A Comparative Static Analysis For Invasive Species Management Under Risk Neutral Preferences

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A COMPARATIVE STATIC ANALYSIS FOR INVASIVE SPECIES MANAGEMENT UNDER RISK NEUTRAL PREFERENCES

by

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ABSTRACT

This thesis investigates the optimal ex-ante mix of self-protection and self-insurance technologies employed to reduce the risk of biological invaders in the presence of exogenous variables within the probability and damage functions. This is accomplished by using a theoretical endogenous risk model that extends previously developed frameworks. This thesis contributes to the previous work in two ways. (1) Employing a general framework with simultaneous decision making over self-protection and self-insurance, this thesis analyzes how each parameter including income, the costs of each activity, an exogenous factor that affects only the probability of an invasion, and a separate exogenous factor that affects only the damages influence the level of self-protection and self-insurance. (2) The comparative static results are derived in the benchmark case of risk neutral preferences and qualitatively compared to an extended case of risk averse preferences.

The results of the analysis indicate that under risk neutral preferences the signs of the comparative statics are unambiguous while under risk aversion the results are not clearly defined. Thus, the ambiguity of signs in the latter case can be attributed to the unobservable utility terms present under risk averse preferences. Therefore, it can be concluded that the model is not capable of yielding a decision criteria that will hold universally because the results are dependent on the nature of the risk averse curve.

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Aquatic Invasive Species	AIS
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National Invasive Species Act	NISA
National Management Plan	NMP
Nonindigenous Aquatic Nuisance Prevention and Control Act	NANCPA
Nonindigenous Invasive Species	NIS
Nonindigenous Species	NS

1. INTRODUCTION

An emerging issue in environmental policy involves investing in technologies that reduce the probability of a biological invasion and the potential consequences in the event of such an occurrence. The probability of a successful invasion is usually not known with certainty but is expected to be small (Leung et al. 2002). Additionally, the potential consequences from a successful invasion are not known, but are expected to be large (Horan et al. 2002). There are typically two types of technologies, namely, self-protection and self-insurance that decision makers can employ to reduce the likelihood of a species invasion and its concomitant consequences. In many instances the use of both technologies is required to effectively prevent and control against harmful non-indigenous or invasive species. The optimal mix of strategies employed can be influenced by many exogenous factors, including those related to specific site and species characteristics, as well as the efficacy of the technologies employed to produce the desired effects.

This thesis follows previous work by Shogren (2000) in determining the optimal decision of a benevolent social planner faced with reducing the risk posed by a biological invader. Two general questions are addressed using a theoretical endogenous risk model. (1) How will the optimal mix of risk reducing technologies (ex-ante) be influenced by changes in exogenous factors that affect the probability of a successful invasion? (2) How will the optimal mix of risk reducing technologies (ex-ante) be influenced by changes in exogenous factors that affect the level of expected damages? Determining the optimal mix of risk reducing strategies is important because of the threat invasive species pose to society and the environment.

Until recently, little attention had been placed on constructing a theoretical framework that addressed the issue of the optimal management of invasive species and the characterization of the optimal mix of ex-ante self-protection and self-insurance strategies. Existing studies have mainly focused on identifying optimal control strategies of a species that has already permeated an area. The potentially enormous costs associated with biological invasions seem to suggest that more effort be devoted to identifying optimal prevention strategies. However, the lack of certainty surrounding the invasion process inhibits the ability to accurately assess many prevention strategies. The suggested model in this paper provides a guide for decision makers in determining optimal levels of prevention and control strategies to employ when faced with the risk from a potential invader.

This thesis contributes to previous work in two ways. (1) This thesis analyzes how each parameter including income, the costs of each activity, an exogenous factor that affects only the probability of an invasion, and a separate exogenous factor that affects only the damages will influence the level of self-protection and self-insurance. (2) The comparative static results are derived under risk neutral and risk averse preferences and qualitatively compared.

To begin the analysis, the benchmark case is considered in which an expected utility maximizer is risk neutral. Although, risk neutrality seems to be the dominate preference for managers faced with biological invaders (Archer and Shogren 1996), this assumption might be too restrictive when evaluating environmental problems which are often associated with large and irreversible consequences that could result in enormous variations of wealth. Thus, the case of a risk averse benevolent social planner is also considered in this analysis in order to illustrate the differences between assuming a risk neutral or risk averse individual.

The results of the comparative static analysis indicate that under risk neutral preferences the signs of the comparative statics are unambiguous while under risk aversion the results are not clearly defined. Thus, the ambiguity can be attributed to the risk behavior defined by the utility function. Under certain additional conditions the signs of the comparative static results can be found but the conclusions would be subject to the certain assumptions. Assigning numerical values to the unobserved utility terms could alleviate some of the ambiguity but this is often difficult and complex.

The remainder of this thesis is organized as follows. Section 2 reviews the problem of invasive species. Section 3 reviews the literature on self-protection and self-insurance. Section 4 presents the general framework followed by a section on the comparative static analysis and an economic interpretation under risk neutral preferences. Section 6 provides the comparative static analysis and economic interpretation as well as assumptions necessary to sign the comparative statics under risk averse preferences. Section 7 provides a discussion of the differences of the risk neutral and risk averse case. Section 8 concludes this thesis.

2. PROBLEM

A necessary first step is to define an invasive species. A non-indigenous species (NS) refers to a species that is not native to the area that it inhabits. Once an NS is introduced in a new habitat it can establish and spread and has the potential to severely alter the environment. If an NS establishes itself in a region outside its native range and causes harm, it is deemed as an "invasive" species (NIS) (Perrings et al. 2002). It is important to distinguish between an NS and an NIS, because not all NS that establish themselves cause harm (National Oceanic Atmospheric Administration 2002). In many cases an invasive species will also provide benefits to the surrounding environment and to society. Thus, limiting the definition of invasive species as those species that result in damages is somewhat misleading because many invaders might have desirable impacts as well. However, many of the impacts are site, species, and user specific.

Regardless of the benefits that an NIS might provide, it is the significant losses that have accumulated as a result of a biological invasion that have garnered most attention. Over the last few decades, increases in noticeable damages have caused considerable concern within biologic and economic communities. The damages associated with invaders have resulted in losses worth billions of dollars to the United States (Pimental et al. 1999). Therefore, substantial resources are delegated to the prevention and control of invasive species. For example, an estimated $45 million is spent annually on the control of the purple loosestrife (*Lythrum salicaria*) (Rodefeld and Zodrow 1996) and approximately $10-$15 million is spent annually on the control of sea lampreys (*Petromyzon marinus*) (Committee for the National Institute for the Environment 1999). Invasive species are thought to be a serious threat because once a species is established it is often costly to control and the damages are often irreversible (National Oceanic Atmospheric Administration 2002).

Some of the well-known impacts from invasive species include environmental degradation, reductions in wildlife population, adverse consequences to human health, and damages to economic structures and equipment. Invasive species are the suspected cause for almost half of all species listed on the endangered species list, making them the second major cause of biodiversity loss (Perrings et al. 2002; Horan et al. 2002). An estimated 109 out of 256 vertebrate extinctions identified worldwide are due to biological invaders (Olson and Roy 2002). For example, since the invasion of the brown tree snake (*Boiga irregularis*) in Guam, twelve different bird species native to the island have disappeared (National Agricultural Library 2003). A reduction in biological diversity could have a significant impact on the stability and productivity of ecosystem processes (Tillman 1999).

Organisms have always traveled outside of their native habitats. However, recent increases in human population and growth followed by increased globalization and trade have resulted in a greater number of species introductions into new habitats (Pimental et al. 1999). Estimates suggest that one out of ten introduced species will become established and of those only one-tenth will cause harm (National Oceanic Atmospheric Administration 2002). These estimates suggest a small risk of invasion but because of the increases in human activities the risk is expected to be growing (Shogren 2000). One study suggests that human activities have caused an increase in the natural spread rate of some aquatic organisms by 50,000 times (National Oceanic Atmospheric Administration 2002). In response to the increased risk from invasions, the National Invasive Species Council was formed in 1999. In January of 2001 the council released the first National Management Plan (NMP) (National Invasive Species Council 2001). The NMP outlines coordinated prevention and control strategies of NIS through education, research, and action efforts (National Invasive Species Council).

There are two distinct ways that the spread of NIS into new habitats has increased from human activities. These include intentional and unintentional introductions. Many species have been intentionally introduced for agricultural, recreational, and ornamental purposes (Pimental et al. 1999). However, the benefits provided by a species, that has been intentionally introduced, are often outweighed by the negative impacts that result once the species establishes and spreads. For instance, the Giant Salvinia (*Salvinia molesta*), which was intentionally introduced in the United States for ornamental purposes, is known for forming dense mats that block sunlight for vegetation. The weed also causes a decrease in the amount of oxygen in the water thereby adversely affecting fish populations (U.S Army Corps of Engineers 2004). Another example is the Nile perch (*Lates niloticus*) that was intentionally introduced in Lake Victoria, Tanzania. The establishment of the Nile perch is responsible for the creation of a $400 million export market for the area (Salamone 2003). However, many negative ecological indirect impacts have come about as a result of the invader including loss of native fish species and water quality problems (Shogren 2000).

Many NIS are also the result of unintentional introductions. There are many pathways in which a species can accidentally spread into a new area, including recreational equipment, boat hulls, and ballast water. For instance, aquatic weeds typically grow within several feet of the waters surface and often get caught in boat propellers. Recreational boaters who visit different areas can easily transfer the species if it is caught or suspended in the equipment. Examples of aquatic and wetland plants and animals that have been transported by these means include Hydrilla (*hydrilla verticillata*), Eurasian water-milfoil (*Myriophyllum spicatum*), Water chestnut (*Trapa natans*), and Water hyacinth (*Eichhornia crassipes*).

Aquatic weeds and other aquatic invasive species (AIS) are particularly problematic. These types of invaders are responsible for significant economic and environmental damages and are amongst the top four threats to the world's oceans (Global Ballast Water Management Programme 2004). The most common way that AIS are unintentionally introduced is via ships' ballast waters (Global Ballast Water Management Programme 2004). The term ballast refers to, "any material that is used to weight and /or balance an object" (Global Ballast Water Management Programme 2004). Cargo ships use ballast water to ensure stability during long trips. Estimates suggest that between 3 and 5 billion tons of ballast water is exchanged internationally per year and during any period an estimated 7,000 different species are present in ships ballast water tanks (Global Ballast Water Management Programme 2004). Ballast water exchange is the main cause for the introduction of such detrimental species as the Round Goby (*Neogobius melanostomus*), Sea Lamprey (*Petromyzon marinus*), and Eurasian Ruffe (*Gymnocephalus cernuus*) (Committee for the National Institute for the Environment 1999).

Several laws and regulations have been proposed and implemented to specifically target AIS, including the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANCPA) of 1990. The legislative act initially focused on prevention and control of AIS in the Great Lakes Region. The Great Lakes Region has been particularly affected by the introduction of invasive species via ballast water since the opening of the St. Lawrence Seaway in 1959. The St. Lawrence Seaway is a channel that runs through the Great Lakes that has enabled more and larger vessels access to the area. Almost 30% of the known 145 introductions of invasive species in the Great Lakes have occurred since the opening of the St. Lawrence Seaway (Horan et al. 2002).

One of the most notorious AIS to enter the Great Lakes Region, and one of the main reasons for the conception of legislation initiatives, including NANCPA, is the zebra mussel (*Dreissena polymorpha*). The zebra mussel is known for causing several billion dollars in damages to Great Lake water users, including municipalities and industries. For instance, the average yearly expenses for control of zebra mussels range from $20,000 for small municipalities, to $360,000 for large municipalities, and as high as $825,000 for nuclear power plants (U.S. Fish and Wildlife Services 2004). Zebra mussels are also responsible for degrading ecosystems and recreational equipment, affecting human and wildlife health, and altering environmental quality.

The Great Lakes Region is just one of many areas that have been severely impacted by unintentional introductions of AIS. Many areas that are surrounded by a body of water are particularly at risk for aquatic invaders. In the United States, AIS "hotspots" include the San Francisco Bay, the Chesapeake Bay, the Gulf of Mexico, the Hawaiian Islands, Florida, and virtually any other area located near a body of water with a major port (U.S. Fish and Wildlife Services 2004). AIS in these areas can be particularly devastating because many of the communities depend on the revenue generated by the economic and recreational use of the water resources to support the local economies (U.S. Fish and Wildlife Services 2004).

In order to extend the protection from the Great Lakes region to other valuable natural resource areas, NANCPA was reauthorized, amended, and renamed the National Invasive

Species Act (NISA) in 1996 (Union of Concerned Scientists 2003). The most current reauthorization of NISA was the National Aquatic Invasive Species Act of 2003 (NAISA). The overall purpose of NAISA is to combat the growing problem of unintentional AIS introductions in the United States through continued and increased prevention and control strategies.

The concern over the mounting problems associated with invasive species has resulted in a rise in the number of legislative actions, which devote significant resources to mitigate possible invaders. However, because of the risk and uncertainty of the problem, determining the optimal allocation of resources to reduce the risk is difficult and complex, but can be addressed using economic decision making models.

3. LITERATURE REVIEW

The invasive species problem is representative of a situation that is risky and uncertain. However, as is the case in other problems, the level of risk can be highly influenced by human actions that prevent an event from occurring or control for the damages if the event does occur. Hence forth in this thesis, the risk reducing technologies of prevention and control shall be referred to as “self-protection” and “self-insurance,” respectively. The distinction of terms follows from Ehrlich and Becker (1972) who denote self-protection as any action that will reduce the probability of an event from happening and self-insurance as any action that will reduce the potential damages if the event occurs.

In Ehrlich and Becker’s (1972) article, the authors discuss the relationship between self-protection and market insurance and between self-insurance and market insurance. They find that market insurance and self-insurance are substitutes while market insurance and self-protection are complements. Since their seminal article, the examination of self-protection and self-insurance has been addressed in numerous applications. Including, Hiebert (1983) who examines the impact of increases in risk aversion and the probability of loss for two separate models. The first model considers only self-protection as it affects only the probability and a second model that considers only self-insurance as it affects only the severity of the losses. Boyer and Dionne (1983) investigate the relationship between self-protection and self-insurance when market insurance is available and when it is not. To accomplish their purpose, they use a model that considers jointly self-protection and self-insurance. Boyer and Dionne (1983) show that risk averse individuals will prefer more self-insurance to self-protection in the absence of market insurance. When market insurance is available, a risk averse decision maker will prefer self-insurance over market insurance. Briys and Schlesinger (1988) test the robustness of the results found under Dionne and Eeckhoudt (1985) who concluded that a more risk averse individual would invest in self-insurance activities but not necessarily in self-protection.

The separate treatment of self-protection and self-insurance is often made for theoretical convenience (Shogren and Crocker 1991). However, since both represent activities that mitigate the risk associated with an event, classifying an activity as a single action is possible. An early paper that considers self-protection as it affects both the probability and severity of health outcomes is in Shogren and Crocker (1991). Shogren and Crocker (1991) investigate the marginal willingness-to-pay for a reduction in an exogenous health risk. The authors discuss how a change in the random variable, representing exogenous risk, that is present in both the probability and loss function, will influence the initial wealth under risk averse preferences. Their efforts differ from previous studies that consider the willingness-to-pay for a reduction in risk. They demonstrate that when self-protection influences both the probability and severity of health outcomes, the presence of the unobserved utility terms inhibits the ability to express the marginal willingness-to-pay for a reduction in risk as the marginal rate of technical substitution between ambient hazard concentrations and self-protection (Shogren and Crocker 1991).

Several years later, Shogren and Crocker (1999) revisit the framework, previously developed in Shogren and Crocker (1991) in which self-protection affects the probability and severity of a health outcome. The purpose of their later article is to discuss the problems associated with assuming additively separable variables in the consequence function. Under the assumption of risk averse preferences, Shogren and Crocker (1999) demonstrate that the result for a change in ambient risk on a change in the level of self-protection is ambiguous.

Although, the action of reducing the probability and reducing the potential damages from an event can be, and are often, referred to as similar activities, in many cases the actions might be different and each independently influences the probability of an event or the expected damages, as previously assumed by Ehrlich and Becker. However, even by explicitly defining each action as separate, the joint consideration of both activities is helpful in many situations including invasive species management issues.

Shogren (2000) appears to be the first to consider both self-protection and self-insurance in the context of invasive species management. Shogren (2000) follows closely the set-up of the model used in previous papers co-written with Crocker (Shogren and Crocker 1991; 1999). In these, the probability of being in a good or bad state is a function of both self-protection and an unidentified exogenous risk. The major difference between the formulation of Shogren's (2000) model to those of Shogren and Crocker (1991; 1999) is that while Shogren and Crocker (1991) assume the costs or losses, associated with the bad state of nature, are subject to the same self-protection activity and exogenous risk that affect the probability of being in either state, Shogren (2000) explicitly defines between self-protection and self-insurance activities that affect either the probability or the damages, respectively. Secondly, in application of the model, as previously mentioned Shogren and Crocker (1991) use their framework to address the willingness-to-pay for a reduction in an exogenous risk by looking at how a change in the risk will influence income. Using the same framework, Shogren and Crocker (1999) consider how a change in the exogenous risk will influence the level of self-protection. Shogren (2000) uses the framework to only verbally address the applicability and implications of the framework for research into exotic invaders.

Since Shogren's (2000) efforts, the numbers of articles that consider the explicit separation of self-protection and self-insurance in a joint framework, particularly for invasive species management, have increased. Considering the two activities as independent but jointly in the same framework has a major advantage when determining the optimal allocation of resources to different activities that mitigate the risks of a biological invader. Most recent efforts are those by Finnoff et al. (2004a), Leung et al. (2004) and Finnoff et al. (2004b).

Finnoff et al. (2004a) simulated invasive species management strategies using a stochastic dynamic programming (SDP) version of the endogenous risk model. In a dynamic framework, the authors investigated how the optimal mix of self-protection and self-insurance will respond to variations in a manager's time preference and risk attitudes. The simulations demonstrate that less risk averse managers who are more far sighted will tend to employ more self-protection and less self-insurance. This finding is supported by Boyer and Dionne (1983), Dionne and Eeckhoudt (1985), and Briys and Shlesinger (1990) who examined the impact of varying degrees of risk aversion on the optimal levels of self-protection and self-insurance, and found that more risk averse individuals will always employ more self-insurance but not necessarily self-protection. Behavior by managers with these preferences results in lower probabilities of invasion, lower invader abundances, less need for adaptation on the part of private firms and greater social welfare (Finnoff et al. 2004a).

In a paper by Leung et al. (2004), the authors generated "rules of thumb" to assist managers in determining optimal prevention and control expenditures in a timely and cohesive manner. Each strategy is dealt with separately following a mathematical approach that uses comparative statics. They provided five general guidelines for managers to follow when investing in control or prevention technologies.

In a subsequent study, Finnoff et al. (2004b) followed the endogenous risk framework used by Leung et al. (2004) and incorporated the concept of feedbacks to determine how the inclusion of feedbacks will influence the optimal strategy mix. Again using a stochastic dynamic programming model the authors are able to simulate the optimal levels of prevention and control when feedback links are included in the analysis. The main findings of the model indicate that feedbacks matter but only in certain dimensions. If the decision maker is aware of the potential feedback links then the decision maker's preferences might indirectly be influenced, in which case, specifically identifying feedbacks might not matter.

Prior to the most recent efforts that explicitly account for self-protection and self-insurance for invasive species management, many studies focused on determining the optimal strategies that reduce the ex-post severity of a known invader since more information is available on the invader and its consequences. Several types of self-insurance strategies are considered including an eradication policy or a positive and continuous control strategy. Sharov and Liebhold demonstrate, using an application of the gypsy moth, that eradication is possible for a newly established species in a well-defined area. Similarly, Olson and Roy (2002) discuss when the eradication of a species is optimal and conclude that it is an optimal solution when the species is newly established and exhibits a high intrinsic growth rate. Typically, however, an eradication policy is seldom considered as a solution because it is often too costly, impractical, and could have significant non-target impacts (Darrigan 2002). For instance, Eiswerth and Van Kooten (2002) find that eradication will always result in a net loss and instead a policy that considers a continuous level of control method is more efficient. However, their application is to the yellow star-thistle, an invasive weed that has spread over 20 million acres in the state of California (Eiswerth and Van Kooten 2002). Since, the yellow star-thistle is not representative of a species that is newly established, it would seem unlikely that an eradication policy would be efficient. In contrast to those studies that identify strategies to reduce ex-post severity, few were identified that considered optimal probability-influencing strategies. However, the enormous costs that are incurred each year to control for invasive species suggests that more efforts be devoted toward identifying optimal self-protection activities.

Similar to the most recent efforts that consider self-protection and self-insurance for invasive species management, this thesis returns to the basic framework proposed by Shogren (2000), which closely follows Shogren and Crocker (1991; 1999). Similar to Shogren (2000) this thesis considers a framework that jointly considers how self-protection and an exogenous variable will influence the ex-ant probability as well as how self-insurance and an exogenous variable will influence the ex-post severity of an invasion. However, unlike Shogren and Crocker (1991; 1999) and Shogren (2000) the model used in this thesis deliberately separates a probability-influencing exogenous variable with a severity-influencing exogenous variable to focus on the probability function and the damage function.

This thesis takes the verbal motivation of Shogren (2000) and rigorously extends the effort in two major ways. (1) This thesis analyzes how each parameter including income, the costs of each activity, an exogenous risk that affects the probability of an invasion, and a separate exogenous risk that affects the damages will influence the levels of simultaneously chosen self-protection and self-insurance. Where as Shogren and Crocker (1991) only consider the willingness-to-pay from changes in an exogenous risk and who later (Shogren and Crocker 1999) consider how a change in self-protection, that influences both ex-ante probability and ex-post severity, is influenced from a change in the random variable representing exogenous risk.

(2) The comparative static results are derived under risk neutral and risk averse preferences and qualitatively compared. Where as Shogren and Crocker (1991; 1999) only consider a risk averse individual, and as demonstrated throughout the literature, the results are highly dependent on several critical ex-ante assumptions regarding the curvature of the probability and utility functions.

4. GENERAL FRAMEWORK

In this section, following Shogren's (2000) framework, a simple, single-period theoretical model is described to help guide decision-makers faced with the risk from a biological invader. A static approach is employed, because by definition, it does not need to account for the additional uncertainties and assumptions necessary to construct an inter-temporal model. The type of framework, used to model the invasive species management questions, is based on the endogenous risk theory that stems from the theory of decision making under uncertainty.

Expected utility is based upon utility theory, the latter of which begins with an axiomatic approach to model individual preferences under certainty (Culp 2003). The axioms enable the characterization of an individual as a rational economic agent who can choose among alternatives whose outcomes are known in a consistent manner (Jehle and Reny 1998). Despite some arguments against the underlying axioms of utility theory, this approach dominates economic analysis (Shogren and Crocker 1999) and has yet to be replaced (Van Kooten and Blackwell 2000).

Many decisions must be made under uncertainty, however. Expected utility theory is an extension of utility theory that defines an individual's preferences over uncertain outcomes and preferences over the gambles that define those outcomes. Similarly, an endogenous risk framework can be used to model decisions under uncertainty, but in addition it accounts for the influence an individual's behavior has on the likelihood and amount of risk incurred.

A utility function that can be defined over risks is usually referred to as a von Neumann-Morgenstern (NM) utility function (Jehle and Reny 1998; Kolstad 2000). A person who exhibits a NM utility function is an expected utility maximizer if the individual always chooses the payoff with the highest expected utility (Jehle and Reny 1998). The maximization of expected utility is often referred to as optimizing behavior (Jehle and Reny 1998).

The relationship between the expected utility of an outcome and the utility of the expected value of the outcome has been used to describe individuals' preferences under risk. There are three main types of risk attitudes, namely, risk aversion, risk loving, and risk neutrality. Each type of attitude is associated with a specific property of the NM utility function (Jehle and Reny 1998). For this analysis, two types of risk attitudes are considered including risk neutral and risk averse. In the next section the analysis begins with an expected utility maximizer, that is to say, a benevolent social planner, who is assumed to be risk neutral. Thus, the individual exhibits a linear utility function and is indifferent between the utility of the expected value and the expected utility of the payoffs in each state. Following the analysis of the risk neutral planner, the case of a risk averse social planner is considered. An individual who is risk averse typically exhibits a concave utility function and prefers the utility of the expected value to the expected utility of the payoffs.

4.1 Definition of Variables

Suppose there are two mutually exclusive and exhaustive states of the world: a good and a bad state of nature. For this analysis, the good state will be referred to as the non-invaded state and denoted as A, while the bad state of nature, denoted as B, will be referred to as the invaded state. The probability of each state is assumed known with certainty. With probability p, the non-invaded state will occur and with probability $(1-p)$, the invaded state will occur. Under several assumptions regarding individual behavior under uncertainty, the utility of a risk can be defined as the expected utility of the payoffs. The expected utility (*EU*) from payoffs in each state of nature is

$$EU\ (p,\ 1\text{-}p,\ A,\ B) = pU(A) + (1\text{-}p)U(B)\ . \tag{E1}$$

The payoff in each state is subject to the total costs of self-protection, *S*, and self-insurance, *X*. The payoff in the invaded state is also subject to potential damages *D*. Substituting this information in provides the following *EU* function

$$pU(M - C_S S - C_X X) + (1-p)U(M - C_S S - C_X X - D)\ , \tag{E2}$$

where *M* denotes the initial wealth of the social planner, the total costs are the product of the quantity of self-protection *S*, and self-insurance *X*, and the cost of each technology are denoted as $C_S > 0$ and $C_X > 0$ respectively.

Recall that within the endogenous risk framework, the individual has the ability to influence the probability of being in either state by employing self-protection activities. However, it is also reasonable to assume that other factors might influence the probability of being in either state. Therefore, let the probability function be denoted as

$$p(S;\alpha) \quad \in (0,1)\ , \tag{E3}$$

where α represents an, as of yet, unspecified exogenous variable that can influence the probability of being in either state.

Now turn to the damage function. Again, under the endogenous risk framework the amount of damages realized in the bad (or invaded) state of nature is dependent on the amount of self-insurance the individual employs. It is also presumed that the level of damages can also be influenced by exogenous factors. Therefore, let the damage function be denoted as

$$D(X;\beta) > 0, \tag{E4}$$

where β represents an unspecified exogenous variable that can influence the amount of damages realized. Substituting the functions (E3) and (E4) into the *EU* function, shown in (E2) yields the benevolent social planner's problem as:

$$\begin{aligned}\max\ EU = {} & p(S;\alpha)U(M - C_S S - C_X X) \\ & + (1 - p(S;\alpha))U(M - C_S S - C_X X - D(X;\beta))\end{aligned} \tag{E5}$$

Two key assumptions are now made:

$$p(\cdot) \quad \in \quad C^{(2)}, \tag{E6}$$

$$D(\cdot) \quad \in \quad C^{(2)}. \tag{E7}$$

Under the assumption that equations (E6) and (E7) hold then both the probability function, $p(\cdot)$, and the damage function, $D(\cdot)$, are twice continuously differentiable. Note that no other assumptions are placed on the function $p(\cdot)$ and $D(\cdot)$.

5. ECONOMIC MODEL: RISK NEUTRAL PREFERENCES

5.1 Theoretical Model

In this section, it is assumed that the individual decision maker is a risk neutral benevolent social planner. The social planner's objective is to maximize expected social welfare by choosing the optimal levels of self-protection and self-insurance when faced with the risk from a potential invader. Recalling the assumption of risk neutrality, in which the utility function is linear, then $U'(\cdot) = 1$ and $U''(\cdot) = 0$, where primes denote relevant derivatives, reveals the planner's problem as

$$\max EU = p(S;\alpha)(M - C_S S - C_X X) + (1 - p(S;\alpha))(M - C_S S - C_X X - D(X;\beta))$$

$$= M - C_S S - C_X X - D(X;\beta)[1 - p(S;\alpha)]. \tag{E8}$$

The first-order necessary conditions for an interior maximum are given by

$$EU_S = p_S(S;\alpha)D(X;\beta) - C_S = 0, \tag{E9}$$

$$EU_X = -C_X - D_X(X;\beta)[1 - p(S;\alpha)] = 0. \tag{E10}$$

where subscripts denote relevant partial derivatives[1]. From equation (E9), the social planner should employ self-protection activities until the marginal cost (C_S) of the activity equals the expected marginal benefit $((p_S(S;\alpha)D(X;\beta))$ realized by the self-protection activity. Note that by way of equation (E9), $p_S(S;\alpha) > 0$ holds, as $D(X;\beta) > 0$ and $C_S > 0$. From equation (E10), the social planner should employ self-insurance technologies until the marginal cost (C_X) of

[1] The subscripts attached to the costs, C, are used for convenience to differentiate the costs of self-protection and self-insurance and do not represent relevant partial derivatives.

those technologies equals the expected marginal benefit $((-D_X(X;\beta)[1-p(S;\alpha)])$ of the self-insurance technology. Note that by way of equation (E10), $D_X(X;\beta)<0$ holds, as $(1-p(S;\alpha))\in(0,1)$ and $C_X>0$.

To start the comparative static analysis, first substitute the simultaneous solutions to equations (E9) and (E10), $S^*(\alpha,\beta,C_S,C_X)$ and $X^*(\alpha,\beta,C_S,C_X)$, into the first-order necessary conditions to obtain identities, namely

$$p_S(S^*(\alpha,\beta,C_S,C_X);\alpha)D(X^*(\alpha,\beta,C_S,C_X);\beta)-C_S\equiv 0, \tag{E11}$$

$$-C_X-[1-p(S^*(\alpha,\beta,C_S,C_X);\alpha)]D_X(X^*(\alpha,\beta,C_S,C_X);\beta)\equiv 0. \tag{E12}$$

Differentiating these identities with respect to the parameters and solving the resulting linear equation using Cramer's rule will yield the comparative static expressions of interest.

The first-order conditions are necessary for a maximum but are not sufficient. The following second-order sufficiency conditions are therefore assumed to hold at the solution:

$$EU_{SS}=p_{SS}(S;\alpha)D(X;\beta)<0, \tag{E13}$$

$$EU_{XX}=-D_{XX}(X;\beta)[1-p(S;\alpha)]<0, \quad \text{and} \tag{E14}$$

$$|A|=-p_{SS}(S;\alpha)D(X;\beta)D_{XX}(X;\beta)[1-p(S;\alpha)]-\left[p_S(S;\alpha)D_X(X;\beta)\right]^2>0, \tag{E15}$$

where $|A|=(EU_{SS})(EU_{XX})-(EU_{SX})^2$. Note that because $D(X;\beta)>0$, $EU_{SS}<0$ if and only if $p_{SS}(S;\alpha)<0$, thereby, revealing that the marginal productivity of self-protection is diminishing. In other words, each additional unit of self-protection employed will increase the probability of being in the good state, but by not as much as the previous unit. Similarly, since $p(S;\alpha)\in(0,1)$, then $EU_{XX}<0$ if and only if $D_{XX}(X;\beta)>0$. Thus, as more self-insurance is employed, less damages accumulate, but at a diminishing rate, thereby reflecting diminishing marginal productivity. Finally, the second order cross partial derivative is shown as

$$EU_{SX} = EU_{XS} = p_S(S;\alpha)D_X(X;\beta) \quad < 0, \tag{E16}$$

in view of the previously established results that $p_S(S;\alpha) > 0$ and $D_X(X;\beta) < 0$.

5.2 Comparative Statics and Economic Interpretation

Recall that the main objective of this thesis is to identify the optimal mix of self-protection and self-insurance when influenced by changes in factors that affect the probability of a successful invasion and the expected damages. The answers to these questions can be addressed using a comparative-static analysis. The analysis will determine how the decision variables *X* and *S* will change in response to a change in the exogenous variables $M, C_S, C_X, \alpha,$ and β. Since the analysis is qualitative, the signs of the comparative-static derivatives are of interest.

To begin, consider how a change in income, *M*, will effect the optimal levels of self-protection and self-insurance. From equations (E11) and (E12) the comparative static results are equal to zero since they are independent of *M*:

$$\frac{\partial S^*}{\partial M} \equiv 0, \tag{E17}$$

$$\frac{\partial X^*}{\partial M} \equiv 0. \tag{E18}$$

From equations (E17) and (E18), the comparative-static results indicate that a risk neutral social planner would not adjust the optimal levels of each technology when initial wealth changes. Recall that an individual with risk neutral preferences exhibits a linear NM utility function, hence the expected utility of the payoffs will always equal the utility of the expected payoffs. This condition will hold for any level of initial wealth in the case of risk neutral preferences.

Now consider how a change in the cost of self-protection, C_S, will influence the optimal levels of S^* and X^*. This requires the partial differentiation of equations (E11) and (E12) with respect to C_S, resulting in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial C_S \\ \partial X^*/\partial C_S \end{bmatrix} \equiv \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{E19}$$

From equation (E19), the comparative static results are

$$\frac{\partial S^*}{\partial C_S} \equiv \frac{\begin{vmatrix} 1 & EU_{SX} \\ 0 & EU_{XX} \end{vmatrix}}{|A|} \equiv \frac{EU_{XX}}{|A|} \quad < 0, \tag{E20}$$

$$\frac{\partial X^*}{\partial C_S} \equiv \frac{\begin{vmatrix} EU_{SS} & 1 \\ EU_{XS} & 0 \end{vmatrix}}{|A|} \equiv \frac{-EU_{XS}}{|A|} \quad > 0. \tag{E21}$$

These results imply that an increase in the cost of self-protection will result in a decrease in the level of self-protection employed and an increase in the level of self-insurance employed. Thus it is optimal to substitute towards the relatively cheaper mitigator.

Consider now how a change in the cost of self-insurance, C_X, will effect the optimal levels of self-protection S^* and X^*. This requires the partial differentiation of equations (E11) and (E12) with respect to C_X, resulting in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial C_X \\ \partial X^*/\partial C_X \end{bmatrix} \equiv \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{E22}$$

From equation (E22) the comparative static results are

$$\frac{\partial S^*}{\partial C_X} \equiv \frac{\begin{vmatrix} 0 & EU_{SX} \\ 1 & EU_{XX} \end{vmatrix}}{|A|} \equiv \frac{-EU_{SX}}{|A|} \quad > 0, \tag{E23}$$

$$\frac{\partial X^*}{\partial C_X} \equiv \frac{\begin{vmatrix} EU_{SS} & 0 \\ EU_{XS} & 1 \end{vmatrix}}{|A|} \equiv \frac{EU_{SS}}{|A|} \quad < 0. \tag{E24}$$

Similar to the prior results, an increase in the cost of one technology will lead to a decrease in the level of that technology and an increase in the level of the other. An economic interpretation of these results suggests that the technologies are substitutes since an increase in the cost of one technology will lead to an increase in the level of the other.

The above results are summarized in Table 1. The signs in parenthesis correspond to the comparative-static derivatives of the endogenous variables, *S* and *X*, with respect to the parameters, M, C_S, and C_X.

Table 1: Risk Neutral Comparative-Static Results for M, C_S, and C_X

	∂M	∂C_S	∂C_X
∂S^*	(0)	(-)	(+)
∂X^*	(0)	(+)	(-)

A negative sign indicates that an increase in one of the exogenous variables will lead to a decrease in the optimal level of the corresponding technology employed. A positive sign indicates that an increase in one of the exogenous variables will lead to an increase in the optimal level of the corresponding technology employed.

Next consider how the optimal levels of self-protection and self-insurance will respond to changes in the unspecified exogenous variable α. Partial differentiation of equations (E11) and (E12) with respect to α results in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^* / \partial \alpha \\ \partial X^* / \partial \alpha \end{bmatrix} \equiv \begin{bmatrix} - p_{S\alpha}(S;\alpha) D(X;\beta) \\ - p_{\alpha}(S;\alpha) D_X(X;\beta) \end{bmatrix}. \tag{E25}$$

From equation (E25), the comparative static results are

$$\frac{\partial S^*}{\partial \alpha} \equiv \frac{- p_{S\alpha} D(EU_{XX}) + p_{\alpha} D_X (EU_{SX})}{|A|}, \tag{E26}$$

$$\frac{\partial X^*}{\partial \alpha} \equiv \frac{- p_{\alpha} D_X (EU_{SS}) + p_{S\alpha} D(EU_{XS})}{|A|}. \tag{E27}$$

In order to sign equations (E26) and (E27), assumptions must be placed on p_{α} and $p_{S\alpha}$. From equations (E13), (E14), and (E15), and (E16) the signs of EU_{SS}, EU_{XX}, $|A|$, and EU_{SX} are known. Hence if p_{α} >0 and $p_{S\alpha} \geq 0$, then it follows that

$$\frac{\partial S^*}{\partial \alpha} > 0 \quad \text{and} \quad \frac{\partial X^*}{\partial \alpha} < 0 .$$

This indicates that an increase in the level of the exogenous variable α will increase the level of self-protection *S*, and decrease the level of self-insurance strategies if:

- An increase in α will lead to an increase in the probability of the good state, and
- An increase in α will not decrease the marginal productivity of self-protection.

In this case, α could represent the efficacy of self-protection technologies. If self-protection efforts are more efficient at preventing the likelihood of an invasion, then it is reasonable to assume that the probability of the good state of nature will increase as well as the marginal productivity of those efforts.

If $p_{\alpha}(S;\alpha) < 0$ and $p_{S\alpha}(S;\alpha) \leq 0,$ then the level of self-protection efforts would decrease and the level of self-insurance would increase. In this instance, α could be interpreted as representing an additional exogenous risk that the social planner has no control over. For instance, climatic and weather variations pose a potential risk that will likely negatively influence the probability of being in the non-invaded state. This type of exogenous risk could also have a negative or zero effect on the marginal productivity of self-protection activities.

Climatic variations and weather events are examples of exogenous risks because they have a significant influence on the dispersal, spread, and population growth of invasive species. For instance, the gypsy moth (*Lymantria dispar*) was transported across a barrier zone during a hurricane in the early 1930s (Olson and Roy 2002). In another example, the seeds from the leafy spurge (*Euphorbia esula*), a noxious weed, can catapult 15 feet from the plant and can spread by way of animals, wind, or waterways (Center for Environmental and Regulatory Information Systems 2004). These cases illustrate that it is reasonable to assume that there exists a negative relationship between an exogenous risk and the probability of being in the good state as well as a negative relationship on the marginal productivity of self-protection efforts. Intuitively, the greater the exogenous risk the less likely that prevention efforts would prove productive. Therefore, more efforts should be devoted to self-insurance because the likelihood of an invasion is greater and less preventable. The overall conditions and corresponding results of the comparative-static derivatives are summarized in Table 2.

Table 2: Risk Neutral Comparative-Static Results for α

	$\frac{\partial S^*}{\partial \alpha}$		$\frac{\partial X^*}{\partial \alpha}$	
	$p_\alpha > 0$	$p_\alpha < 0$	$p_\alpha > 0$	$p_\alpha < 0$
$p_{S\alpha} > 0$	(+)		(-)	
$p_{S\alpha} < 0$		(-)		(+)
$p_{S\alpha} = 0$	(+)	(-)	(-)	(+)

Finally, consider how the optimal levels of self-protection and self-insurance will respond to changes in the unspecified exogenous variable β . Partial differentiation of equations (E11) and (E12) with respect to β results in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial \beta \\ \partial X^*/\partial \beta \end{bmatrix} \equiv \begin{bmatrix} -p_S(S;\alpha)D_\beta(X;\beta) \\ D_{X\beta}(X;\beta)[1-p(S;\alpha)] \end{bmatrix}. \tag{E28}$$

From equation (E28) the comparative static results are

$$\frac{\partial S^*}{\partial \beta} \equiv \frac{-p_S D_\beta (EU_{XX}) - D_{X\beta}[1-p](EU_{SX})}{|A|}, \tag{E29}$$

$$\frac{\partial X^*}{\partial \beta} \equiv \frac{D_{X\beta}[1-p](EU_{SS}) + p_S D_\beta (EU_{XS})}{|A|} \ . \tag{E30}$$

In order to sign equations (E29) and (E30), assumptions must be placed on D_β and $D_{X\beta}$. If $D_\beta > 0$ and $D_{X\beta} \geq 0$, then

$$\frac{\partial S^*}{\partial \beta} > 0 \quad \text{and} \quad \frac{\partial X^*}{\partial \beta} < 0 .$$

This implies that an increase in the level of the exogenous variable β will increase the level of self-protection *S*, and decrease the level of self-insurance strategies if:

- An increase in β will lead to an increase in the damages, and
- An increase in β does not increase the marginal benefits of self-insurance.

In this case, β could be interpreted as representing quantified values of market or non-market "bads" that have a negative impact on economic structures or the environment. For instance, as previously mentioned, zebra mussels are known to cause significant damages to municipalities. A species that is suspected to pose a similar threat is the brown mussel (*Perna perna*). While no impacts or losses from the introduction of the brown mussel have been recorded yet, the similar biological composition of the species to the zebra mussel has led many to suspect that similar damages will result if the species becomes invasive. Since the species is expected to result in significant damages, a resource planner would likely employ more efforts toward prevention of the species and hence reduce control efforts.

If the opposite conditions are true, that is $D_\beta(X;\beta) < 0$ and $D_{X\beta}(X;\beta) \leq 0$, then β could be seen as representing the efficacy of self-insurance or control technologies. In this instance, the level of self-protection would decrease and the level of self-insurance would increase. If a control policy is more effective at reducing the current infestation of a species then the damages will be less. Additionally, an increase in the effectiveness of control will not decrease the marginal benefits of self-insurance. This result is intuitive since the resource manager would not need to invest in as many prevention efforts, which in many cases might be considered more risky (Dionne and Eeckhoudt 1985) if the species can be more efficiently controlled through self-insurance efforts.

The exogenous variable β could also be representative of market or non-market "beneficial" or "good" impacts. For example, a social planner would not want to expend efforts to prevent a species that is expected to result in positive impacts. The analysis indicates that the optimal solution is to reduce self-protection efforts, allowing some level of invasion to occur and use resources to control for any damages that might accumulate from the species. Control efforts are still warranted because, as mentioned earlier, in many cases a species will also have negative impacts. The overall conditions and corresponding results of the comparative-static derivatives are summarized in Table 3.

Table 3: Risk Neutral Comparative-Static Results for β

	$\frac{\partial S^*}{\partial \beta}$		$\frac{\partial X^*}{\partial \beta}$	
	$D_\beta > 0$	$D_\beta < 0$	$D_\beta > 0$	$D_\beta < 0$
$D_{X\beta} > 0$	(+)		(-)	
$D_{X\beta} < 0$		(-)		(+)
$D_{X\beta} = 0$	(+)	(-)	(-)	(+)

In summary, it was found that under risk neutral preferences, the results of the comparative static analysis indicate that when there is an increase in the probability of no losses or greater expected damages, then the risk neutral social planner's optimal solution would be to increase self-protection and decrease self-insurance efforts. Conversely, if there is an increase in the probability of losses or a decrease in expected damages associated with an invasive species, then the risk neutral planner's optimal solution is to decrease self-protection efforts and increase self-insurance efforts. In the next section, the comparative static analysis is performed again but investigates the optimal solution for a risk averse benevolent planner.

6. ECONOMIC MODEL: RISK AVERSE PREFERENCES

6.1 Theoretical Model

This section considers the more analytically complex case of a risk averse benevolent social planner. Under the assumption of risk aversion, the planner's utility function exhibits the properties $U'(\cdot) > 0$ and $U''(\cdot) < 0$, which indicate that the marginal utility of income is increasing at a decreasing rate. The risk averse planner's problem is shown in (E5) and restated below as

$$\max EU = p(S;\alpha)U(M - C_S S - C_X X) + (1 - p(S;\alpha))U(M - C_S S - C_X X - D(X;\beta))$$

where, for simplification, define

$$A = (M - C_S S - C_X X) \text{ and } B = (M - C_S S - C_X X - D(X;\beta)).$$

The first-order necessary conditions for an interior maximum are given by

$$EU_S = p_S(S;\alpha)[U(A) - U(B)] - C_S[p(S;\alpha)U'(A) + (1 - p(S;\alpha))U'(B)] = 0, \tag{E31}$$

$$EU_X = -p(S;\alpha)U'(A)C_X - (1 - p(S;\alpha))U'(B)[C_X + D_X(X;\beta)] = 0. \tag{E32}$$

From equation (E31), the social planner should employ self-protection activities until the expected marginal costs $(C_S[p(S;\alpha)U'(A) + (1 - p(S;\alpha))U'(B)])$ of the activity equals the expected marginal benefits ($p_S(S;\alpha)[U(A) - U(B)]$) realized by the self-protection activity. Note that by way of equation (E31), $p_S(S;\alpha) > 0$ holds, as previously found in the risk neutral case, as $[U(A) - U(B)] > 0$, $C_S > 0$, and $[p(S;\alpha)U'(A) + (1 - p(S;\alpha))U'(B)] > 0$. From equation (E32), the social planner should employ self-insurance activities until the expected marginal costs $[-p(S;\alpha)U'(A)C_X]$ equal the expected marginal

benefits $(1-p(S;\alpha))U'(B)[C_X + D_X(X;\beta)]$. It must therefore be the case that at the optimal

choice, $D_X(X;\beta) < 0$ and the absolute value of a marginal reduction in damages from increased

self-insurance is greater than the increase in the marginal cost of self-insurance, that

is, $|D_X(X;\beta)| > C_X$.

Substituting the simultaneous solutions to equations (E31) and (E32), namely

$S^*(M, C_S, C_X, \alpha, \beta)$ and $X^*(M, C_S, C_X, \alpha, \beta)$, into the first-order necessary conditions results in

the following identities, shown in equations (E33) and (E34). To simplify notation, let

$\delta = (M, C_S, C_X, \alpha, \beta)$ therefore,

$$
\begin{aligned}
EU_S = {} & p_S(S^*(\delta);\alpha))[U(M - C_S S^*(\delta) - C_X X^*(\delta) \\
& - U(M - C_S S^*(\delta) - C_X X^*(\delta) - D(X^*((\delta);\beta)] \\
& - C_S[p(S^*((\delta);\alpha)U'(M - C_S S^*(\delta) - C_X X^*(\delta) \\
& + (1 - p(S^*((\delta);\alpha)U'(M - C_S S^*(\delta) - C_X X^*(\delta) - D(X^*((\delta);\beta)] = 0,
\end{aligned}
\tag{E33}
$$

$$
\begin{aligned}
EU_X = {} & -[p(S^*((\delta);\alpha)U'(M - C_S S^*(\delta) - C_X X^*(\delta))(C_X)] \\
& - (1 - p(S^*((\delta);\alpha))U'(M - C_S S^*(\delta) - C_X X^*(\delta))[C_X + D_X(X^*(\delta)); \beta)] = 0.
\end{aligned}
\tag{E34}
$$

The following second-order sufficiency conditions hold at the solution:

$$
EU_{SS} = \begin{bmatrix} p_{SS}(\cdot)[U(A) - U(B)] \\ \qquad + C_S[p(\cdot)U''(A)C_S - 2p_S(\cdot)U'(A)] \\ \qquad + C_S[U''(B)C_S(1 - p(\cdot)) + 2p_S(\cdot)U'(B)] \end{bmatrix} < 0\,, \tag{E35}
$$

$$
EU_{XX} = \begin{bmatrix} C_X{}^2 p(\cdot)U''(A)] + (1 - p(\cdot))U''(B)[C_X + D_X(\cdot)]^2 \\ \qquad - (1 - p(\cdot))U'(B)D_{XX}(\cdot) \end{bmatrix} < 0\text{, and} \tag{E36}
$$

$$
|A| = (EU_{SS})(EU_{XX}) - (EU_{SX})^2 > 0. \tag{E37}
$$

Note that before, under risk neutral preferences, the second-order sufficiency conditions hold as $p_{SS} < 0$ and $D_{XX} > 0$. In reality, it might be reasonable to predict that the marginal productivity of self-protection and self-insurance are diminishing regardless of the type of risk behavior of the social planner. However, analytically, the model does not indicate whether either risk reducing technology is subject to diminishing marginal returns, as previously found under risk neutrality, without additional assumptions on the magnitude of the unobservable utility terms.

Finally, the second order cross partial derivative is shown as

$$EU_{SX} = EU_{XS} = \begin{bmatrix} -p_S(\cdot)U'(A)C_X + p(\cdot)U''(A)C_X C_S \\ \qquad +[D_X(X;\beta) + C_X][p_S(\cdot)U'(B) + (1-p(\cdot))U''(B)C_S] \end{bmatrix}. \qquad \text{(E38)}$$

All terms in equation (E38), but the last are found to be negative. Therefore, in order to determine the sign of equation (E38), requires the knowledge of the magnitude of $p_S(\cdot)U'(B)$ and $(1-p(\cdot))U''(B)C_S$. Hence, the sign of the second order cross partial derivative, EU_{SX}, can be positive, negative, or zero, in contrast to the risk neutral case, in which $EU_{SX} < 0$ holds.

6.2 Comparative Statics and Economic Interpretation

The same approach used for the risk neutral case is used to determine how the decision variables *X* and *S* will change in response to a change in the parameters M, C_S, C_X, α, and β under risk averse preferences.

To begin, consider how a change in income, *M*, will effect S^* and X^*. The partial differentiation of equations (E33) and (E34) with respect to *M*, results in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial M \\ \partial X^*/\partial M \end{bmatrix} \equiv \begin{bmatrix} -EU_{SM} \\ -EU_{XM} \end{bmatrix}, \tag{E39}$$

where

$$EU_{SM} = \left[p_S(\cdot)U'(A) - C_S\, p(\cdot)U''(A)\right] - \left[p_S(\cdot)U'(B) + (1-p(\cdot))U''(B)C_S\right], \tag{E40}$$

$$EU_{XM} = -C_X\, p(\cdot)U''(A) - (1-p(\cdot))U''(B)[C_X + D_X(\cdot)]. \tag{E41}$$

Plugging in equations (E40) and (E41) into equation (E39) yields the comparative static results as

$$\frac{\partial S^*}{\partial M} \equiv \frac{-(EU_{SM})(EU_{XX}) + (EU_{XM})(EU_{SX})}{|A|}, \tag{E42}$$

$$\frac{\partial X^*}{\partial M} \equiv \frac{-(EU_{XM})(EU_{SS}) + (EU_{SM})(EU_{XS})}{|A|}. \tag{E43}$$

From equations (E42) and (E43), the comparative-static results indicate that a risk averse social planner could increase or decrease the level of self-protection and the level of self-insurance when initial wealth increases. In contrast, it was found that under risk neutrality, the planner would not adjust the levels of either technology due to a change in income. This result was due to the risk neutral planner's linear utility function. Under risk aversion, the planner exhibits a concave utility function indicating that lower levels of initial income will result in larger changes of utility than if the planner begins with a higher initial income. Therefore, the optimal levels of self-protection and self-insurance that a risk averse individual will employ depend on the location of the initial wealth. In order to determine the relevant signs of EU_{SM} and EU_{XM} and ultimately the signs of equations (E42) and (E43) would require the knowledge of the magnitude of the unobservable utility terms.

Now consider how a change in the cost of self-insurance C_X, will affect the optimal levels of self-protection S^* and self-insurance X^*. This requires the partial differentiation of equations (E33) and (E34) with respect to C_X, resulting in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^* / \partial C_X \\ \partial X^* / \partial C_X \end{bmatrix} \equiv \begin{bmatrix} -EU_{SC_X} \\ -EU_{XC_X} \end{bmatrix}, \tag{E44}$$

where,

$$EU_{SC_X} = X[C_S(1-p(\cdot))U''(B) + p_S(\cdot)U'(B)] + X[p(\cdot)C_S U''(A) - p_S(\cdot)U'(A)], \tag{E45}$$

$$EU_{XC_X} = \begin{bmatrix} X[C_X p(\cdot)U''(A) + (1-p(\cdot))U''(B)[C_X + D_X(\cdot)]] \\ - p(\cdot)U'(A) - (1-p(\cdot))U'(B) \end{bmatrix}. \tag{E46}$$

Plugging in equations (E45) and (E46) into equation (E44) yields the comparative static results as

$$\frac{\partial S^*}{\partial C_X} = \frac{-(EU_{SC_X})(EU_{XX}) + (EU_{XC_X})(EU_{SX})}{|A|}, \tag{E47}$$

$$\frac{\partial X^*}{\partial C_X} = \frac{-(EU_{XC_X})(EU_{SS}) + (EU_{SC_X})(EU_{XS})}{|A|}. \tag{E48}$$

These results imply that an increase in the cost of self-insurance could result in a decrease or an increase in the level of self-protection and in the level of self-insurance. In contrast, under risk neutrality, an increase in the cost of self-insurance would lead to an increase in the cost of self-protection and a decrease in self-insurance.

Consider now how a change in the cost of self-protection C_S, will affect the optimal levels of self-protection S^* and X^*. This requires the partial differentiation of equations (E33) and (E34) with respect to C_S, resulting in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial C_S \\ \partial X^*/\partial C_S \end{bmatrix} \equiv \begin{bmatrix} -EU_{SC_S} \\ -EU_{XC_S} \end{bmatrix}, \tag{E49}$$

where,

$$EU_{SC_S} = \begin{bmatrix} S[C_S(1-p(\cdot))U''(B) + p_S(\cdot)U'(B)] \\ \qquad + S[p(\cdot)U''(A)C_S - p_S(\cdot)U'(A)] - p(\cdot)U'(A) - (1-p(\cdot))U'(B) \end{bmatrix}, \tag{E50}$$

$$EU_{XC_S} = S[C_X\, p(\cdot)U''(A) + (1-p(\cdot))U''(B)[C_X + D_X(\cdot)]]. \tag{E51}$$

Plugging in equations (E50) and (E51) into equation (E49) yields the comparative static results as

$$\frac{\partial S^*}{\partial C_S} = \frac{-(EU_{SC_S})(EU_{XX}) + (EU_{XC_S})(EU_{SX})}{|A|}, \tag{E52}$$

$$\frac{\partial X^*}{\partial C_S} = \frac{-(EU_{XC_S})(EU_{SS}) + (EU_{SC_S})(EU_{XS})}{|A|}. \tag{E53}$$

In comparison to a risk neutral planner, who would substitute towards the relatively cheaper mitigator, a risk averse planner could decrease or increase one, or both activities if the price of one risk reducing activity were to increase, indicating that under risk averse preferences the comparative static results are ambiguous.

The comparative static results found under risk neutrality support the widely accepted idea that the two types of technologies are substitutes. However, under risk averse preferences, it is unclear how the levels of self-protection and self-insurance will change when the cost of either technology changes. It is thus possible for the risk reducing technologies to be substitutes or complements. Without relying on the model to help the planner make a decision, it might be reasonable to assume that a risk averse planner, faced with a fixed income and only two goods, will likely switch to the cheaper technology when there is an increase in the cost of one technology. It would require knowledge of the magnitude of the unobservable utility terms in order to sign equations (E52) and (E53).

Next, consider how the optimal levels of self-protection and self-insurance will respond to changes in the unspecified exogenous variable α. Partial differentiation of equations (E33) and (E34) with respect to α results in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^{*}/\partial\alpha \\ \partial X^{*}/\partial\alpha \end{bmatrix} \equiv \begin{bmatrix} -EU_{S\alpha} \\ -EU_{X\alpha} \end{bmatrix}, \tag{E54}$$

where,

$$EU_{S\alpha} = p_{S\alpha}(\cdot)[U(A) - U(B)] + C_S\, p_{\alpha}(\cdot)[U'(B) - U'(A)], \tag{E55}$$

$$EU_{X\alpha} = -p_{\alpha}(\cdot)U'(A)C_X + p_{\alpha}(\cdot)U'(B)[C_X + D_X(\cdot)]. \tag{E56}$$

Plugging in equations (E55) and (E56) into equation (E54) yields the comparative static results as

$$\frac{\partial S^{*}}{\partial\alpha} = \frac{-(EU_{S\alpha})(EU_{XX}) + (EU_{X\alpha})(EU_{SX})}{|A|}, \tag{E57}$$

$$\frac{\partial X^{*}}{\partial\alpha} = \frac{-(EU_{X\alpha})(EU_{SS}) + (EU_{S\alpha})(EU_{XS})}{|A|}. \tag{E58}$$

Regardless of the signs of $p_{\alpha}(\cdot)$ and $p_{S\alpha}(\cdot)$, the comparative static derivatives $\partial S^{*}/\partial\alpha$ and $\partial X^{*}/\partial\alpha$ are ambiguous because the sign of EU_{SX} is unknown and the magnitude of the unobservable utility terms are unknown. Therefore, it is unclear how a risk averse planner would alter the optimal levels of self-protection and self-insurance when faced with a change in an exogenous factor that affects the probability of an invasion. In comparison to the risk neutral case, in which the comparative static derivatives were signed, the ambiguity in the risk averse case could be attributed to the assumptions placed on the functional form of the utility function.

Finally, consider how the optimal levels of self-protection and self-insurance will respond to changes in the unspecified exogenous variable β. Partial differentiation of equations (E33) and (E34) with respect to β results in

$$\begin{bmatrix} EU_{SS} & EU_{SX} \\ EU_{XS} & EU_{XX} \end{bmatrix} \begin{bmatrix} \partial S^*/\partial\beta \\ \partial X^*/\partial\beta \end{bmatrix} \equiv \begin{bmatrix} -EU_{S\beta} \\ -EU_{X\beta} \end{bmatrix}, \tag{E59}$$

where,

$$EU_{S\beta} = D_{\beta}(\cdot)[U''(B)(1-p(\cdot))C_S + p_S(\cdot)U'(B)] \ , \tag{E60}$$

$$EU_{X\beta} = D_{\beta}(\cdot)(1-p(\cdot))U''(B)[C_X + D_X(\cdot)] - (1-p(\cdot))D_{X\beta}(\cdot)U'(B). \tag{E61}$$

Plugging in equations (E60) and (E61) into equation (E59) yields the comparative static results as

$$\frac{\partial S^*}{\partial\beta} = \frac{-(EU_{S\beta})(EU_{XX}) + (EU_{X\beta})(EU_{SX})}{|A|}, \tag{E62}$$

$$\frac{\partial X^*}{\partial\beta} = \frac{-(EU_{X\beta})(EU_{SS}) + (EU_{S\beta})(EU_{XS})}{|A|}. \tag{E63}$$

In comparison to the results under risk neutral preferences, the signs of the partial derivative of the choice variables, *S* and *X*, with respect to β are ambiguous regardless of the assumptions placed on $D_{\beta}(\cdot)$ and $D_{X\beta}(\cdot)$. Thus, for a risk averse social planner facing a change in an exogenous factor that affects the damage function, the comparative static results indicate that the planner could decrease or increase one, or both activities.

6.3 Ad Hoc Assumptions

Under certain ad hoc assumptions, the comparative statics under risk averse preferences can be signed. In this section, several assumptions are made to demonstrate how a risk averse planner might adjust the levels of self-protection and self-insurance to employ in response to changes in α and β. It must be noted, that a change in any one of the assumptions could lead to different outcomes.

To begin, assume as before that equations (E6) and (E7) still hold and that the following are found to be true:

$$U'(.) > 0 \text{ and } U''(.) < 0 . \tag{E64}$$

Equation (E64) simply states that the utility function is increasing and strictly concave, and implies the following two results seeing as $A > B$:

$$U(A) > U(B), \tag{E65}$$

$$U'(A) < U'(B). \tag{E66}$$

From equation (E65) it is seen that the utility in the non-invaded state is greater than the utility in the invaded state, which is subject to expected damages. Equation (E66) states that the marginal utility of income in A is less than the marginal utility of income in B. This is because an additional dollar is worth more when the individual has less initial income. Also assume that

$$p_S(\cdot) > 0 \text{ and } p_{SS}(\cdot) < 0 \tag{E67}$$

From equation (E67) the probability of the non-invaded state increases with increases in the level of self-protection but at a diminishing rate. Furthermore, assume that

$$D_X(\cdot) < 0 \text{ and } D_{XX}(\cdot) > 0 \tag{E68}$$

Equation (E68) states that damages decrease when the social planner engages in a higher level of self-insurance *X*, but at a decreasing rate, to reflect the diminishing marginal effectiveness of self-insurance.

Now recall the second order cross partial of self-protection and self-insurance, EU_{SX}, restated below as

$$EU_{SX} = EU_{XS} = \begin{bmatrix} -p_S(\cdot)U'(A)C_X + p(\cdot)U''(A)C_X C_S \\ +[D_X(X;\beta)+C_X][p_S(\cdot)U'(B)+(1-p(\cdot))U''(B)C_S] \end{bmatrix}.$$

From the assumption that equations (E6), (E7), and (E64-E68) hold, it can be shown that all terms on the right-hand side are negative, with the exception of the last term. The second-order cross partial derivative EU_{SX}, will be negative, as found under risk neutrality, if the magnitude of $p_S(\cdot)U'(B)$ is greater than or equal to the magnitude of $(1-p(\cdot))U''(B)C_S$. This is stated as the following assumption

$$[p_S(\cdot)U'(B)+(1-p(\cdot))U''(B)C_S] \geq 0. \tag{E69}$$

Assuming that equation (E69) holds then $EU_{SX} \leq 0$. Under the assumption that equations (E6), (E7), and (E64-E69) hold, it is now possible to determine $\partial S^* / \partial \alpha$ and $\partial X^* / \partial \alpha$. Recall, however, that to sign equations (E55) and (E56) requires assumptions on the sign of $p_\alpha(\cdot)$ and $p_{S\alpha}(\cdot)$. If $p_\alpha(\cdot) > 0$ and $p_{S\alpha}(\cdot) \geq 0$, then equation (E55), or $EU_{S\alpha}$ is positive and (E56), or $EU_{X\alpha}$ is negative. If the opposite condition holds in which $p_\alpha(\cdot) < 0$ and $p_{S\alpha}(\cdot) \leq 0$, then equation (E55) is negative and (E56) is positive. Thus, under the assumption that equations (E6), (E7), and (E64-E69) hold, then the results from the comparative statics indicate that a risk averse planner would adjust the levels of self-protection and self-insurance in the same direction as a risk neutral planner when the exogenous factor that affects the probability of an invasion increases. These results are shown in Table 4 below.

Table 4: Risk Averse Comparative-Static Results for α

	$\frac{\partial S^*}{\partial \alpha}$		$\frac{\partial X^*}{\partial \alpha}$	
	$p_\alpha > 0$	$p_\alpha < 0$	$p_\alpha > 0$	$p_\alpha < 0$
$p_{S\alpha} > 0$	(+)		(-)	
$p_{S\alpha} < 0$		(-)		(+)
$p_{S\alpha} = 0$	(+)	(-)	(-)	(+)

Assuming equations (E6), (E7), and (E64-E69) continue to hold, turn to the situation of determining how a risk averse planner would adjust the levels of self-protection and self-insurance from a change in an exogenous risk that only affects the expected damages. As before, the signs of D_β and $D_{X\beta}$ are required to sign $EU_{S\beta}$ and $EU_{X\beta}$. In order to alleviate some of the ambiguity from the mathematical computations, the following assumption is also required:

$$D_{X\beta} = 0. \tag{E70}$$

Equation (E70) states that a change in the exogenous factor variable that affects expected damages will not influence the marginal benefits of self-insurance. This assumption will eliminate the second term in equation (E61). Therefore, when $D_\beta > 0$ and $D_{X\beta} = 0$, then $EU_{S\beta} < 0$ and $EU_{X\beta} > 0$. Conversely, when $D_\beta < 0$ and $D_{X\beta} = 0$, then $EU_{S\beta} > 0$ and

$EU_{X\beta} < 0$. Plugging in the respective signs into the comparative statics provides the following results shown in Table 5.

Table 5: Risk Averse Comparative-Static Results for β

	$\frac{\partial S^*}{\partial \beta}$		$\frac{\partial X^*}{\partial \beta}$	
	$D_\beta > 0$	$D_\beta < 0$	$D_\beta > 0$	$D_\beta < 0$
$D_{X\beta} = 0$	(-)	(+)	(+)	(-)

In comparison to the results found under risk neutrality, the findings under risk averse preferences are the opposite. The results shown in Table 5 indicate that under the assumption that equations (E6), (E7), and (E64-E70) hold, and under the assumption that an increase in β will increase expected damages then a risk averse planner would decrease the level of self-protection and increase the level of self-insurance. In other words, if the planner expects greater damages, then the optimal solution would be to decrease self-protection activities and increase self-insurance activities. One possible explanation of these results is that a risk averse planner would more likely invest in less risky activities, since self-insurance efforts are typically considered more efficient (Dionne and Eeckhoudt 1985).

As previously mentioned, violation of any of the above assumptions could result in different conclusions. Also, assuming equation (E69) holds, stating that $EU_{SX} < 0$, is a strong assumption. Without further knowledge of the magnitude of $p_S(\cdot)U'(B)$ in relation to the magnitude of $(1-p(\cdot))U''(B)C_S$, determining the sign of EU_{SX} is practically infeasible.

7. DISCUSSION

The purpose of a decision model is to assist the decision maker in the selection of appropriate choices for their situation. If the comparative static analysis yields results, which are refuted then another type of model or functional form might be more appropriate since the model is supposed to explain and yield insight into real-life behavior. The results obtained from this thesis, under the assumption of risk neutral preferences, using the endogenous risk model provide intuitive results, which suggest that the model is appropriate to use when evaluating the invasive species management problem. However, in contrast to the results found under risk neutral preferences, under risk averse preferences the results are inherently ambiguous. Therefore, in the case of a risk averse social planner, the decision maker must make choices based on other methods of evaluation instead of relying on an analytical model to describe what the planner should do. While the results obtained from the analysis that considers risk averse behavior does not provide any unambiguous findings, it does provide a basis for future research to achieve results consistent with real-life behavior.

The ambiguity of the analysis under risk averse preferences can be derived from the explicit account of the comparative static results previously shown. However, one could also have reached this conclusion from viewing the first-order necessary conditions. From the "conjugate pairs theorem," in order for a general maximization problem to have refutable implications, the parameters can only enter a single first-order equations, otherwise the results will be ambiguous (Silberberg and Suen 2000). From equations (E33) and (E34), which show the simultaneous first-order equations under risk averse preferences, the parameters enter both equations and therefore the ambiguity in comparative statics under risk averse preferences can be anticipated.

Since the assumption of preferences was the only change between the two models, the ambiguity between them can be attributed to the assumption of risk aversion. Under risk averse preferences, the utility function is no longer linear, but increasing at a diminishing rate. To account for the functional form requires the presence of the utility function in the first-order conditions, where as under risk neutrality, the utility function is linear and therefore the slope of the utility function is constant across all values of income.

This thesis demonstrates that algebraic manipulation of the comparative statics and numerous assumptions are required in order to determine results for a risk averse social planner. However, these results are subject to the assumptions, which in many cases might not hold. In other instances, determining the numerical values of the parameters might determine whether these assumptions hold, but the assignment of numerical values to the unobservable utility terms is often difficult and in many cases infeasible.

8. CONCLUSION

Biological invaders present a serious risk to society because of the considerable adverse consequences that typically result from such events. Previous analysis of invasive species focused mainly on management for dealing with a biological invader that has been introduced and established. Recognition of the growing threat of invaders has prompted more recent resources devoted to reducing the risk of invaders. Thus, in response efforts are directed toward determining the optimal allocation of resources towards the mix of prevention and control technologies against a potential invader.

The endogenous risk framework, used in this thesis, to determine the optimal mix of risk reducing strategies, yields results that are dependent on the assumptions regarding the risk behavior of the social planner. If the social planner is risk neutral, the results are clearly defined and indicate that self-protection and self-insurance are substitute goods. The results also indicate that a risk neutral planner will increase self-protection and decrease self-insurance from an increase in the probability of no losses or greater expected damages. Conversely, a risk neutral planner would decrease self-protection and increase self-insurance from an increase in the probability of losses or greater expected benefits from an invader. However, under risk averse preferences, the model does not yield unambiguous results. Thus, it can be concluded that the model is not capable of yielding a decision criteria that will hold universally because the results are dependent on the curvature of the probability and utility functions.

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