health Code for Mammals, Birds and Bees.
- Convention on Wetlands of International Importance Especially as Waterfowl habitat. Parties to the RAMSAR convention on Wetlands, 1971.
- United Nations Convention on the Law of the Sea (UNCLOS), 1982.

Non-binding international agreements:

- European Inland Fisheries Advisory Commission (EIFAC).
- Food and Agricultural Organization of the United Nations (FAO) - Code of Conduct for the Import and Release of Exotic Biological Control Agents.
- Food and Agricultural Organization of the United Nations (FAO) - Code of Conduct for Responsible Fisheries, 1995.
- International Civil Aviation Organisation - Resolution A-32-9: Preventing the introduction of invasive alien species, 1998.
- International Council for the Exploration of the Seas (ICES) - ICES Code of Pratice on the Introduction and Transfers of Marine Organisms, 1994.
- International Maritime Organization of the United Nations (IMO) - Guidelines for the Control and Management of Ships Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens.
- World Conservation Union IUCN Species Survival Commission (SSC) - IUCN Guidelines for the Prevention of Biodiversity Loss Caused By Alien Invasive Species.

A1.2 Community legislation

A1.2.2 Council Directives 77/93/EEC and 2000/29/EC

A directive that deals with harmful organisms and introduces the concept of protected zones is Council Directive 77/93/EEC of 21 December 1976, on protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community. It has subsequently been replaced by Council Directive 2000/29/EC of 8 May 2000.

The directive defines harmful organisms as "pests of plants or of plant products, which belong to the animal or plant kingdoms, or which are viruses, mycoplasmas or other pathogens." Instead of reproducing the entire directive here, the preamble of the directive is used as it notes the basic issues dealt with in the directive, including[49]:

(2) Plant production is very important to the Community.
(3) Plant production yields are consistently reduced through the effects of harmful organisms.
(4) The protection of plants against such organisms is absolutely necessary not only to avoid reduced yields but also to increase agricultural productivity.
(5) Action aimed at the systematic eradication of harmful organisms within the Community, established by the plant health regime applicable in the Community as an area without internal frontiers, would have only limited effect if protective measures against their introduction into the Community were not applied at the same time.
(6) The need for such measures has long been recognised and they have formed the subject of many national regulations and international conventions, including the International Plant Protection Convention (IPPC) of 6 December 1951 concluded at the United Nations Food and Agricultural Organisation (FAO), which is of worldwide interest.
(7) One of the most important measures consists in listing the particularly dangerous harmful organisms whose introduction into the Community must be prohibited and also the harmful organisms whose introduction into the Member States when carried by certain plants or plant products must also be prohibited.

[49] Source for the following excerpt from this directive is EC 2000.

(8) The presence of some of these harmful organisms, when plants or plant products are introduced from countries in which these organisms occur, cannot be effectively checked. It is therefore necessary to make minimum provision for bans on the introduction of certain plants and plant products, or to provide for special checks to be made in the producer countries. …

(11) Temporary safeguard measures not laid down in this Directive should normally be adopted by the Member State where the problem originates in the case of imminent danger of the introduction or spread of harmful organisms. The Commission should be informed of all events which require the adoption of safeguard measures. …

(17) In the case of importations of plants or plant products from third countries the authorities responsible in such countries for issuing certificates should be, in principle, those empowered under the IPPC. It could be desirable to establish lists of these authorities for the non-contracting third countries.

(18) The procedure applicable to certain types of amendments to be made to the Annexes to this Directive should be simplified. …

(21) It is appropriate to provide in certain cases that the official inspection of plants, plant products and other objects coming from third countries should be carried out by the Commission in the third country of origin. …

(23) The scope of the regime should no longer be restricted to trade between Member States and third countries, but should also be extended to marketing within single Member States.

(24) In principle, all parts of the Community should benefit from the same degree of protection against harmful organisms. However, differences in ecological conditions and in the distribution of certain harmful organisms must be taken into account. In consequence, "protected zones" exposed to particular plant health risks should be defined and should be accorded special protection under conditions compatible with the internal market.

(25) The application of the Community plant health regime to the Community as an area without internal frontiers, and the introduction of protected zones make it necessary to distinguish between requirements applicable to Community products on the one hand and those applicable to imports from third countries on the other, and to identify harmful organisms relevant for protected zones.

(26) The most appropriate place for carrying out plant-health checks is the place of production. In respect of Community products, these checks must therefore be made mandatory at the place of production and should extend to all relevant plants and plant products grown, produced, used or otherwise present there, and to the growing medium used there. For the efficient operation of such a system of checks, all producers should be officially registered.

(27) To ensure more effective application of the Community plant-health regime in the internal market, it must be possible to use, for the purpose of plant-health checks, available official manpower other than that of Member States' official plant-protection services, whose training should be coordinated and supported financially by the Community.

(28) If the results of the checks are satisfactory, instead of the phytosanitary certificate used in international trade, Community products will bear an agreed mark (plant passport), adapted to the type of product, in order to ensure its free movement throughout the Community or those parts thereof for which it is valid.

(29) The official measures to be taken when the results of the checks are not satisfactory should be specified.

(30) To ensure compliance with the Community plant-health regime in the context of the internal market, a system of official checks during marketing should be established. This system should be as reliable and uniform as possible throughout the Community but should exclude specific controls at borders between Member States.

(31) In the framework of the internal market, products originating in third countries should in principle be subjected to plant-health checks on first introduction into the Community. If the results of the checks are satisfactory, third country products should be issued with a plant passport ensuring free movement in the same way as Community products.

(32) In order to confront the situation created by the completion of the internal market with the necessary guarantees, it is essential to reinforce the plant-health inspection infrastructure at national and Community level at the Community's external frontiers, paying particular attention to those Member States which, by reason of their geographical situation, are points of entry to the Community. The Commission will propose the inclusion in the General Budget of the European Union of the necessary appropriations for that purpose. …

(34) It is no longer possible for Member States to adopt any special plant-health provisions on the introduction into their territory of plants or plant products originating in other Member States. All provisions on plant-health requirements for plants and plant products should be established at Community level.

(35) It is necessary to establish a system of Community financial contributions to share at Community level the burden of possible risks which might remain in trade under the Community plant-health regime.

(36) In order to prevent infections by harmful organisms introduced from third countries, there should be a Community financial contribution aimed at reinforcing the plant health inspection infrastructure at the Community's external frontiers.

(37) The regime should also provide for adequate contributions to certain expenses for specific measures, which Member States have adopted to control and, where applicable, eradicate infections by harmful organisms introduced from third countries or from other areas in the Community, and, where possible, to repair the damage caused. …

A1.2.3 Council Directive 92/43/EEC

The threat presented by IAS to natural ecosystems is covered in Council Directive 92/43/EEC of 21 May 1992, on the conservation of natural habitats and of wild fauna and flora. Its aims are set in Article 2 as:[50]

1. The aim of this Directive shall be to contribute towards ensuring bio-diversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the Member States to which the Treaty applies.
2. Measures taken pursuant to this Directive shall be designed to maintain or restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest.
3. Measures taken pursuant to this Directive shall take account of economic, social and cultural requirements and regional and local characteristics.

The relevant part regarding IAS is Article 22 on supplementary provisions, which states that:

In implementing the provisions of this Directive, Member States shall:
(a) study the desirability of re-introducing species … that are native to their territory where this might contribute to their conservation …;
(b) ensure that the deliberate introduction into the wild of any species which is not native to their territory is regulated so as not to prejudice natural habitats within their natural range or the wild native fauna and flora and, if they consider it necessary, prohibit such introduction. The results of the assessment undertaken shall be forwarded to the committee for information;

A1.2.4 Council Regulation 338/97

Trade aspects of IAS that threaten ecological systems are considered in Council Regulation 338/97 of 9 December 1996, on the protection of species of wild fauna and flora by regulating trade therein. Its objective is set in Article 1 as:[51]

The object of this Regulation is to protect species of wild fauna and flora and to guarantee their conservation by regulating trade therein in accordance with the following Articles.

IAS are to be included in Annex B as defined in Article 3 on 'Scope', which determines that:

2. Annex B shall contain: …
(d) species in relation to which it has been established that the introduction of live specimens into the natural habitat of the Community would constitute an ecological threat to wild species of fauna and flora indigenous to the Community.

Whereas Council Directive 2000/29/EC allows trade restrictions in relation to species that threaten plant production, Council Regulation 338/97 does the same for species that threaten natural environment. Again, the approach is based on a blacklist (Annex B). Article 4 on 'Introduction into the Community' sets conditions for species import in Annex B:

2. The introduction into the Community of specimens of the species listed in Annex B shall be subject to completion of the necessary checks and the prior presentation, at the border customs office at the point of introduction, of an import permit issued by a management authority of the Member State of destination.
…
6. In consultation with the countries of origin concerned … and taking account of any opinion from the Scientific Review Group, the Commission may establish general restrictions, or restrictions relating to certain countries of origin, on the introduction into the Community: …
(d) of live specimens of species for which it has been established that their introduction into the natural environment of the Community presents an ecological threat to wild species of fauna and flora indigenous to the Community.

A1.3 Finnish national legislation

A1.3.1 Act on the Protection of Plant Health

The Act on the Protection of Plant Health of 2004 replaced the Plant Protection Act of 1994. The new Act is essentially similar to the old one, but it identifies in greater detail responsibilities of the authorities. The relevant parts of the Act are discussed below.[52]

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[50] Source for all the following excerpts from this directive is EC (1992).
[51] Source for all the following excerpts from this regulation is EC (1996).

2 § Scope of application
This Act applies to procedures that are used to maintain a favourable state of plant health and that can be undertaken to counter plant pests and to prevent their spread. …
… The Ministry of Agriculture and Forestry issues a regulation defining the plant pests that the procedures set out in moment 1 can apply to. The Act can also be applied to counter and prevent the spread of plant pests and other organisms that are new or whose impacts are unpredictable, and that cause immediate threat to plant health.

3 § Definitions
For the purposes of this Act: …
3) a plant pest is defined as any detrimental organism of animal or plant kingdom., fungus, bacterium, phytoplasm, virus or other disease agent which can cause direct or indirect damage to cultivated plants, natural plants or products derived from them, and which can be found in plants or plant products.

The Act explicitly states that in addition to the species in the blacklist, it can be applied to species outside that list if they pose a threat to plant health. It is also stated that it may also be applied to those pests that may cause direct or indirect damage to natural plants or plant products. Further relevant parts of the Act include the following:

7 § Importation and exportation
Certain plants, plant products and other material with which the plant pest can easily spread, may be imported only when accompanied by a plant health certificate or other certificate indicating plant health. …

10 § Obligation of notification
Any person who knows or suspects that a plant pest … exists on property, part of property, plantation, store, transport vehicle or building owned or operated by that person, is obliged without delay to inform the local TE-Centre or the Plant Production Inspection Centre. …

11 § Countering plant pests
To counter the plant pests or to prevent their spread, it is possible to:
1) order the land owner, producer or the owner or operator of the property or part of the property to perform essential procedures deemed necessary in order to eradicate the plant pest present on the property;
2) order an essential clean-up or disinfection and the method of essential clean-up and disinfection of a building, work or transportation vehicle or any other object contaminated by the plant pest;
3) order an essential clean up, disinfection or disposal of plants or packages or packaging material of plant origin, and to order the essential method of clean up, disinfection or disposal or to set essential restraints as to how plants or packages or packaging material of plant origin can be used;
4) issue essential bans, conditions and restrictions regarding cultivation, transport or trade in plants;
5) issue orders regarding essential procedures to be performed in cultivation, harvest and trade in plants;
6) issue essential bans or conditions regarding marketing, importation and exportation of plants, plant products, plant pests, and other objects in which the plant pest can easily spread; and
7) oblige the actor to follow any other essential restrictions, bans and procedures to counter plant pests or prevent their spread.
…
The Ministry of Agriculture and Forestry can also permit the Plant Production Inspection Centre to carry out procedures … for plant pests that are not named in a regulation ... If such a plant pest causes immediate threat to plant health and the matter is urgent, the Plant Production Inspection Centre can also undertake essential counter procedures … before a permission is given.

14 § Officials
Execution and monitoring of the compliance with this Act … are to be carried out by the Plant Production Inspection Centre, which is to be assisted in monitoring by the rural departments of the TE-Centres. …

23 § Executive assistance
The monitoring officials are entitled to executive assistance from customs, frontier guard and police and rescue services to carry out the procedures required by this Act and the regulations and obligations based on this Act.

11§ points out that the Ministry of Agriculture and Forestry may permit actions regarding pests that have not (yet) been included in the appropriate annex of Directive 2000/29/EC. Further, the Plant Production Inspection Centre (i.e. the relevant authority) may take such action even when not ordered by the Ministry, if they see that the threat is imminent. The authority responsible is also specifically

[52] Source for all the following excerpts from this Act is Government of Finland (2003). There is no official translation of the Act. The translation is done by the author and is probably inaccurate in legal terms.

named in the Act. In addition, the fact that plant protection authorities are now entitled to assistance from the customs, border control, police and rescue officials is new to the Act.

As for penal provisions and compensation payments, the Act states the following:

29 § Penal provisions
Any person who intentionally or due to negligence
1) without the registration required in 4 § markets, imports for marketing, stores or imports plants, plant products or other objects in which the plant pest can easily spread, …
6) fails the obligation of notification of the presence of the plant pest as set in 10 §,
7) breaches the orders, bans, conditions or restrictions as set in 11 § …
is to be sentenced, if the deed does not carry a heavier penalty on basis of another Act, to pay fines for endangering plant health.

30 § Compensation for damages and expenditure caused by plant pest counter decision
The expenditure and damages to a producer caused by a decision to counter a plant pest new to Finland (plant pests to be eradicated) are compensated for by the State. In addition, partial compensation can be paid for the expenditure and damages to a producer caused by a decision to counter and prevent the spread of a plant pest that already exists in Finland and causes direct or indirect damage, but that cannot be eradicated (plant pests to be controlled/countered). A pre-requisite for receiving compensation is that the plant … has been in production ...
Expenditure and damages that are compensated … include:
1) disinfection, counter and eradication expenditure directly caused by performing an issued order, and the value of the articles disposed of or damaged due to the counter procedure;
2) the economic damage or expenditure caused by prohibition of sale, transfer, transport or use, or by a comparable restriction based on an issued order; and
3) the economic damage or expenditure caused by interruption of plant production based on an issued order. …

31 § Denial of compensation
The compensation as set in 30 § will not however be paid:
1) for damage and expenditure caused by defects that are due to the plant pest; …
4) for expenditure or damages that the actor has caused intentionally or due to gross negligence by failing to follow good production practice.

The penal provisions and the compensation procedure state that compensation is primarily paid for pests that are to be eradicated, as opposed to those that are merely controlled. As is evident by comparing the above with Council Directive 2000/29/EC, the Directive is executed by means of this Act. Its main points are that it obligates individual farmers to inform the authorities of quarantine pest observations, as well as to follow any orders regarding eradication. It also sets out the punishments for not following the instructions. It also sets out the right of the producer to get compensation for the control and eradication costs as well as for the value of the lost crop.

A1.3.2 Nature Conservation Act

Another piece of national legislation dealing with invasions is the Nature Conservation Act (1096/1996)[53], which in Section 43 on 'Preventing the spread of non-native species' states:

Non-native species falling outside the purview of the Hunting Act of Fishing Act are not to be released into the wild if there is cause to suspect that the species may become established permanently.

Non-native plant species without an established range in the Finnish wild are not to be planted or sown outside a garden, field or other site designated for special purposes, nor in natural waters, in so far as there is cause to suspect that the species may become established permanently. This shall not apply, however, to the planting or sowing of trees for the purpose of forestry.

If a non-native plant or animal species is known to spread rapidly in the wild, and there is reasonable cause to suspect that it might constitute a health hazard or have a detrimental effect on an indigenous Finnish species, the Ministry of the Environment may issue any regulations as prove necessary for preventing the spread of such a species. Measures for preventing the spread of animal disease are set forth in the Animal Diseases Act.

[53] Source for the excerpt: Government of Finland (1996). Translation obtained from the Ministry of the Environment.

A1.3.3 Other legislation

Three other pieces of national legislation that deal with IAS from their own perspectives are the Animal Diseases Act (e.g. Article 13), Hunting Act and Fishing Act (Government of Finland 1980; 1982; 1993; Nummi 2000). These in principle dictate that species of foreign origin cannot be imported to Finland or released in the wild without permission from the appropriate Ministry. The relevant translated sections of the Hunting Act and Fishing Act are provided below.

Hunting Act – Article 42 (Government of Finland 1982):

Section 42 – The import and release of animals of foreign origin
(1) It is forbidden to import or release bird or mammal species of foreign origin as well as game strains of foreign origin without the permission of the Ministry of Agriculture and Forestry. Statement on permit application must be requested from the Ministry of the Environment. Permission must be refused if significant harm will be caused by the measure to the natural environment or to naturally occurring fauna. Provisions on how importing and releasing are to be carried out may be laid down in the permit. (1268/1993)
(2) The provisions of subsection 1 also apply to the bringing of an animal from Åland to some other area of Finland and to the release of that animal into the area in question.

Fishing Act – Article 94 (Government of Finland 1993):

…
(2) The import of a fish or crayfish species not occurring naturally in Finland or of their stock or gametes is allowed only by permission of the Ministry concerned and on the terms and conditions specified by it. Permission must be denied if the measure may cause significant harm to nature or wild animals. Provisions on fish or crayfish species that can be imported freely, shall be given by decree as necessary (252/1998)

APPENDIX 2 – MARKET AND TRADE EFFECTS

A2.1 Domestic market effects

Market effects are possible if the invasion results in damages to a production process. In such a case, more inputs are typically needed to produce the same quantity of outputs. These inputs (for instance control substances as well as additional labour and machinery) are costly, and thus the general implication is that the costs of production increase. This translates into a shift of the domestic supply curve.

Depending on the market structure, some share of these additional costs is passed on to consumers. The same effect takes place if the invasion results in production losses to such an extent that the prices increase because of the diminished quantity supplied. As the product prices increase, the consumers suffer a loss of consumer surplus, because they have to pay more for the product. Also producers may suffer losses due to the increased production costs. What in the end happens depends on the market structure. The impact of increased costs on producers and consumers is presented below under different types of market structure. To start with, Figure A49 presents the situation in which there is no foreign trade and supply and demand are both elastic.

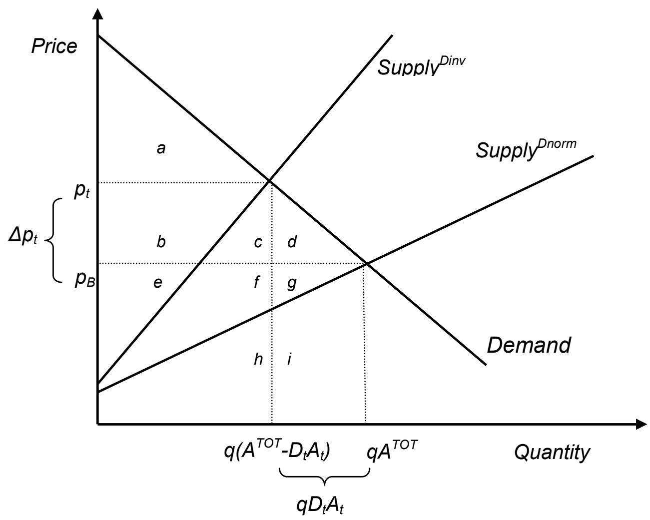

Figure A49. Elastic demand and elastic supply with and without the pest invasion.

The supply (demand) curve depicts the quantity supplied (demanded) at each price level of the affected agricultural product. Invasion induces a leftward shift in the supply curve: at each price level less is supplied as production costs have increased. The supply curve thus shifts from the normal pre-invasion position ($Supply^{Dnorm}$) to the new post-invasion ($Supply^{Dinv}$) position. If neither the supply nor the demand curve is perfectly elastic or perfectly inelastic, the shift in the supply results in consumer surplus being reduced from area $a + b + c + d$ to just a. Supply change thus results in the consumers losing $b + c + d$ in consumer surplus. Hence, the consumers unambiguously lose in the case of an invasion. Part of the consumer loss goes to producers and part to overall welfare loss. The overall impact on producers is unclear and depends on the market structure. We assume the demand curve to be linear over the (relatively small) price range considered. This is not too restrictive an assumption for as long as the price changes and changes in supply are not very big.

If supply is perfectly inelastic (vertical supply curve), the situation is as presented in Figure A50. Perfectly inelastic supply means that there is a fixed quantity of the good that can be produced. In such a case shift of the supply curve results in consumer surplus being reduced from area $j + k + l$ to just j. Supply change thus results in the consumers losing $k + l$ in consumer surplus. Hence, again the consumers unambiguously lose in the case of an invasion and the impact on producers is still ambiguous.

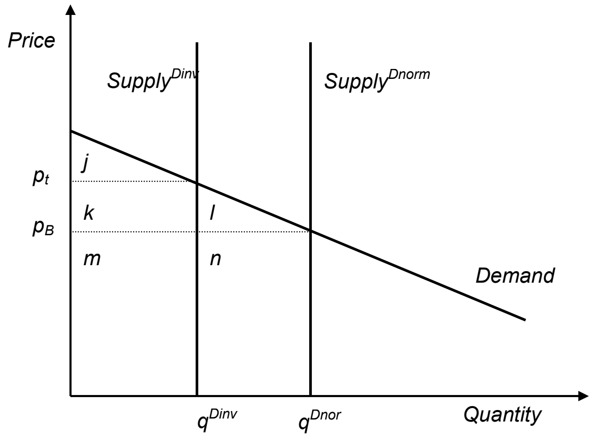

Figure A50. Elastic demand and perfectly inelastic supply with and without the pest invasion.

If supply is elastic, but demand is perfectly elastic, as presented in Figure A51, change in the supply curve results in no consumer surplus effects. This is because, due to the perfectly elastic demand, any price changes are absorbed by the producers and consumers remain unaffected. If demand is perfectly elastic, it means that with any price above the demand curve none of the consumers would be buying anything domestically. Hence the price cannot be set above the demand curve, if the producers are to sell any quantity. This is the only case in which the consumers are unaffected by the invasion.

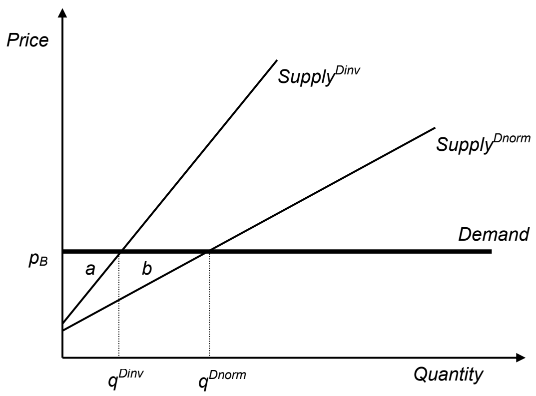

Figure A51. Perfectly elastic demand and elastic supply with and without the pest invasion.

However, we have so far assumed that there is no foreign trade. Let us now add foreign trade to the diagrams. The effective world price of the agricultural product is denoted by p^W, $Supply^{Dnorm}$ denotes normal (pre-invasion) domestic supply and $Supply^{Dinv}$ post-invasion domestic supply. World price is assumed horizontal (any quantity can be provided internationally at that price) and domestic supply has the standard upward-sloping form. The world price is assumed to include the transportation costs. There are three possible cases regarding the relationship of domestic and world prices. Each is presented briefly below.

1. Pre- and post-invasion domestic prices above world price

The case where the world price is lower than the domestic price at the domestic market equilibrium is presented in Figure A52. In such a case, the pre-invasion equilibrium is when the quantity q^W is provided at the price p^W, with q^{Dnorm} of the quantity supplied by domestic producers. The impact of the invasion is that the market equilibrium remains the same, but the share of domestic production is reduced from q^{Dnorm} to q^{Dinv}. The consumers are thus not affected, but the domestic producers will unambiguously lose the area $a + b$ in producer surplus. The gainers in this case are the international producers.

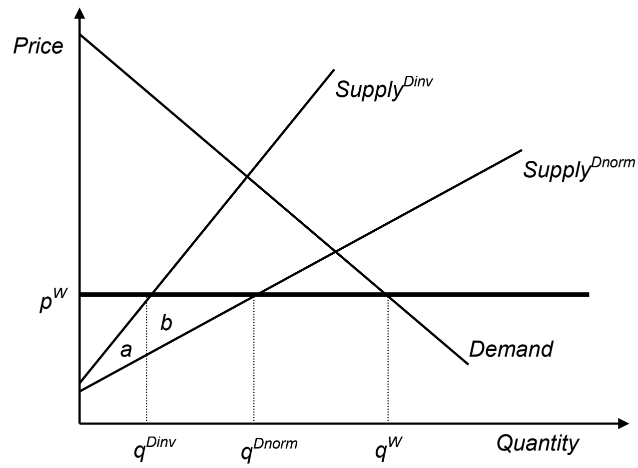

Figure A52. World price below domestic price at domestic market equilibrium.

<u>2. Pre- and post-invasion domestic prices below world price</u>

In this case the equilibrium price is below the world price, as presented in Figure A53. This may be the case when price transfers are imperfect, for instance if the international transportation cost is large relative to the product price. This may to some extent be the case in Finnish potato markets. The initial equilibrium is at q^{Dnorm}, p^{Dnorm}. The post-invasion equilibrium is still below the world price, at q^{Dinv}, p^{Dinv}. In other words, in this case whether there is or is not a world price is irrelevant and standard analysis of Figure A49 applies.

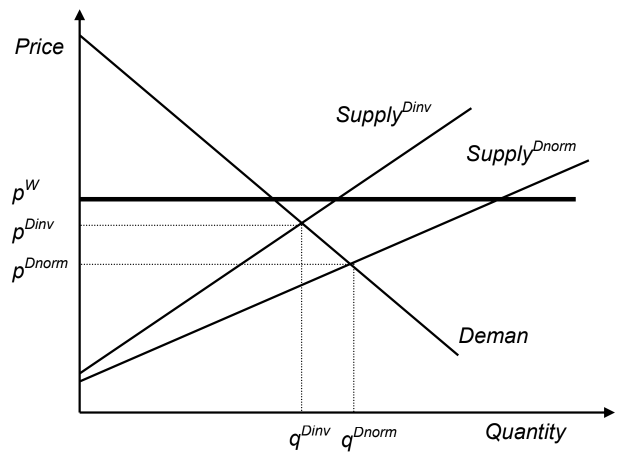

Figure A53. World price above domestic price at domestic market equilibrium.

<u>3. Only pre-invasion domestic price below world price</u>

The third case is when the initial price is below the world price at q^{Dnorm}, p^{Dnorm} but the domestic post-invasion equilibrium would be above the world price. This is presented in Figure A54. In this case the post-invasion equilibrium would be at q^W, p^W, with the quantity q^{Dinv} provided by the domestic producers. The consumers would lose the trapezoidal area bordered by p^W, p^{Dnorm} and the demand curve in consumer surplus, but since the world price acts as a maximum price, the impact is not as large as in the first case above. The domestic producers on the other hand would lose the triangular area bordered by the pre- and post-invasion supply curves and p^{Dnorm} in producer surplus, but gain the area bordered by p^W, p^{Dnorm} and the post-invasion supply curve.

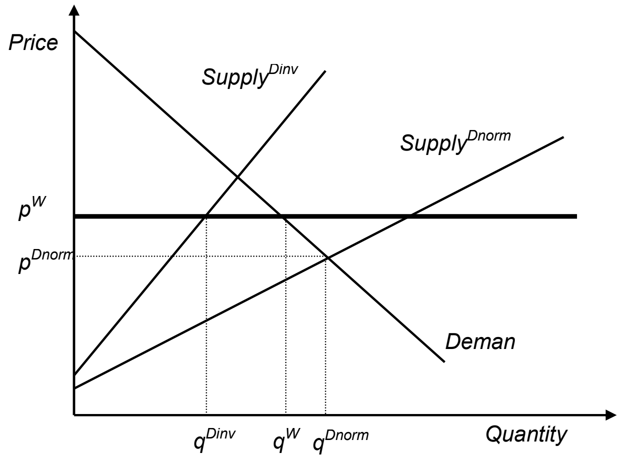

Figure A54. World price between old and new domestic price at domestic market equilibrium.

A final point to note about the domestic market effects is that in cases with no foreign trade, they are to a large extent transfers from consumers to producers or vice versa. If we are only concerned about aggregate figures, market effects may not count as a cost as such. If we are concerned about distribution of income, then they may count as a cost (or benefit). With foreign trade added, the domestic market effects may act as a cost if we are concerned about the specific country in question. This is because some proportion of income may be transferred to international producers. Again it is, however, only a transfer, with one country benefiting and another losing. It depends on the precise market structure as well as our point of view whether such impacts are counted as costs (or benefits) or not.

A2.2 Trade effects

It is reasonable to argue that free trade is not a goal in itself, only the means for a better livelihood. If the negative side effects of free trade, including invasions by exotic organisms, become large relative to the benefits, some kind of trade protection is well justified. The impact of the invasion may reflect on the international market. Many IAS are fearsome for countries that have thus far managed to stay free of them. The case is all the more so if the clean country is dependent on the activity that the species threatens. For instance, for Finland, which still is relatively dependent on its forestry sector, an invasion by the pinewood nematode would have significant impacts. Such countries are likely to take action to protect themselves from the risk, and these actions naturally affect international trade flows: if there is no outright ban on imports, they will at least become more expensive due to surveillance and quarantine procedures. Let us consider this situation from the importing country point of view, assuming elastic demand and domestic supply.

We use the first case diagram (Figure A52) from previous section here. From purely supply and demand point of view (i.e. excluding the real reasons for the protection system, such as protecting animal, plant or human health), the system is equivalent to the price of imports increasing. It is thus a fairly typical non-tariff barrier (NTB) that results in an increase in the effective world price. This can be represented by an upward shift of the effective world price curve, as demonstrated in Figure A55.

The effect of the protection system as such is to decrease the equilibrium quantity (from q^W to q^{WP}) and increase the equilibrium price (from p^W to p^{WP}). In both pre- and post-invasion cases, the quantity of domestic production increases. Thus the system gives the domestic producers an advantage they did not have prior to the protection system. Consumers on the other hand lose the area bordered by p^W, p^{WP} and the demand curve in consumer surplus. The additional expenditure goes to domestic producers, not their international counterparts.

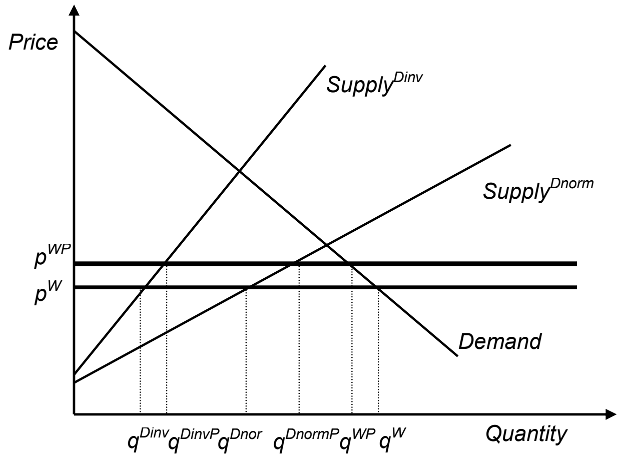

Figure A55. World and domestic supply with protection system added.

For the protection system to be internationally justifiable, it has to serve its primary purpose, i.e. in this instance protect human, animal, plant or environmental health. Thus from biosecurity point of view the price increase caused by the introduction of the protection system can be considered to be a risk premium that has to be paid if we wish to protect ourselves from the threat posed by invasive species. At best this protection can prevent the shift in the domestic supply curve by preventing the additional production costs from materialising. In such a case the domestic producers would gain a double benefit: first, they would not face the increasing costs implied by the upward shift in the domestic supply curve. Second, they would enjoy the benefits of increasing world price, which would increase the market share of domestic production. If the increase in import price is large enough, it is even possible that the domestic producers end up producing the entire amount demanded.

From the point of view of an exporting country the situation is somewhat different. The analysis above can be extended to consider a case in which increased domestic production costs result in loss of market share in world markets. This is likely to result in losses to domestic producers. For consumers the result is ambiguous as it depends on what happens to domestic prices – they may decrease if the supply is diverted from exports to domestic consumption. However, in this case consumers are not likely to be negatively affected.

More interestingly, there may be effects that are likely to be far more important than the mere loss of international market share caused by increase in production costs. These include the impacts of international regulation and reputation. A country infested by a potentially dangerous invasive alien species is likely to find its foreign commerce restricted in products that may harbour and spread the harmful species. This has been illustrated by for instance the BSE in the United Kingdom or more recently by the avian influenza in Turkey and Rumania, who both have seen their bird-related exports no longer accepted by the European Union.

On the other hand, a protection system against an invasive pest may promote exports of the domestically produced product. This is the case in for instance the European Union protected zone system, where imports of pest-related products from outside the protected zone system or designated buffer zones are restricted or banned. A protected zone exporter can on the other hand export wherever s/he wants to. Further, the reputation of a country as a safe, pest-free producer that does not need to rely extensively on chemical control substances may earn that country a comparative advantage in producing certain products. This advantage can be lost following an invasion, and it is well known that losing a reputation is quick and easy but regaining it requires a lot of time and effort.

This concludes the brief discussion of IAS trade impacts. It is perhaps worth emphasising that closer analysis of trade impacts is excluded from this study because the case study does not require it. In many other cases, trade impacts are likely to be of immense importance.

APPENDIX 3 – THE ASSUMPTIONS USED IN THE ANALYTICAL AND EMPIRICAL MODELS

Assumption	*Why is it needed*	*Is it realistic*
Reactive control is only damage reducing, not production enhancing	Crop yields with control application should be between the yield obtained in the absence of the pest and the yield obtained when the pest is not controlled at all. In other words, control should reduce the damage, but it should not boost production such that it would be used also in the absence of the pest.	Yes, pesticides in general are not production enhancing.
The two policy strategies have no external costs or benefits	The policy analysis of the strategies requires that all the appropriate costs and benefits are included in the model. If this is not the case, the analysis may end up preferring the 'wrong' policy.	Not terribly realistic. Protection systems may result in trade distortion and thus have an impact on the economy, whereas reactive control with pesticides often results in at least some environmental damage. However, the problem can be mitigated by qualitative analysis and acknowledgement of such effects and their relative importance – as has been done in this study.
Entire prevention costs can be fully transferred to consumers	It is assumed that consumers pay the prevention costs. Thus there would have to be a mechanism that charges the consumers for these costs.	In our two sector case, the consumers can be equated with taxpayers and as such the mechanism is possible. In the real world, the case would not be so simple, as all the taxpayers would not be consumers. However, as potato is a fairly popular food, the assumption is probably quite reasonable.
Producers are price-taking profit maximisers	To assume rational behaviour by the producers. In the model there is a representative i^{th} producer, whose decisions have no impact on the price of the output.	Probably fairly realistic. There are many producers in the Finnish potato sector, and they in general have no influence over the price.
International price transfers may be imperfect, i.e. prices are allowed to increase due to damages	In the model it is assumed that the price may rise following the invasion, if the aggregate quantity produced is reduced. This is not restrictive in that the price transfers *do not have* to be imperfect.	Probably quite justified. Potato is a fairly cheap product, yet the transport expenses from Central Europe to Finland are fairly high. It has been suggested that the price would need to double in Finland to make large scale imports profitable. As we are projecting price increases of much less than 100%, the assumption seems valid. Second, Finnish potato can perhaps be seen as a different product than imported potato, thus the domestic price may well increase above the world price.
The demand curve is linear over the price range considered	Needed to estimate changes in consumer surplus. The formula used calculates the change in consumer surplus as the area bounded by the y-axis, the old price, the new price and the demand curve. If demand curve is non-linear, estimation of this area is more complex. If demand curve in reality is convex, the area is over-estimated when a linear demand curve is used.	Probably a reasonable approximation given the small projected price changes.
Price changes are fully transferred to consumers	Needed to be able to estimate the change in consumer surplus. The model calculates the producer effects from the change in producer price, and consumer effects from the change in consumer price. Thus, although the two prices need not be same, the change has to be equal in absolute terms. Thus, it is assumed that 0.10€ increase in producer price leads to 0.10€ change in consumer price.	Difficult to say. However, it is worth remembering that this is again a question of distribution, not of efficiency.

Control costs are linear.	The assumption of linear costs makes the analysis easier and the results simpler to interpret. In addition, information on the type of non-linearities would not be readily available and would constitute one more stochastic element in the analysis.	The resources available to both plant protection authorities and individual producers are limited. Hence at larger levels of control activity, the costs may start to increase rapidly. Over moderate control levels, the assumption is realistic.
The society is a risk neutral cost minimiser	Risk neutrality is needed when there are probabilistic events. Also needed to establish the objective of the society. If the society was not a cost minimiser, a strategy might be chosen for instance on the basis of only one of the sectors. For example, if one of two strategies is on aggregate cheaper, but another strategy is chosen because it results in the consumers losing less, the society would not be cost-minimising on aggregate.	Fairly realistic. It is quite well agreed upon that society is risk neutral. Cost minimisation is probably also true in principle, although the different sectors may have powerful lobbying emphasising the sector effects and thus influencing the outcome. Important especially if the cost difference of the strategies is small.
The pest is host-specific and causes no external health, cultural, ecological or food safety damage	The external costs of the two strategies were already ruled out, and this assumption rules out any environmental effect the pest itself might have. If one of the strategies implies that the pest is present and the other that it is not, then in calculating the costs of the strategy where the pest is present, all relevant costs need to be accounted for. This would also naturally include not only the pest impact on the produced good, but also on all other matters. Notice that these other matters could be positive as well as negative.	CPB seems to occupy a more or less empty niche in Finland and thus any ecological damage would probably be quite limited. Also health and cultural damaged are likely to be limited. Thus the assumption seems plausible.

APPENDIX 4 – MATLAB CODE

ajotiedosto.m

```
% ##################################################################
% COLORADO POTATO BEETLE PROTECTION SYSTEM:
% ANALYSIS OF STRATEGIES OVER TIME
% Jaakko Heikkilä, MTT Economic Research
% April 4, 2005.
% This script executes the analysis
% ##################################################################

clear variables; clc;

tic
n = 300000;      % number of iterations
y = 50;          % number of years (note: change this also in set_parameters file).

% CREATE THE EMPTY MATRICES

ZP_vec = zeros(y,n); H1_vec = ZP_vec; H2_vec = ZP_vec;
dCS1_vec = ZP_vec; dCS2_vec = ZP_vec; dPS1_vec = ZP_vec; dPS2_vec = ZP_vec;

% EXECUTE ANALYSIS

for i = 1:n
[ZP_vec(:,i),  ...
dCS1_vec(:,i), dCS2_vec(:,i), ...
dPS1_vec(:,i), dPS2_vec(:,i), H1_vec(:,i), H2_vec(:,i)] = CPB_analysis;

          if i==n/4; disp('25% laskettu'), datestr(now,13)
          end
          if i==n/2; disp('50% laskettu'), datestr(now,13)
          end
          if i==n/4*3; disp('75% laskettu'), datestr(now,13)
          end
end

disp('Strategy costs calculated')

adapTot1=sum(dPS1_vec+dCS1_vec); adapTot2=sum(dPS2_vec+dCS2_vec);
ZPTot=sum(ZP_vec);

S1 = adapTot1./ZPTot; S2 = adapTot2./ZPTot;
choiceS1a(S1>=1)=1; choiceS1b(S1<1)=1; choiceS2a(S2>=1)=1; choiceS2b(S2<1)=1;

% REPORT THE RESULTS

format short g
format compact

%disp('Cases')

Protection = [sum(choiceS1a) sum(choiceS2a)]
Adaptation = [sum(choiceS1b) sum(choiceS2b)]

%disp('Costs')

Mean_Cost_of_Adaptation = [mean(adapTot1) mean(adapTot2)]
Mean_Cost_of_Protection = [mean(ZPTot)]

Median_Cost_of_Adaptation = [median(adapTot1) median(adapTot2)]
Median_Cost_of_Protection = [median(ZPTot)]

Min_Cost_of_Adaptation = [min(adapTot1) min(adapTot2)]
Max_Cost_of_Adaptation = [max(adapTot1) max(adapTot2)]

Min_Cost_of_Protection = [min(ZPTot)]
Max_Cost_of_Protection = [max(ZPTot)]

%disp('BR-ratios')

Mean_BC_Ratio = [mean(S1) mean(S2)]
Median_BC_Ratio = [median(S1) median(S2)]
Min_BC_Ratio = [min(S1) min(S2)]
Max_BC_Ratio = [max(S1) max(S2)]
```

ajotiedosto.m continued…

```
Annual_Mean_Cost_of_Protection = mean(ZP_vec');
Annual_Mean_Cost_of_Adaptation1 = mean(dCS1_vec'+dPS1_vec'); Annual_Mean_Cost_of_Adaptation2 =
mean(dCS2_vec'+dPS2_vec');

Annual_Min_Cost_of_Protection = min(ZP_vec');
Annual_Min_Cost_of_Adaptation1 = min(dCS1_vec'+dPS1_vec'); Annual_Min_Cost_of_Adaptation2 =
min(dCS2_vec'+dPS2_vec');

Annual_Max_Cost_of_Protection = max(ZP_vec');
Annual_Max_Cost_of_Adaptation1 = max(dCS1_vec'+dPS1_vec'); Annual_Max_Cost_of_Adaptation2 =
max(dCS2_vec'+dPS2_vec');

dPS1Tot=sum(dPS1_vec); dPS2Tot=sum(dPS2_vec);
dCS1Tot=sum(dCS1_vec); dCS2Tot=sum(dCS2_vec);

Mean_Cost_to_Producers = [mean(dPS1Tot) mean(dPS2Tot)]
Mean_Cost_to_Consumers = [mean(dCS1Tot) mean(dCS2Tot)]

Net_Benefit1 = (dCS1_vec + dPS1_vec) - ZP_vec;
Net_Benefit2 = (dCS2_vec + dPS2_vec) - ZP_vec;

Annual_Net_Benefit1 = mean(Net_Benefit1');
Annual_Net_Benefit2 = mean(Net_Benefit2');

Total_Net_Benefit1 = sum(Net_Benefit1);
Total_Net_Benefit2 = sum(Net_Benefit2);

% SAVE THE RESULTS

save ('results')

toc, datestr(now,13)
```

CPB_analysis.m

```
% ####################################################################
% COLORADO POTATO BEETLE PROTECTION SYSTEM:
% ANALYSIS OF STRATEGIES OVER TIME
% Jaakko Heikkilä, MTT Economic Research
% April 4, 2005.
% This script undertakes the analysis, as guided by ajotiedosto
% ####################################################################

function [ZP, dCS1, dCS2, dPS1, dPS2, H1, H2] = CPB_analysis()
clear variables                          % clears the Workspace
set_parameters                           % run m-file that determines the basic parameters
define_trends                            % run m-file that creates the trends
create_variables                         % run m-file that creates the variables
pakkaa                                   % run m-file that frees up some memory

% CREATE EMPTY MATRICES FOR THE VARIABLES

t = years; i = runs;

H1 = zeros(t,i); H2 = zeros(t,i);
dp1 = zeros(t,i); dp2 = zeros(t,i);
ZP = zeros(t,i); df = zeros(t,i); Z = zeros(t,i);
dPS1 = zeros(t,i); dPS2 = zeros(t,i);
dCS1 = zeros(t,i); dCS2 = zeros(t,i);

% RANDOM INVASION AND FAILURE MATRIX IS CREATED

for t=1:years                            % all the following is carried out for time defined by
years
        for i=1:runs                     % as well as iterations defined by runs

        inv_rand(t,i) = rand;            % random, uniformly distributed matrix inv_rand
        if inv_rand(t,i)<invprob(t);
            inv(t,i)=1;                  % if it is less than invprob, invasion is 1 (true)
        else inv(t,i)=0; end;            % and zero otherwise

        fail_rand(t,i) = rand;           % random, uniformly distributed matrix fail_rand
        if fail_rand(t,i)<failprob(t);   % if fail < failprob, failure is 1 (true) and 0 otherwise
        fail(t,i) = 1;
        else fail(t,i) = 0; end

    end
end
```

CPB_analysis.m continued…

```
% THE INVASION SCENARIOS ARE CREATED

H1 = inv .* initc .* s;                 % set the initial conditions for hectarages in Scens 1 and2
H2 = H1;                                % i.e. this much comes in every year

for t=2:years                           % all the following is carried out for time defined by
years
        for i=1:runs                    % as well as iterations defined by runs

% SCENARIO 1

H1(t,i) = H1(t,i) .* (1 - (H1(t-1,i) .* wintsurv(t-1,i) / Htot)) ...
    + (H1(t-1,i) .* wintsurv(t-1,i) .* spread(t-1,i) ...
    / (1 + ((spread(t-1,i) - 1) .* H1(t-1,i) .* wintsurv(t-1,i) / Htot)));

% SCENARIO 2

H2(t,i) = H2(t,i) .* (1 - (H2(t-1,i) .* wintsurv(t-1,i) / Htot))...
    + H2(t-1,i) .* wintsurv(t-1,i) + linspread(t-1,i) .* wintsurv(t-1,i) .* (H2(t-1,i)/(H2(t-
1,i)+o));

        end
end

pakkaa

% DETERMINE THE INVASION INDUCED PRICE CHANGES

        dp1 = -D .* p .* elast .* (H1/Htot);
        dp2 = -D .* p .* elast .* (H2/Htot);

% CREATE DISCOUNT FACTOR

for t=1:years
    for i=1:runs
        df(t,i) = 1 / ((1+r)^((t)-1));
    end
end


% CALCULATE ADAPTATION COSTS

dPS1 = (q .* D * p .* H1 + pzzi .* H1-((Htot-H1) * q .* dp1)-(H1 * q .* (1-D) .* dp1)) .* df;
dPS2 = (q .* D * p .* H2 + pzzi .* H2-((Htot-H2) * q .* dp2)-(H2 * q .* (1-D) .* dp2)) .* df;

dCS1 = (dp1 * Htot * q .* D .*(H1/Htot)/2 + (dp1 .* (Htot * q .* (1-D .* H1/Htot)))) .* df;
dCS2 = (dp2 * Htot * q .* D .*(H2/Htot)/2 + (dp2 .* (Htot * q .* (1-D .* H2/Htot)))) .* df;

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% CALCULATE PROTECTION COSTS

Z = inv .* initc;       % set the initial conditions for hectarages

for t=2:years
        for i=1:runs
         Z(t,i) = Z(t,i) + fail(t-1,i) .* fail_area(t-1) .* Z(t-1,i) .* wintsurv(t-1,i);
        end
end

ZP = (F1 + F2 + V1 .* Z .* g + (V2 + V3) .* Z) .* df; % calculate protection cost based on area

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```

set_parameters.m

```
% ###################################################################
% COLORADO POTATO BEETLE PROTECTION SYSTEM:
% ANALYSIS OF STRATEGIES OVER TIME
% Jaakko Heikkilä, MTT Economic Research
% March 4, 2005.
% This script is used to define the parameter values
% ###################################################################

% DEFINE THE VALUES FOR THE FOLLOWING CONSTANT PARAMETERS
runs = 1;               % how many iterations are made
years = 50;             % how many years are included
pzzi_base = 100;        % reactive control costs 100 e/ha
p = 0.20;               % pre-invasion producer price 0.20 e/kg
elast = -2;             % yield effect on price -2
q = 24400;              % quantity produced 24400 kg/ha
r = 0.02;               % discount rate 2%
F1 = 36222;             % fixed costs (labour + bought services) 36222 e/yr
F2 = 1605;              % fixed costs (misc costs) 1605 e/yr
V1 = 256.00;            % variable costs (inspection visits) 256 e/visit
V2_base = 20.00;        % variable costs (control substances) 20 e/ha
V3 = 610.00;            % variable costs (eradication and compensation) 610 e/ha
Htot = 29100;           % total production area 29100 ha
g = 4;                  % inspection visits = controlled area * g
invprob_base = 0.33;    % invasion probability 33%
failprob_base = 0.30;   % protection system failure probability 30%
failarea_base = 0.20;   % protection system failure area, 20% of infected area
o = 000000000000000000000000000000000.1;   % something small

% DEFINE THE TREND AS 0 = NO TREND, 1 = SLOW OR 2 = RAPID TREND
invasion_probability = 1;
invasion_magnitude = 1;
winter_survival = 1;
variable_prevention_costs = 1;
variable_reactive_costs = 1;

% THE FOLLOWING SET THE TRENDS IN PROTECTION FAILURE
trend_failprob = 0.05;  %failure probability increases over time (note, not when trend = 0)
trend_failarea = 0.05;  %failure area increases over time (note, not when trend = 0)

% DEFINE THE MEANS FOR THE VARIABLES THAT ARE ALLOWED TO FLUCTUATE
D_mean = 0.10;          % mean damage 10% of crop
initc_mean = 400;       % initial control magnitude 400 ha
s_mean = 1.5;           % spread in the initial year from the initial magnitude if no action taken
spread_mean = 1.8;      % spread rate in logistic spread scenario
linspread_mean = 400;   % in linear spread scenario mean annual spread 400 ha
wintsurv_mean = 0.30;   % determines proportion of population (area) that survives the winter

% DEFINE THE VARIANCES FOR THE VARIABLES THAT ARE ALLOWED TO FLUCTUATE
D_var = 0.005;
initc_var = 20000;
s_var = 0.05;
spread_var = 0.4;
linspread_var = 10000;
wintsurv_var = 0.02;
```

create_variables.m

```
% ################################################################
% COLORADO POTATO BEETLE PROTECTION SYSTEM:
% ANALYSIS OF STRATEGIES OVER TIME
% Jaakko Heikkilä, MTT Economic Research
% March 4, 2005.
% This script creates the variables needed
% ################################################################

for t = 1:years
    for i = 1:runs
            resist_trend_AVx(t,i) = (1+(t-1)*resist_trend_AV);
            resist_trend_pzzix(t,i) = (1+(t-1)*resist_trend_pzzi);
        end
    end

    for t = 1:years
            inv_trendx(t) = (1+(t-1)*inv_trend);
            trend_failprobx(t) = (1+(t-1)*trend_failprob);
            trend_failareax(t) = (1+(t-1)*trend_failarea);
        end

        invprob = invprob_base.*inv_trendx';
        failprob = failprob_base.*trend_failprobx';
        fail_area = failarea_base.*trend_failareax';
        V2 = V2_base.*resist_trend_AVx;
        pzzi = pzzi_base.*resist_trend_pzzix;
        invprob(invprob<0)=0;
        invprob(invprob>1)=1;
        failprob(failprob<0)=0;
        failprob(failprob>1)=1;
        fail_area(fail_area<0)=0;
        fail_area(fail_area>1)=1;

% DAMAGE
D = D_mean + sqrt(D_var) .* randn(years,runs);
D(D<0)=0;

% INITIAL YEAR SPREAD MULTIPLIED
s = s_mean + sqrt(s_var) .* randn(years,runs);
s(s<1)=1;

% LINEAR SPREAD AREA
linspread = linspread_mean + sqrt(linspread_var) .* randn(years,runs);
linspread(linspread<0)=0;

% LOGISTIC SPREAD RATE

spread = spread_mean + sqrt(spread_var) .* randn(years,runs);
spread(spread<1)=1;

for t = 1:years
    for i = 1:runs

wintsurv(t,i) = wintsurv_mean*(1+(t-1)*wintsurv_trend) + sqrt(wintsurv_var) .* randn(1,1);
initc(t,i) = initc_mean*(1+(t-1)*initc_trend) + sqrt(initc_var) * randn(1,1);

    end
end

wintsurv(wintsurv<0)=0; wintsurv(wintsurv>1)=1;
initc(initc<0)=0;
```

define_trends.m

```
% ####################################################################
% COLORADO POTATO BEETLE PROTECTION SYSTEM:
% ANALYSIS OF STRATEGIES OVER TIME
% Jaakko Heikkilä, MTT Economic Research
% March 4, 2005.
% This script is used to create the trends
% ####################################################################

% SET TREND LEVELS FOR NO, SLOW AND RAPID

% TREND IN INVASION PROBABILITY AND MAGNITUDE
inv_trend_no = 0.00;  initc_trend_no = 0.00;
inv_trend_slow = 0.01; initc_trend_slow = 0.01;
inv_trend_rapid = 0.02; initc_trend_rapid = 0.02;

% TREND IN WINTER SURVIVAL
wintsurv_trend_no = 0.00;
wintsurv_trend_slow = 0.01;
wintsurv_trend_rapid = 0.02;

% TREND IN PESTICIDE RESISTANCE
resist_trend_AV_no = 0.00; resist_trend_pzzi_no = 0.00;
resist_trend_AV_slow = 0.02; resist_trend_pzzi_slow = 0.02;
resist_trend_AV_rapid = 0.03; resist_trend_pzzi_rapid = 0.03;

% DETERMINES THE TREND VARIABLES

if invasion_probability == 0; inv_trend = inv_trend_no;
elseif invasion_probability == 1; inv_trend = inv_trend_slow;
elseif invasion_probability == 2; inv_trend = inv_trend_rapid; end

if invasion_magnitude == 0; initc_trend = initc_trend_no;
elseif invasion_magnitude == 1; initc_trend = initc_trend_slow;
elseif invasion_magnitude == 2; initc_trend = initc_trend_rapid; end

if winter_survival == 0; wintsurv_trend = wintsurv_trend_no;
elseif winter_survival == 1; wintsurv_trend = wintsurv_trend_slow;
elseif winter_survival == 2; wintsurv_trend = wintsurv_trend_rapid; end

if variable_prevention_costs == 0; resist_trend_AV = resist_trend_AV_no;
elseif variable_prevention_costs == 1; resist_trend_AV = resist_trend_AV_slow;
elseif variable_prevention_costs == 2; resist_trend_AV = resist_trend_AV_rapid; end

if variable_reactive_costs == 0; resist_trend_pzzi = resist_trend_pzzi_no;
elseif variable_reactive_costs == 1; resist_trend_pzzi = resist_trend_pzzi_slow;
elseif variable_reactive_costs == 2; resist_trend_pzzi = resist_trend_pzzi_rapid; end
```

pakkaa.m

```
cwd = pwd;
  cd(tempdir);
  pack
  cd(cwd)
```

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